Nanaimo River Estuary Restoration: An Assessment of Berm Removal on Benthic Macroinvertebrates in Tidal Channels

by

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Approval

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Ethics Statement

The author, whose name appears on the title page of this work, has obtained, for the research described in this work, either:

a. human research ethics approval from the Simon Fraser University Office of Research Ethics

or

b. advance approval of the animal care protocol from the University Animal Care Committee of Simon Fraser University

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Abstract

Macroinvertebrates in two berm-impacted tidal channels (Site A and Site B) were compared to a natural channel (Site C) to determine short-term response to berm removal restoration using a BACI study design. Multivariate analysis indicates that the benthic community composition shifted from before berm removal to after berm removal conditions but not in a predictable organized way. Total abundance was highest at Site A in both conditions (before and after berm-removal). Invertebrate diversity was similar and low among sites. Biomass was highest at Site C. Organic matter percentage was highest at Site C in both conditions and it appeared to increase in Site A and Site B after berm removal. Silt & Clay (>0.0063mm) were statistically different in Site C compared to Site A and Site B although very fine sand was the highest in percentage among sites and in both conditions. Berms affect channel and benthic invertebrate dynamics; time and more research are needed to fully restore the Nanaimo estuary.

Keywords: Tidal channel; Benthic macroinvertebrate; Sediment; Detritus; Berm; Estuary restoration

Dedication

I would like to dedicate this paper to the Master of Science in Ecological Restoration SFU/BCIT 2020 cohort with whom I have overcome so many obstacles with (either physically, socially or emotionally). Thank you for all the shared food in class including the memories on field trips and socials. I am glad to have worked with such dedicated, supportive group of passionate individuals especially during the trying times of 2020 during the (COVID-19) pandemic.

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Thank you to my dear family for all the support (financially and emotionally) and encouragement through this academic journey and in the rest of my life. There is no better group of people to turn to in time of need, “Live Long and Prosper”. Thank you to my friends who stuck by me through thick and thin. You all have been important to the milestones I have achieved in this project and in my personal life and I will be forever grateful for your reassurance.

This project and study would not have been possible without the partnership of the Nature Trust of BC. Thank you to Tom Reid, Steven Henstra, Curtis Rispin and Peter dekoning (now DFO) for all the site information provided and the budget to carry out major parts of this research. Thank you to the taxonomists and staff of Biologica Environmental Services Ltd especially Tara Macdonald, Jenny Thompson and Sarah Steinerstauch for the logistics and processing of my benthic samples.

I would like to acknowledge Dr. Leah Bendell-young and Dr. Jeremy Venditti for their lab space and equipment use, including Morgan Wright for showing me how to use the proper equipment for my analysis. Thank you to Dr. Susan Owen, Dr. Shawn Chartrand, Rebecca Ho and other faculty and staff members of ER in SFU. Thank you to Dr. Anayansi Cohen-Fernández, Dr. Ken Ashley, Dr. Doug Ransome, Dr. Eric Anderson, Dave Harper and other Faculty and staff members of ER in BCIT including Giti Abouhamzeh, Millie Kuyer and Laurie Stott.

Finally, thank you to Alex Harris who worked on-site, shared expenses and experiences of working in an estuary on a student’s budget with me. Thank you to my colleagues that helped me figure out solutions I could not immediately see, we have accomplished something good and it would only get better for all of us from here on.

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List of Acronyms

ANOVA	Analysis of Variance
ARP	Applied Research Project
BACI	Before and After Control Impact
BC	British Columbia
BCIT	British Columbia Institute of Technology
DO	Dissolved Oxygen
GIS	Geographic Information System
LOI	Loss-on-Ignition
LWD	Large Woody Debris
NMDS	Non-metric Multidimensional Scaling
PVC	Polyvinyl Chloride
SFU	Simon Fraser University
TOC	Total Organic Carbon
USGS	United States Geological Survey

Chapter 1. Introduction

1.1. Background

Estuaries are generally semi-enclosed coastal bodies of water with free connection to the sea forming transitional zones between terrestrial, riverine and marine ecosystems (Seliskar et al. 1983; Simenstad 1983). They are among the most biologically productive ecosystems on the planet (Robb 2014). In British Columbia, they account for less than 3% of its 27,000km coastline but supports about 80% of all its coastal wildlife (Robb 2014; Shaw 2012). However, many estuaries in BC, especially tidal salt marsh habitat have been largely altered by human activities such as conversion to agricultural land and the construction of berms, dikes, levees and shoreline armoring for flood control that alter physical processes such as hydrological flow and tidal flushing (Hood 2014; Park et al. 2017). These changes can also have adverse effects on the biological processes and components in estuarine ecosystems (Woo et al. 2018). This can include communities of marine, riverine, diadromous and estuarine adult and juvenile fish inhabiting estuarine ecosystems (Hwang et al. 2017).

Among the most important species in terms of management and restoration of estuaries are the pacific salmon (*Oncorhynchus spp.*). Certain species especially Chinook and Chum inhabit tidal channels in estuaries before migrating out to sea. Tidal channels are dendritic channels that connect freshwater channels to the open estuary while serving as nurseries for juvenile fish (Walton et al. 2013; Visintainer et al. 2006). In tidal channels, most juvenile pacific salmon rely partly on benthic invertebrates as a food source while using estuarine environments (Shaw 2012; Sibert 1979; Woo et al. 2018). Chinook salmon populations have largely been on the decline in recent years partly attributed to reduction in juvenile rearing habitat in estuarine environment (Woo et al. 2018). Breaching and in some cases complete removal of human engineered flood control structures that alter the natural physical and biological processes in the landscape have been suggested as ways to restore benthic ecosystem dynamics(Park et al. 2017; Simenstad & Cordell 2000).

The partial breaching of flood control barriers has its benefits such as reduced mosquito breeding sites, increased waterfowl nesting & foraging space, and from a monetary perspective, reduces the cost of a restoration (Seliskar et al. 1983) However, partial breaching is sometimes not enough to restore benthic biomass primary production for energy transfer to higher trophic organisms (Stocks & Grassle 2003). . Dendritic tidal channels affected by flood control structures can offer a different perspective from mudflats, sloughs and nearshore environment which are the usual habitat areas used to study the effects of restoration on benthic community assemblages that serve as part of the food source for juvenile salmonids(Hwang et al. 2017). The composition and structure of the benthic invertebrate community in this habitat can be an indicator of prey availability and overall environmental health. Linking the benthic community to physical components such as substrate stability & tranport, organic matter content, water temperature, salinity, dissolved oxygen (DO) and pH of the site may help identify factors contributing to limited productivity and strategies for improvement in management (Woo et al. 2018). These factors often help influence channel dynamics that might alter quality of fish habitat in tidal marsh habitat for different juvenile salmonids (Kneib 1984; Walton et al. 2013; Woo et al. 2018).

1.2. Goal and Objectives

The purpose of this research is to evaluate invertebrate communities among sites with varying levels of berm impacts in the Nanaimo estuary. This helps to determine if there is an environmental benefit to full berm removal over partial breaching compared to natural sites and evaluate if there is an effect on juvenile salmonid benthic prey availability. By collecting data and studying hypothesised mechanisms possibly responsible for similarity or heterogeneity in invertebrate abundance and diversity among sites, benthic estuarine restoration measures may be linked to quality of juvenile salmon rearing habitat (Borja et al. 2010). Benthic invertebrates can be classified by substrate, size, type and location (Herman et al. 1999). Classification by size focusing on the size class macrobenthos was the method used for this study.

This research could offer an insight to the efficacy of established protocols in the removal of flood control structures in estuaries for the improvement of fish habitat quality and potentially benefit monitoring of estuarine benthic ecosystem health during the overall estuary restoration process. My goal was achieved through the following objectives :

- Comparing the differences in macroinvertebrate abundance, richness, diversity and biomass among sites and in different conditions (before berm removal and after berm removal).
- Comparing the differences in Sediment grain size particles and organic matter content of soil among sites and in different conditions (before berm removal and after berm removal) and analyzing how these variables affect benthic invertebrate composition.
- Comparing water temperature in channels at sites and checking if presence or absence of the berm had a short-term influence on changes in water temperature.

Chapter 2. Materials & Methods

2.1. Study Area Description

The Nanaimo River estuary is the largest estuary on Vancouver Island draining an area of approximately 84,000 hectares from the Nanaimo and Chase River watersheds. It can also be influenced by the Fraser River in May and June when the Fraser is in freshet (Catherine Berris Associates Inc. 2006; Shaw 2012). Northwesterly winds affect the delta with tidal flushing increasing towards the northern part of the estuary during strong winds. The tides are mainly diurnal with two highs and two lows of different heights in a tidal day of about 25 hours corresponding to those in the Strait of Georgia (Shaw 2012) whose location is seen Figure 1 below. Sites selected for the research sampling were in the salt marsh affected by these tidal cycles.

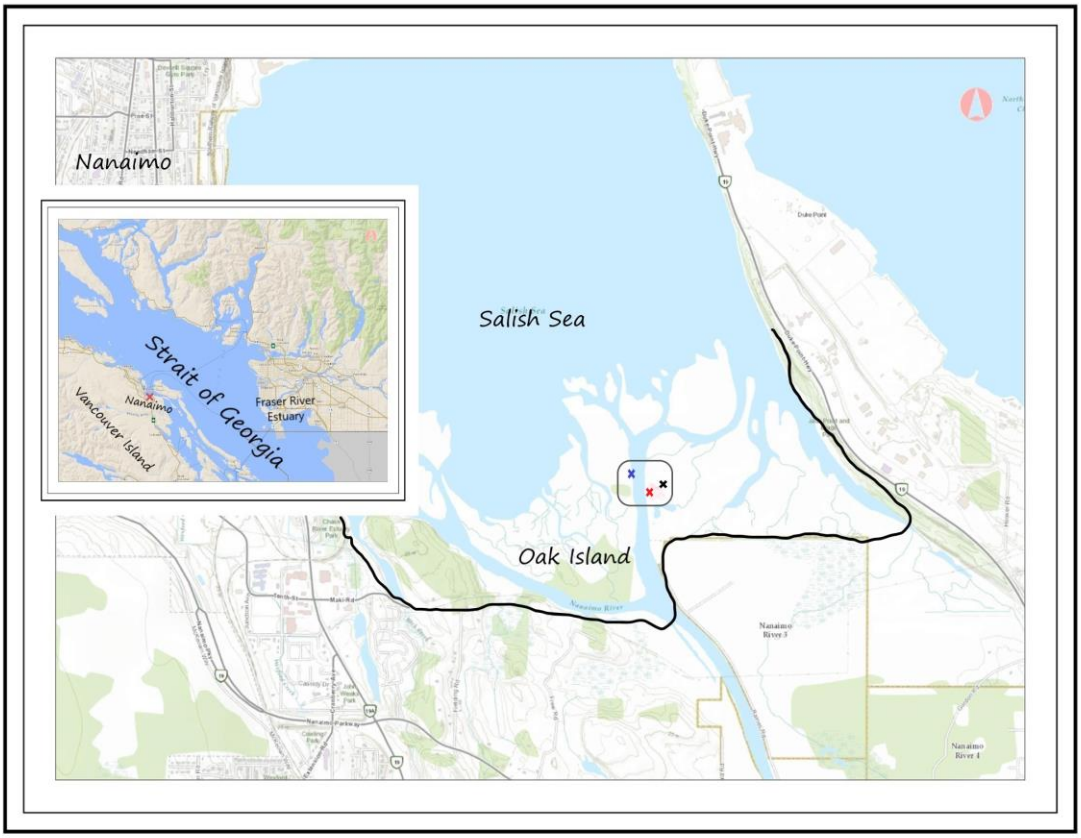

Figure 1. Maps of study site on a geographical regional and local scale .The "X" symbols in the rectangular symbol of the larger map denote the exact study location in the estuary and approximate location of channels and the black line demarcates the approximate boundary area of the Nanaimo estuary managed by Nature Trust of BC. The red X symbol in the smaller embedded map denotes where the estuary is located on a larger scale. (Images: Are adapted from maps.gov.bc.ca)

The estuary supports a diverse number of bird species, deer and small mammals including 18 blue and 15 red-listed species (Catherine Berris Associates Inc. 2006; Shaw 2012). The estuary supports intertidal, riparian and marsh floral communities. The upland flora is representative of the Coastal Douglas-fir moist maritime bio-geoclimatic subzone (Catherine Berris Associates Inc. 2006). Historically, the estuary supported five species of salmon including three genetically unique runs of chinook salmon (*Oncorhynchus tshawytscha*) (Shaw 2012). Two different Spring stocks and one Fall stock have been recorded to use the estuary (Healey 1980; Carl & Healey 1984).

Since pre-colonial times, the Nanaimo estuary has been an important economic and cultural resource to the Snuneymuxw First Nation (Catherine Berris Associates Inc. 2006) . Post-European settlers immigrating to the region; the surrounding area has been subjected to coal mining in the 1850s, extensive tree harvests for forestry and land development for agriculture after the coal mines were depleted. Much of the estuary is considered crown land, some parts are owned by the Nanaimo Port Authority and there are Indian reserves located in and around the estuary. Some land parcels are privately owned but a significant land mass at the mouth of the estuary has bee acquired by Nature Trust of British Columbia (Catherine Berris Associates Inc. 2006; Shaw 2012).

Berm structure in the estuary was presumed to have been erected sometime in the early 1900s with the current structure occupying approximately 8,260m^3 of area in the estuary. Previous restoration by dike breaching began in 1988 with the most recent works done in 2006 along Holden Creek, one of the three tributaries that contributes freshwater to the estuary (Shaw 2012). The most recent restoration activity was completed by removing 2.5km of berm (approximately 1,887m^3) in the tidal salt marsh of the estuary in August of 2019 as the first part of a three-year plan by Nature Trust of British Columbia to restore fully functioning biological and physical processes to the ecosystem.

My research design involved a Before and After Controlled Impact (BACI) sampling design looking at channels with different levels of berm impact which includes site A (Ahead channel), Site B (Behind Berm channel) and Site C (Oak Island channel). Site C was used for the reference conditions because it was not in the area impacted by any berm structures located within the estuary. The sites (channels) were selected based on their proximity to the intended restoration project and the proximity to the main Nanaimo channel based on flow gradient as seen in Figure 2. The overall berm structures were divided into five sections and year-one of this project involved removal of section one described in Figure 3 below.

Figure 2. Map showing study channels labelled Site A(yellow), Site B(red) and Site C(blue) and the proximity of berm (black line) intended to be removed in 2019 and the lower part of the eastern main channel of the Nanaimo River flowing through the Nanaimo estuary. (Image: Adapted from maps.gov.bc.ca)

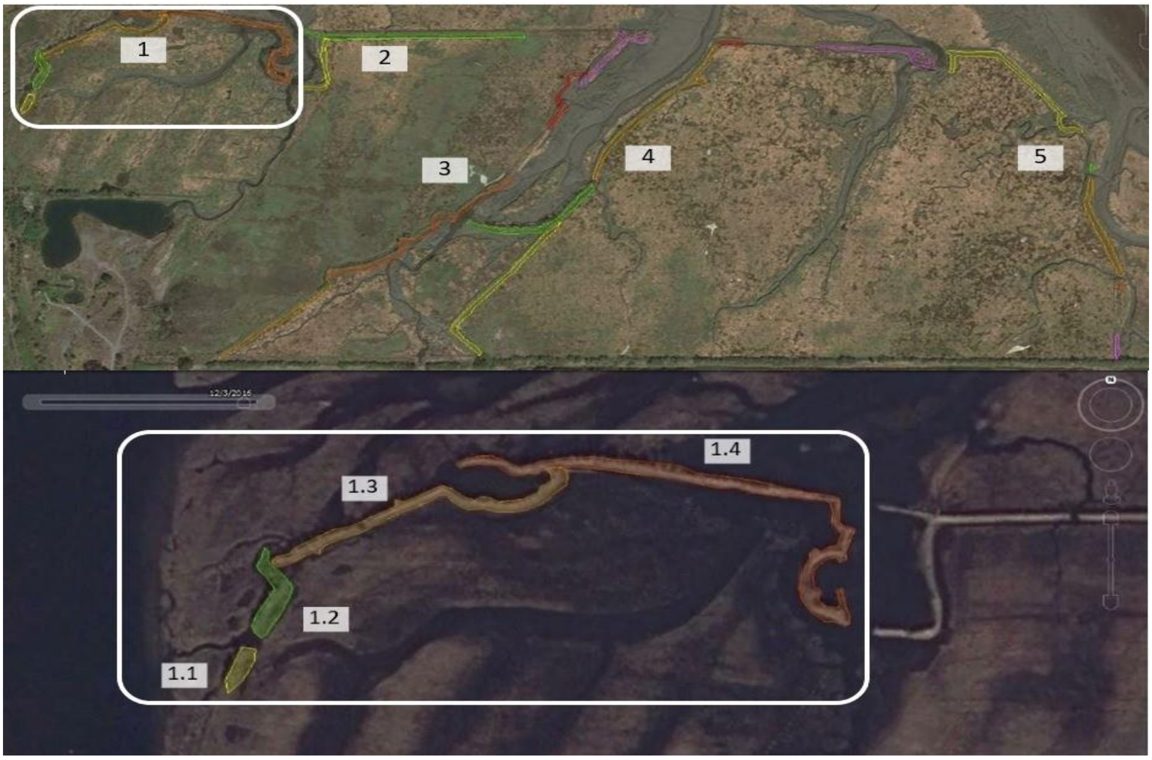

Figure 3. Maps showing parts of section one (white box) of the berm removal plan for year-one of the restoration project and the overall sections of the berm structures to be removed by the end of the restoration project in Nanaimo estuary, Nanaimo, BC. (Image: Adapted from deKoning, 2019)

Although the channels for site A and B were connected by a small pool as a result of an earlier breach; the assumption was that they would present different environmental conditions for sampling due to different levels of tidal flushing exposure. This is because Site A was directly connected to the main stem of the Nanaimo River and was seaward of the berm while Site B was leeward of the berm. The length of each channel was measured using satellite imagery on ArcGIS and ground-truthed using a measuring tape on site for additional accuracy to get an idea of what can be appropriate for sampling distancing.

2.2. Benthic Invertebrate Collection

Based on consultation with biologists from Biologica Consulting, it was initially decided that 10 replicate samples in each creek for a total of 60 benthic samples was suitable coverage for the study design and questions I was asking for the purpose of the study sites for benthic sampling. This is displayed in Figure 4 below.

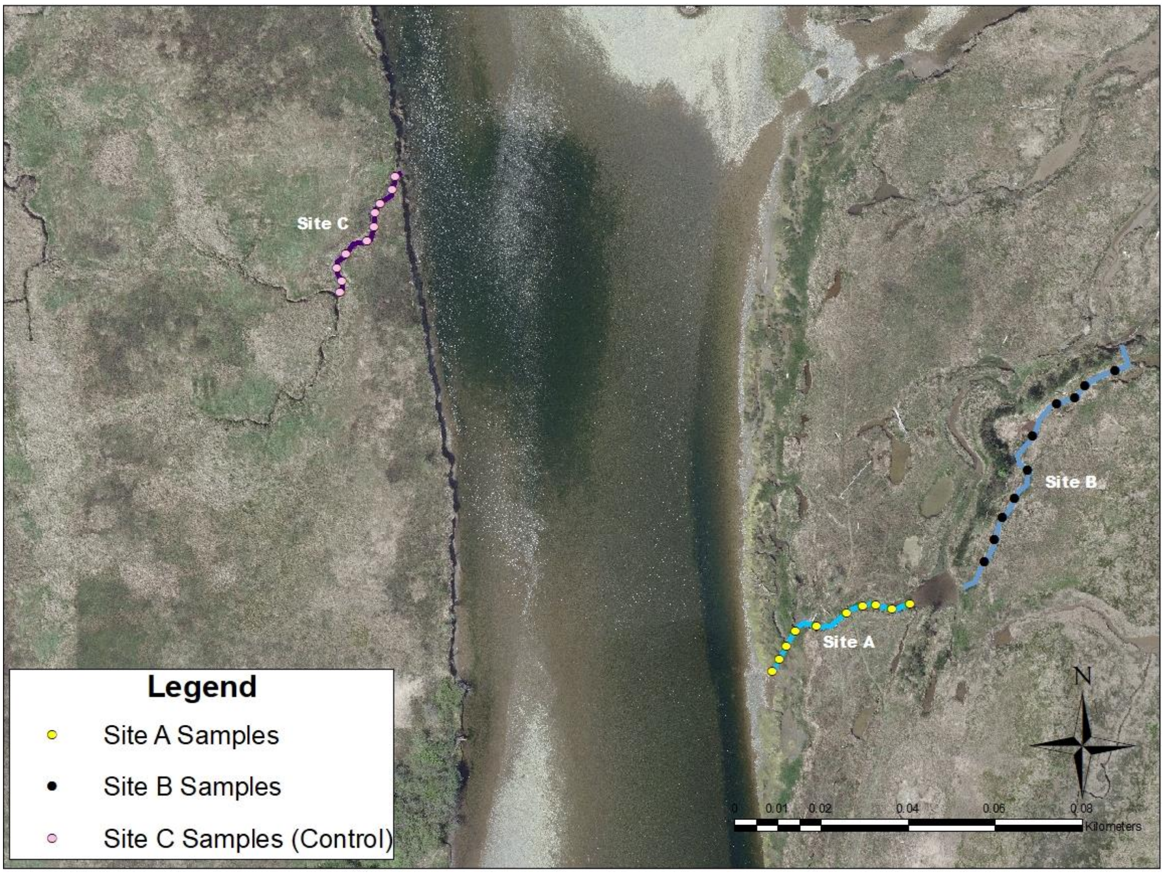

Figure 4. Map showing channels where benthic samples were collected including the lower portion of the eastern main channel of the Nanaimo River flowing through the Nanaimo estuary (Image: Adapted from nanaimo.ca/ortho/)

Sampling occurred from the beginning of July before berm removal to the end of August after the berm removal for the site had been completed. Using a random number generator, a point along each channel thalweg was selected for sampling and marked using wooden stakes and wired coloured flags for repeated measurements (i.e. before and after) at the same site for the duration of the study. Although the distances for sampling were randomly generated a minimum distance of 2 meters was maintained between samples to maintain independence among samples due to the small spatial scale of the sample size. The protocol followed was loosely based on the unpublished Benthic Invertebrate Standard Operating Procedures Manual by the US Geological Survey (USGS), San Francisco Bay Estuary Field Station with adjustments considered for the recommendations made by Biologica Environmental Services; a Canadian consulting company helping with the processing and identification of the benthic invertebrates . The samples were collected using a cylindrical corer made from a PVC pipe with a diameter of 10cm with the aid of a shovel. Soil core samples were taken to a depth of 10cm from the bottom of each creek as close to the middle of the channel as possible at low tide. Each 10cm soil sample was washed and filtered on site through a No.35 (500 µm) sieve screen using water on site from the main channel of the Nanaimo river. Whatever remained on the sieve was preserved in a 1 litre plastic jar using a 500ml solution combination of 4-parts waters and 1-part formalin. The samples were stored in a cooler after collection and transported to a lab for sorting.

Figure 5. Photo of PVC corer used to extract sediment containing benthic invertebrate samples and soil samples for a study done on behalf of the Nature Trust of BC during a restoration project started in 2019 at the Nanaimo estuary, Nanaimo, BC.

2.3. Benthic Invertebrate Processing

The benthic invertebrate samples were sorted in a lab to separate the invertebrates from the organic debris and sediment using dissecting forceps and a dissecting microscope. Gloves, protective googles and a fume hood was used for personal protection. Using the protocol devised by Biologica Environmental Services each sample was stained with Rose Bengal dye while soaked in ethanol and spread out on a tray where taxa >1.5 cm was pulled out from the whole sample for a whole count prior to sub-sampling (one-quarter) for each sample. This is to ensure rare and large taxa are not missed when sub-sampling. Abundance was then calculated by multiplying the split by the raw count to get an extrapolated total for each sample. The sorted benthic invertebrate samples were stored in ethanol, relabelled accordingly and sent to Biologica Environmental Services to calculate abundance and help with taxa identification to family level. However due to time and budget constraints only 18 samples in total (3 before and 3 after from each channel) was processed to species level identification.

Invertebrates belonging to the Acari subclass and Insecta order were noted but considered terrestrial not benthic invertebrates. Copepoda, Ostracoda and egg masses were considered pelagic prey and Nematoda although a benthic invertebrate captured on the 0.5mm screen was considered a meioinvertebrate because it was not retained on a 1mm screen. Therefore, these specimens were not included in our sample analysis.

2.4. Sediment and Organic Matter Collection

Separate soil samples were collected to extrapolate soil particle size and measure organic matter content of the sediment in each tidal channel. The same corer used for benthic collection was used to collect soil samples for sediment and organic matter analysis. In each channel that was sampled for benthic invertebrates, 3 replicate soil samples each a meter apart from the next were taken to a depth of 10 cm both before and after the restoration process for a total of 18 samples. Each soil sediment sample was stored in a plastic Ziploc, placed in a cooler and then transported to a fridge off site for later processing. The location of each sediment sample was also flagged for sampling after berm removal was completed. The samples were taken at low tide for convenience and easy accessibility to the channels.

2.5. Sediment Grain Size and Organic Matter Processing

The samples were put in foil containers and dried in an oven at 60ºc for 48 hours to remove water content until no net weigh loss was observed. Each soil sample collected at each site was then weighed and filtered to remove large debris and cut in half to be used separately for grain size analysis and organic content analysis. The grain size portion was incinerated to completely remove organic matter content. Each sample was then weighed again and filtered through sieve sizes classes >2mm, (gravel),) 0.5mm – 2mm (very coarse and coarse sand), 0.25mm – 0.5mm (medium sand), 0.125mm – 0.25mm (fine sand, 0.063mm – 0.125mm (very fine sand) and <0.063mm (silt and clay) using a sieve shaker machine for 5 minutes to determine the above classes of grain sizes and whole phi for particle size. A picture of the sieve shaker during the sieving process can be seen in Appendix C (Figure 26). The weight of each grain size class measured was recorded and the total for each site was calculated by summing the weights of each class for the samples of each site and presented as fraction of the overall weight of the dried samples from each site.

Percent organic matter was determined through Total Organic Carbon (TOC) via Loss-on-Ignition (LOI) technique (i.e. difference in weights between the dry sample and burnt sample) using ~2 g sub-sample of soil from each of the 18 samples through incineration in a muffler furnace at 550ºc for at least 8 hours. The results were recorded as a percentage of the sample as seen in Figure 5 (Schumacher 2002; Wright et al. 2008)

Figure 6. Sub-samples of a Soil Sediment Sample after testing for TOC vial LOI. Samples were taken from tidal channels during a restoration project began in 2019 by Nature Trust of BC in Nanaimo estuary, Nanaimo BC. Three samples were taken per site at each condition (before and after berm removal).

2.6. Temperature Loggers

Temperature loggers were installed in at 49°08'12" N 123°53'42" W for the bermed channel in Site A and 49°08'14" N 123°53'48" W for the control channel in Site C to measure the daily water temperature every 30 seconds as the tide rises in each channel for the month of July and the first two weeks of August. The daily average was computed in an Excel and I used R to display the daily mean water temperature over time.

Chapter 3. Results

3.1. Organic Matter Analysis

A balanced one-way ANOVA was conducted to test for differences in the organic portion of my soil analysis. As the same sites were used before and after berm removal, the response variable was the difference in organic matter between the 2 repeated measures. The results indicated that there was no difference between organic matter before and after removal dates at Sites A, B or C ($F_{2,6}$=2.14, p-value=0.198). However, as seen in Figure 7, the samples from sites A and B appeared to increase in organic matter percentage after the berm was removed while organic matter content at Site C remained unchanged. As sample size was small in this study (three for each of Sites A, B and C), we conducted a post-hoc power analysis to look at the effect size we had the power to detect (and understand the risk of making a Type II error in interpreting the ANOVA result). The effect size we observed was 0.71 which is interpreted as a very large effect size (Cohen 1988 deems >0.14 as Large), or in other words 71% of the variance in the model is attributed to differences in organic matter. With this large an effect size, to find significance in our results with the recommended 80% power, we would have needed to process 5 additional before and after samples (or 8 per site) at each of sites A, B, and C. Therefore, non-significance in our ANOVA is because of lack of statistical power from a small sample size. In Figure 7, the before and after increase in organic matter is shown for all sites showing that A and B increase. Additionally, site C samples displayed the most organic matter content in both conditions (before and after berm removal).

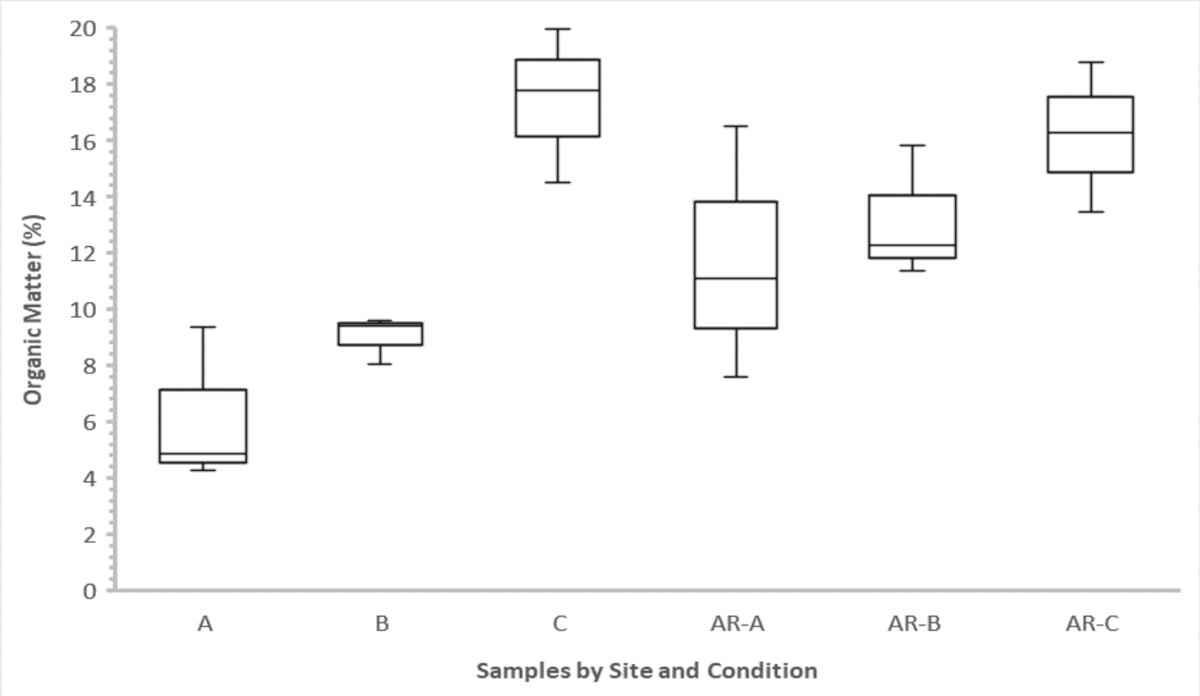

Figure 7. Percent organic matter of ~2g of sediment samples collected from 3 different sites(Site A, Site B and Site C) before and after berm removal at Nanaimo estuary, Nanaimo, BC. Three sediment samples were collected at each site for each condition. Median ±Standard error is shown including medians (horizontal line), the lower and upper 25th and 75th percentiles (boundaries of the box) and minimum and maximum values(whiskers).

3.2. Grain Size Analysis

Results of grain size analysis determined there was no significant difference between percent gravel (p=0.49), very, coarse & coarse sand (0.19), medium sand (p= 0.39), fine sand(p=0.17), very fine sand (p=0.08) before and after berm removal at the three sites. However, percent silt & clay appeared to have significant difference (p=0.039). Non-parametric Wilcox pairwise comparisons (pairwise.wilcox.test) suggest that Site C is significantly different that Sites A and B, indicated in Figure 8. See Appendix B (Figure19) for the summary of other grain sizes and Appendix A (Table 5 and Table 6) for the summary of analysis.

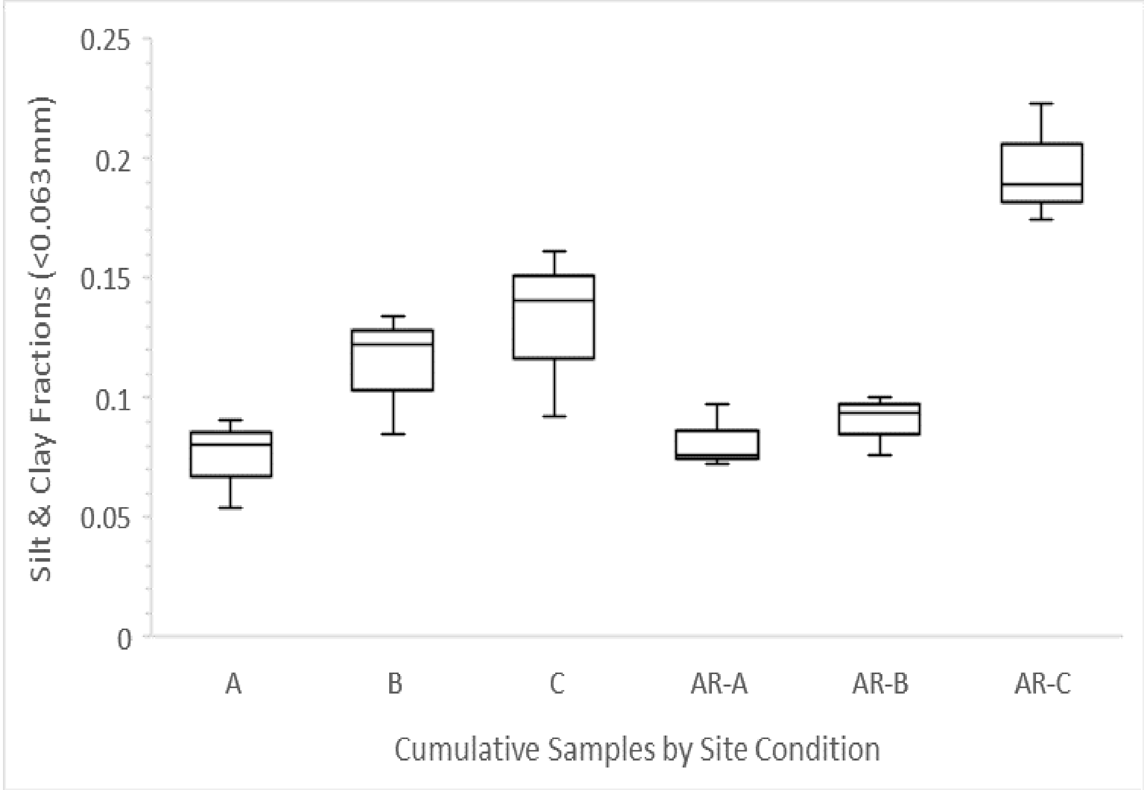

Figure 8. Boxplots of Silt & Clay grain size of sediment samples collected from 3 sites before and after berm removal during a project in 2019 by Nature Trust of BC in Nanaimo estuary, Nanaimo, BC. Three samples per site and condition were collected and percentages are shown as a fraction of 1. Median ±Standard error is shown including medians (horizontal line), the lower and upper 25th and 75th percentiles (boundaries of the box) and minimum and maximum values(whiskers).

The average combined percentage of the six grain size classes for each site at each condition was determine as shown in Figure 9. The sediment sample fractions appear to mainly compromise of fine sand, medium sand and very fine sand. Gravel was the lowest followed by silt & clay fractions. Site A displayed the highest amount of gravel before and after berm removal (14.33%; 13.59%) with site B the lowest in both conditions (1.51%; 5.28%). Coarse sand was highest in Site A with (19.54%; 17.97%) for before and after berm removal respectively. Medium sand did not follow a trend and was highest in Site A and Site B at 28.26% and 27.58% respectively before berm removal and lowest at Site C after berm removal. Fine sand was similar across the sites in both conditions except for before berm removal for Site A (18.20%) which also happens to be the lowest. Very fine sand was highest in Site C in both conditions (23.17%; 22.73%) and lowest at Site A before berm removal at 12.17%. Silt & Clay was highest in Site C in both conditions (13.16%; 19.57%); multiple comparison tests showed changes at Site C for silt & clay were significantly different than those observed at Site A and B. No other grain size classes showed changes that were significant between sites.

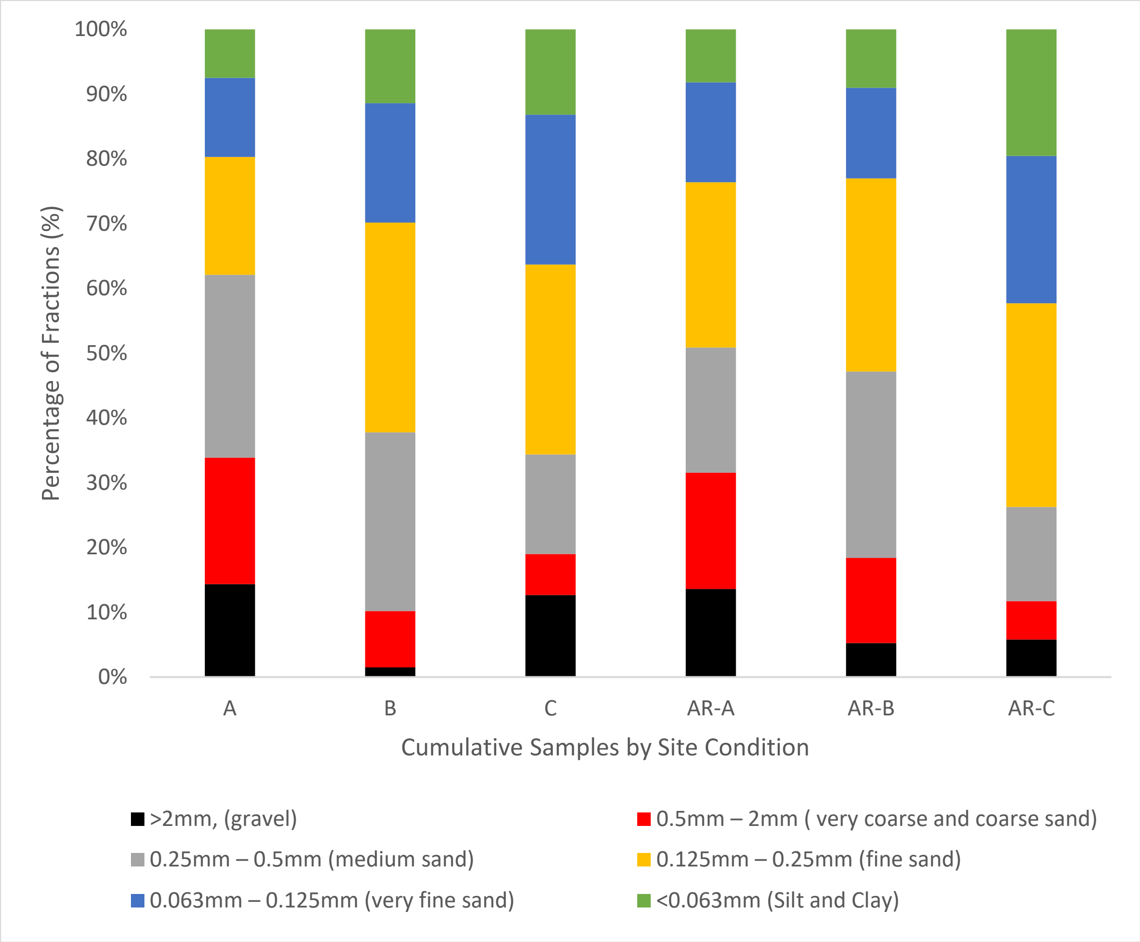

Figure 9. Average percentage of grain sizes (gravel, very coarse & coarse sand, medium sand, fine sand, very fine sand, Silt & clay) of sediment collected from 3 sites in Nanaimo estuary, Nanaimo, BC. Three sediment samples were collected at each site for each condition (before berm removal and after berm removal).

3.3. Water Temperature Data

Figure 10 shows temperature measurements at 30 second intervals. The reference channel had a high of 29.90ºC and a low of 10.59ºC for every 30-second measurement taken and a daily average high of 21.62ºC and low of 15.91ºC respectively. The bermed channel had a 30-second measurement high of 28.8ºC and 9.48ºC and a daily average high of 22.61ºC and a low of 16.24ºC respectively.

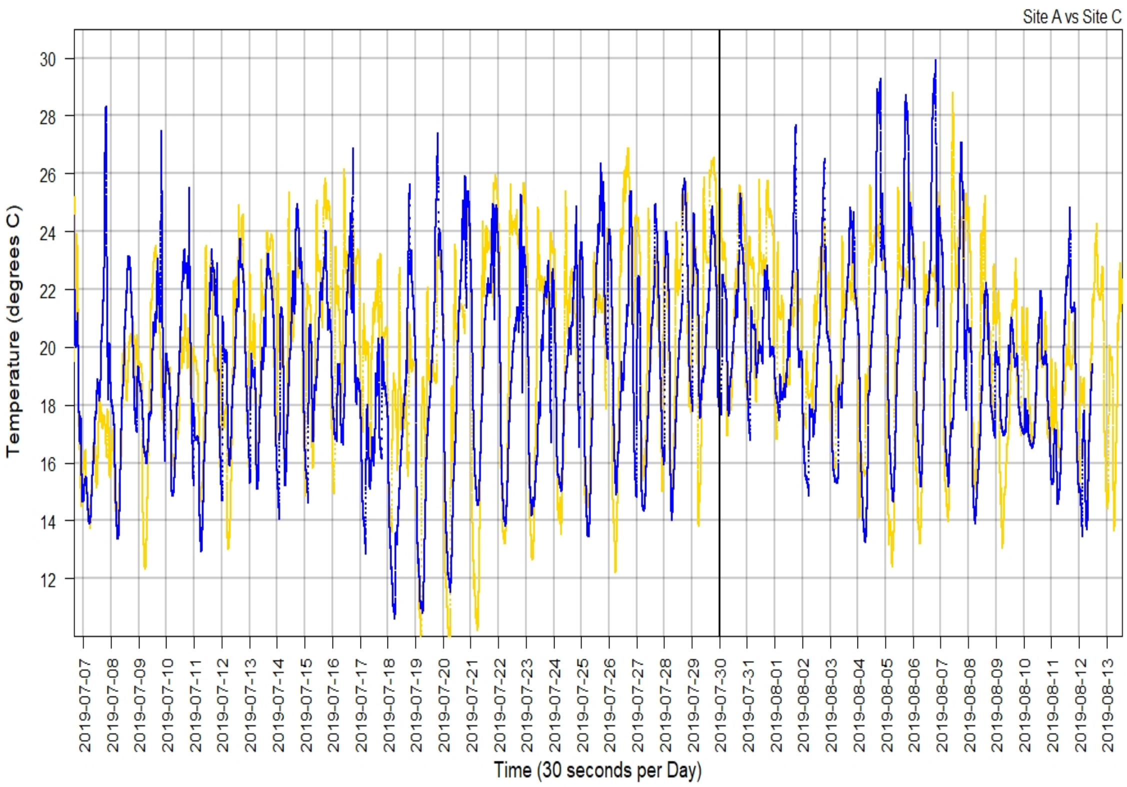

Figure 10. Temperature trends for every 30 seconds between 6th July 2019 and 13th August 2019 for both Site C channel (blue) and Site A channel (gold) with the vertical black Line indicating the Date the Berm removal started in Nanaimo estuary, Nanaimo BC.

The daily average temperatures in Site C channel appears to be slightly lower than the Site A even after the berm came down on the 30th of July 2019. However in general the trend in temperatures seemed to follow the same pattern with identical temperatures for a two day period between August 7th 2019 – August 9th 2019 despite the differences in channel characteristics with Site C being narrower, deeper and more vegetated around the banks than Site A which had wider, flatter, less vegetated banks . This is indicated in Figure 11 below.

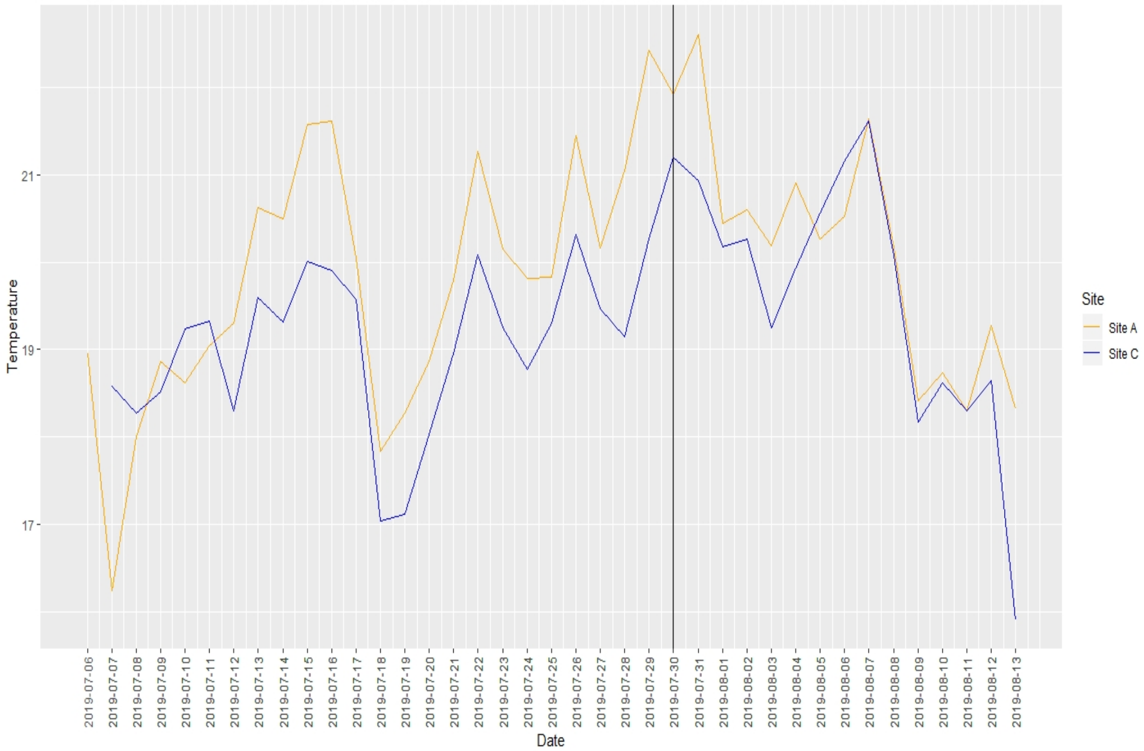

Figure 11. Daily Average Temperature Measurements for Site C (control) channel (blue) and Site A (bermed) channel (orange) with the vertical Back line showing the Date the Berm removal started in Nanaimo estuary, Nanaimo BC.

3.4. Benthic Invertebrate Assessment

There were 33 unique taxa identified in all samples collected in the study sites of the Nanaimo estuary. Identification was mostly done to family level, however higher order taxa than family was identified when there was no lower taxa identification. This included variables such as Family richness, Simpson's diversity index, Shannon-Wiener diversity index. However, Total biomass was measured by phylum as indicated by Appendix A (Table 1). In terms of family richness, Sites A and C had the highest with a value of 18 for both seen in Figure 12. Biomass varied among samples and conditions but was highest at Site C before berm removal as seen in Figure 13.

A total abundance of 12022 individuals was extrapolated from the samples. Total abundance was notably highest in Site A with a combined value of 6450 for both conditions and higher before berm removal at Site A with a value of 3608 as indicated in Figure 14. The Sabellidae family had the most total abundance with a total value of 3414. It was recorded the highest in Site A among all sites after berm removal indicated by Figure . The top ten families in terms of abundance is seen in Figure 16 below, refer to Appendix A (Table 1) and Appendix D (Table 8) for a full list of total abundance, biomass and family taxa collected and calculated for the study.

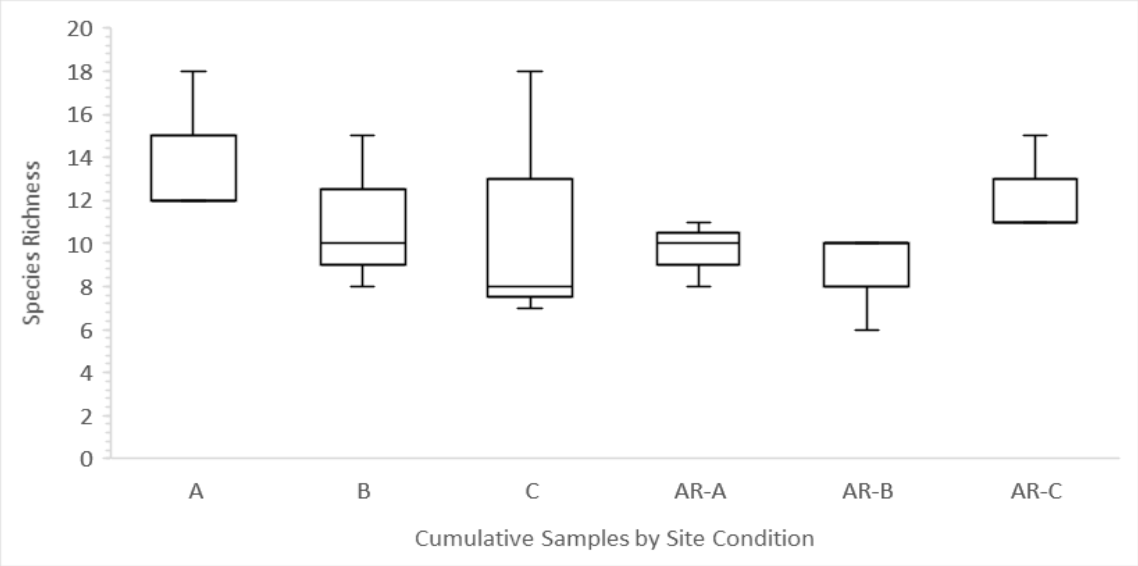

Figure 12. Boxplots showing cumulative Family richness of samples at sites by condition. Median ±Standard error is shown including medians (horizontal line), the lower and upper 25th and 75th percentiles (boundaries of the box) and minimum and maximum values(whiskers).

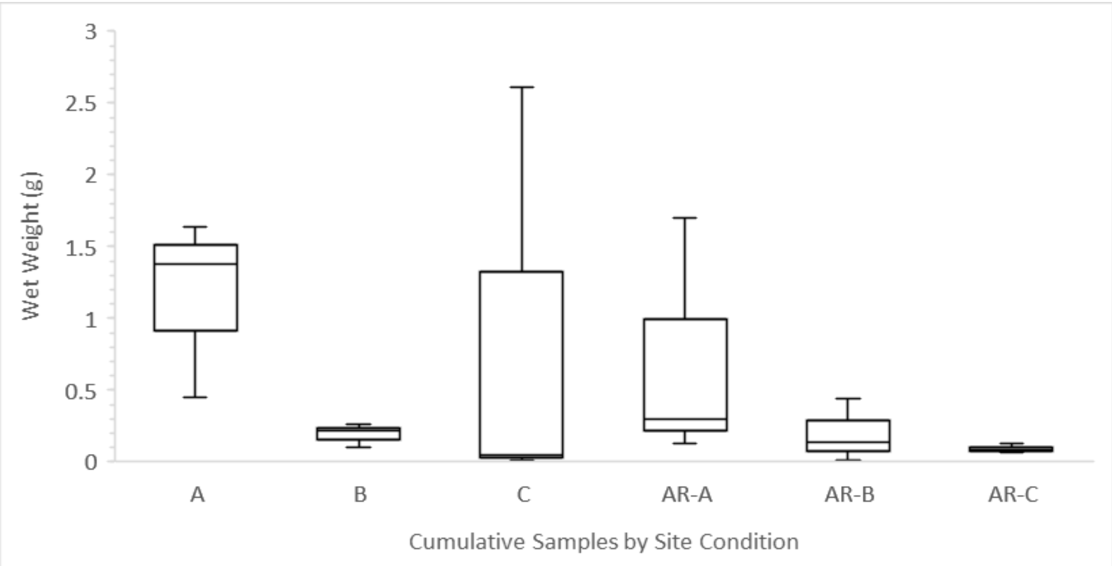

Figure 13. Boxplots showing cumulative biomass of samples at sites by condition. Median ±Standard error is shown including medians (horizontal line), the lower and upper 25th and 75th percentiles (boundaries of the box) and minimum and maximum values(whiskers).

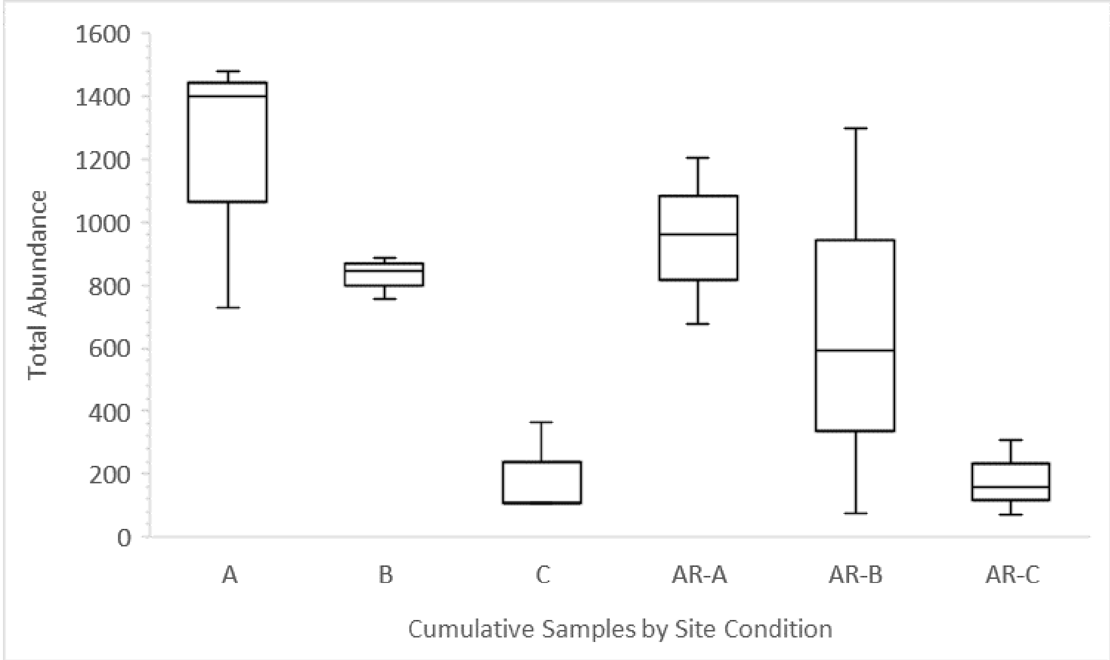

Figure 14. Boxplots showing cumulative Total Abundances of samples at sites by condition. Median ±Standard error is shown including medians (horizontal line), the lower and upper 25th and 75th percentiles (boundaries of the box) and minimum and maximum values(whiskers).

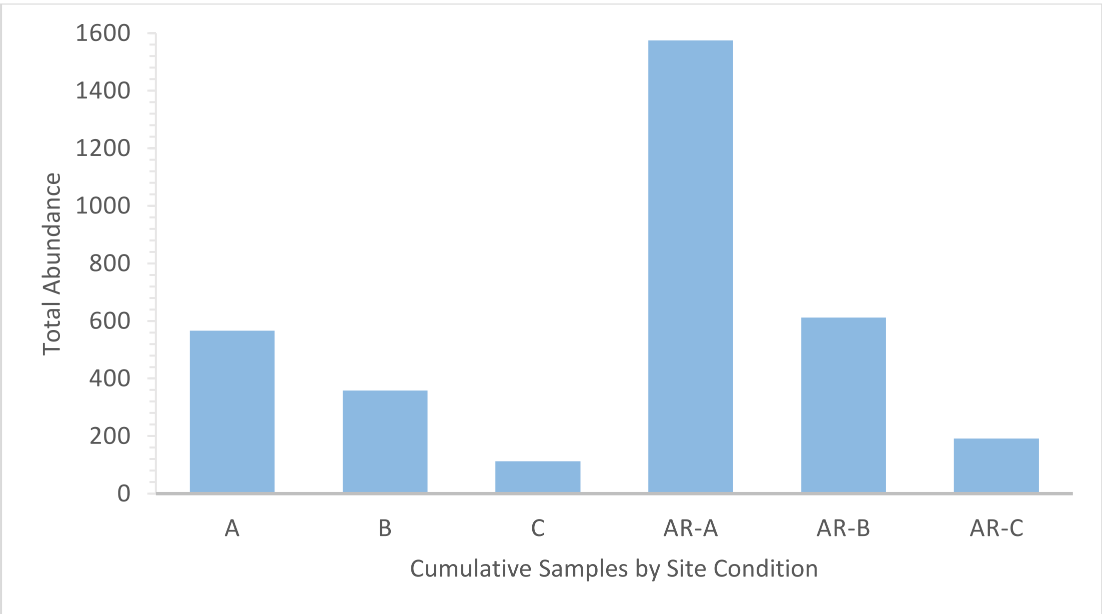

Figure 15. Bar chart showing Total Abundance of the Sabellidae family. The Total Abundance from the three benthic samples were combined separately at each site by condition (before berm removal and after berm removal) for a restoration project by Nature Trust BC started in 2019 in the Nanaimo estuary, Nanaimo BC.

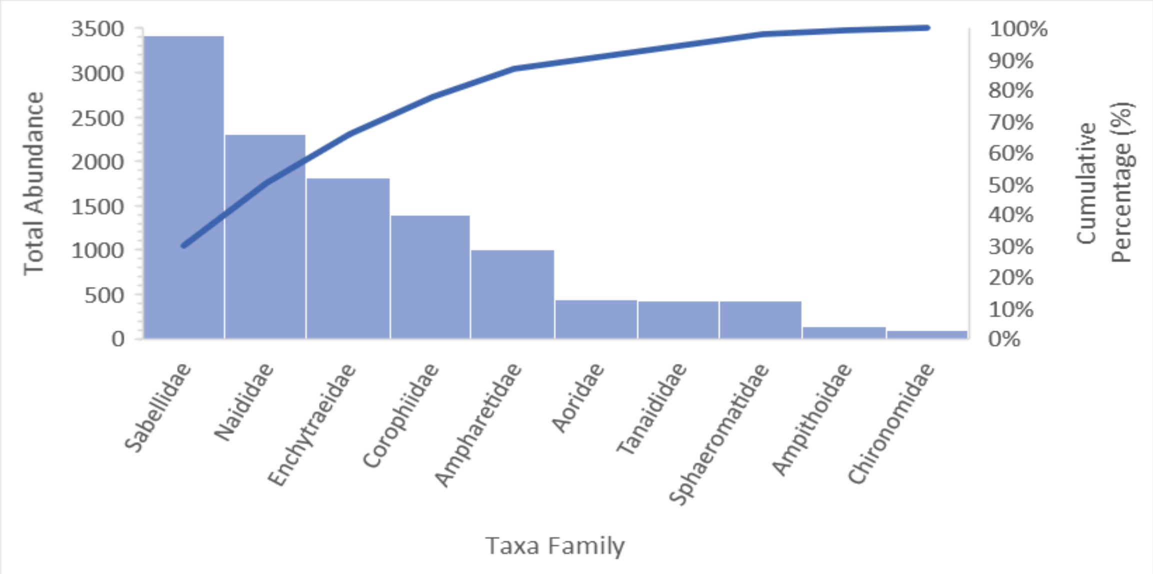

Figure 16. Pareto chart showing the cumulative Total Abundance of the top ten families collected from all samples and all sites across both conditions (before berm removal and after berm removal) for a restoration project by Nature Trust BC started in 2019 in the Nanaimo estuary, Nanaimo BC.

The Kruskal-Wallis rank sum test was used to test for significant differences in the benthic invertebrate community. The summary can be seen in Appendix A (Table 3). Models created were unable to find a significant effect between sites and condition (before berm removal and after berm removal) for the benthic samples that were taken. However, the Kruskal-Wallis statistical test for differences in Shannon-Wiener diversity did get close to showing a significant difference (p-value = 0.05091) despite the low statistical power .

Non-metric Multidimensional Scaling (NMDS) was also used to analyze the directionality of Total Abundance among sites at the different conditions (Before and After berm removal). NMDS helps to interpret information from multiple dimensions (multiple community measures) using rank orders (Lefcheck 2012). Based on the results seen in Figure 17, the benthic communities composition shifted from before berm removal to after berm removal conditions but not all in predictable and organized way .

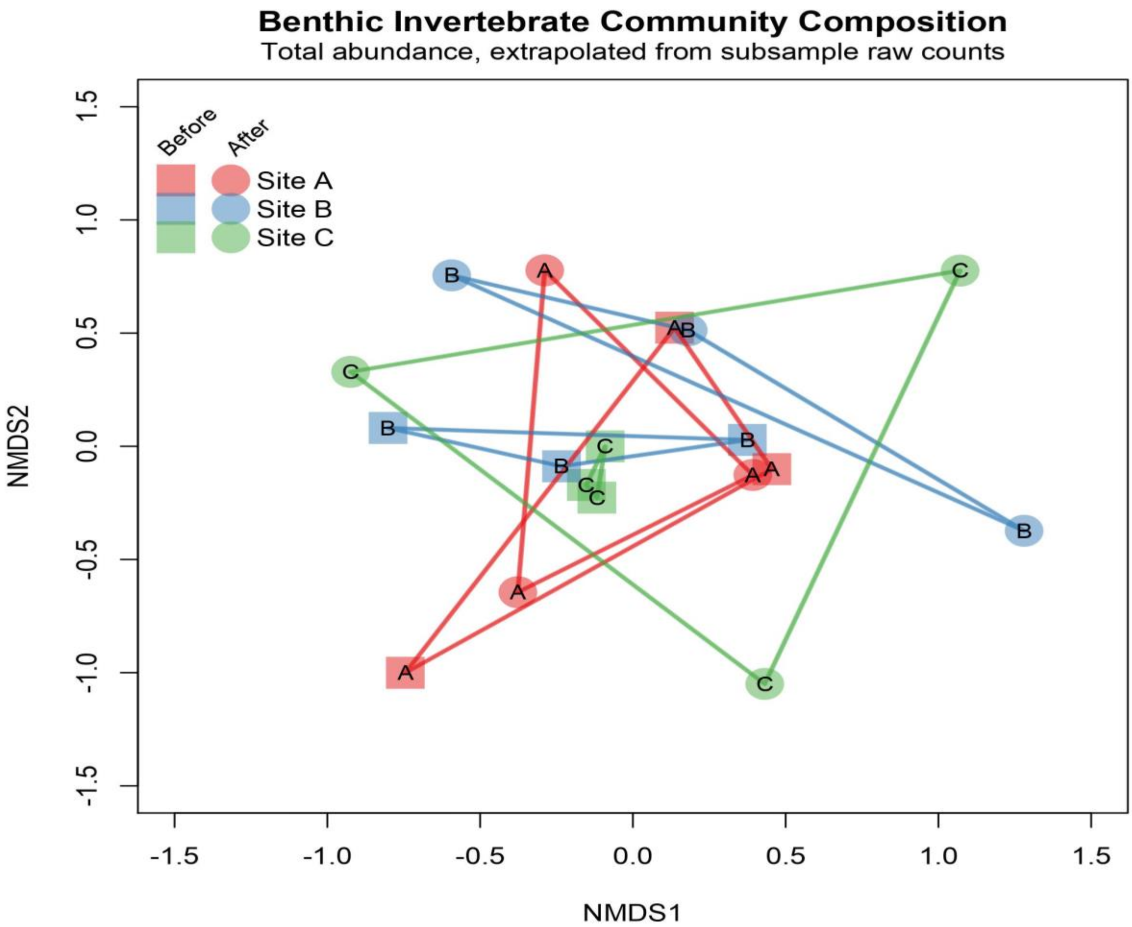

Figure 17. Non-metric Multidimensional Scaling (NMDS) of Total Abundance for benthic communities' composition in tidal channels using 3 samples collected per site at three sites (A, B and C) affected by section one of the berm structure during a restoration project in 2019 at Nanaimo estuary, Nanaimo BC.

Chapter 4. Discussion

The main purpose of this study was to reveal the short-term response of invertebrate communities to berm removal as a restoration effort and provide useful baseline data (pre-berm removal) for future monitoring . Variables that were considered included invertebrate total abundance, invertebrate family richness, invertebrate biomass, sediment grain size, organic matter content and water temperature. This research has been focused around a small spatial extent with the goal of observing the environmental response to full berm removal treatment. This study has the potential to guide future research and restoration efforts in the Nanaimo estuary as most of the estuary still needs some sort of restoration intervention. The interpretation of these results does not comprehensively reflect the actual state of conditions in the estuary all year round or on a landscape scale, but it is an examination of what happens in the late summer period. Additionally, the experimental design can be used as a template to study and restore the estuary on a larger temporal and spatial scale.

4.1. Organic Matter Content

As stated in the results, based on the samples analysed it would not be accurate to quantify how much of an effect the berm has on the influx of organic matter within the sediments of the channels and how much influence the organic matter has on the different families of invertebrates that was noticed in the estuary. Power analysis suggested that a sample size of 8 from each site would have the power (power = 0.85) to detect statistical differences between sites. As the effect size was large between sites, this result suffers from lack of power, rather than lack of differences between sites and a larger sample size is recommended before interpreting if berm removal did affect organic matter content on the impacted site.

Something to keep in mind is that the process used in measuring organic matter did not distinguish natural sources of organic matter from those due to anthropogenic influences. However, trapping and holding of detritus is mainly influenced by marsh structure such as marsh elevation, erect emergent vegetation and Large Woody Debris (LWD) (Maier & Simenstad 2009). Estuaries receive steady inputs of detritus from several sources including vegetation from landward and downstream transport from upland areas a watershed(Shaffer et al. 2017). Inputs from the river can be a major source of organic matter to estuarine systems providing up to 80-87% of the estuarine organic matter (Simenstad et al. 2005) Knowing the main contributors of detritus to the Nanaimo estuary and how the berm affects its transport within the estuary might contribute to an explanation on how the distribution of detritivores and their patchiness in community density might be affected (Shreffler et al. 1992). Organic matter has also been known to influence variables such as pH and turbidity including mitigating toxicity of certain contaminants to benthic invertebrates (Swartz et al. 1990; Sibley et al. 1996; Li et al. 2013). Increase in organic matter will increase soil pH, increase turbidity and help in binding contaminants to sediment particles so that they are not directly ingested by most benthic invertebrates. These outcomes can influence community composition. In most case, the outcomes are not harmful to invertebrates, but they are not always beneficial to the fish that feed on the invertebrates

4.2. Grain Size

The statistical difference in percent Silt & Clay among the sites at different conditions might be due to higher exposure to tidal flushing in Site C. Silt & Clay particle sizes are smaller and easier to transport so the lack of restrictions plus higher organic matter at Site C should make for easier retention in the channels. It may also be the contributing factor to why there is less richness and abundance in Site C. The occurrence of clay particles within soil samples is needed for substrate stability between sediment particles; they help with binding and retain nutrients important to benthic communities. Higher amounts of fine sand and very fine sand might be indicative of low dissolved oxygen levels are typical of estuaries (Wallace 1990; Dernie, Kaiser, Richardson, et al. 2003). Some studies suggest that infilling rates of sediment collected in the channels can be dominated by unconsolidated sand mainly through physical processes(Dernie, Kaiser & Warwick 2003)

Studies indicate that benthic communities in sandy habitats recover faster from disturbance than depositional (silt & clay) sediments(Dernie, Kaiser & Warwick 2003). Since sites examined were higher in sand grain sizes, one can infer the lower amounts of silt & clay is a good sign to have. Methods for more comprehensive analyses of sediment structure and how they affect benthic communities are available(Sibert 1981; McGreer et al. 1984). However, they were outside the scope, budget and time of this research. Dramatic shifts in estuary water quality associated with flood control structures removal is possible and these shifts can affect the detrital systems in the estuary temporarily reducing food resources(Shaffer et al. 2017)However, due to the restrictive timeframe of this study, these shifts were not prominent during the study. Globally, there is no consensus to the current knowledge of how benthic fauna–sediment relationship works as studies have shown much greater variability in the fauna associations that occur within different sediments. Nonetheless, experimental evidence suggests that such relationships do exist(Dernie, Kaiser, Richardson, et al. 2003).

4.3. Water Temperature

Despite the construction work that removed a lot of vegetation and exposed more of the banks and channel to direct sunlight in the bermed area (Site A and Site B); both Site A (berm impacted) and Site C the unimpacted site had similar water temperatures in terms of daily highs and lows. The main trend noticeable about the temperature data is a slight but steady decrease in temperatures in both channels beginning in the month of August 2019 which might indicate the influence of seasonality on water temperatures. Summer rains during the period of measurement might have also influenced temperature measurements but predicted substantial differences in daily average temperatures in Site C is due to its deeper, narrower and more vegetated banks was not noted. Also, the logger in the bermed channel was placed slightly under a large root wad for protection while the logger in the reference channel was placed in an area with smaller coarse woody debris. These observations and conditions are not enough to explain the similarity in water temperature or effects on invertebrate species composition in tidal channels. However increased temperature coupled with possible interactions with increased dissolved CO_2 levels in the water could lead to a change in the invertebrate community composition (Meadows et al. 2015; Vafeiadou et al. 2018). This could have major implications in terms of habitat suitability not just for salmonid prey but also for juvenile salmonids survival. A study done during fish population assessment indicated that chinook salmon in the Nanaimo estuary were able to tolerate higher than normally preferred temperatures (Healey 1980). Berm removal leads to disturbance in the land scape and the work done in the Nanaimo estuary has temporarily exposed several tidal channels to direct sunlight which theoretically should lead to increased temperature. Increased temperature affects oxygen requirements for benthic organisms (Vaquer-Sunyer & Duarte 2011).

4.4. Benthic Invertebrate Community

Multivariate analysis of the benthic community suggested that the benthic community composition shifted from before berm removal to after berm removal conditions but not all in the same way or a predictable pattern. A larger sample would be necessary to tease out pattern in the benthic community structure, but the result suggests that the differences observed a few weeks after the berm removal were subtle and dynamic at all three study sites.

Several invertebrate taxa were observed but not included in calculations of invertebrate metrics. These included organisms belonged to the Ostracoda class; Acari and Copepoda subclasses; Insecta order and egg masses. Most of these taxa were considered pelagic prey not benthic prey. The Nematoda phylum although considered benthic invertebrates were classified as meioinvertebrates because they were not retained on a 1 mm screen. These specimens contributed to the community of organisms at each site and are additional to the invertebrate community on site. Previous studies determined that chum diet in the Nanaimo estuary consisted heavily of harpacticoid copepods with juvenile chinook somewhat dependent on epibenthos between March and early April which are meiobenthic. Decapod larvae and amphipods were preferred in April and May, and mysids and insect larvae in May – July for the times the juvenile salmonids mostly inhabited the estuary (Healey 1979; Naiman & Sibert 1979; Sibert 1979; Healey 1980). Families in the dipteran order (Ceratopogonidae, Chironomidae, Dolichopodidae, Muscidae, Tabanidae, Tipulidae) typically associated as pollution tolerant species and indicators of a heavily disturbed environment were present in samples collected but not the most abundant order of taxa. Dipteran larvae have also been known to be prey for juvenile salmonids and the adults are food source for adult salmon (Shreffler et al. 1992; Woo et al. 2018). The total abundance of dipterans was more numerous in both conditions (before and after berm removal) for Sites A and B than in Site C. It is possible that if current and future restorations activities were conducted in times when salmonids mostly use the estuary; salmonids that do use the tidal channels post-restoration will chose to selectively feed on chironomid and other dipteran larvae over pelagic prey due to turbidity of water conditions that restrict ideal feeding conditions ((Shreffler et al. 1992). Timing of the restoration operation was not scheduled to salmonid fish use nor was salmonid gut content analysis available for comparison so a direct comparison of on how what was seen could reflects salmonid prey availability could not be made. However it can be stated that most of the benthic invertebrate families were either filter feeders or detritivores, with the exceptions of a few that were either fungivores, predators and those that fed on living algae (Day 1964; Rotramel 1975; Myers & Lowry 2003; Sket & Bruce 2003; Glazier 2009; Myers 2009; Govedich & Brinkhurst 2010; Verdonschot 2015; Peart & Ahyong 2016; Gerhardt & Hribar 2019; Thorp & Martin 2019).

A major premise of this study was that, within the given timeframe the benthic community within the berm affected sites would change (or at best, increase) in abundance and diversity after berm removal. It appears though that the timeframe (a month) was not enough to see major changes in the benthic communities with limited sample sizes in our study. However, Thorne et al. (2012) did show that it is possible for benthic fauna to show partial to full recovery in terms of concentration and abundance compared to control sites after as few as two tidal cycles. However, deductions drawn from such limited timeframes might not be valid for benthic communities over seasonal and/or yearly assessments. Similarly, budget and the limitations this imposes on sample size is an important consideration in study design. The problem then becomes defining the appropriate length of time for monitoring recovery of a disturbed benthic system, and ensuring long-term monitoring has the power to be able to detect these major changes over time. Questions that may arise as a result of this study include “what my expectations of the benthic community composition was before the study was conducted?" and "Is the benthic community expected to change after full recovery at the impacted sites?". The truth is I don't have an answer to those questions based on the limited data collected and the fact that this study has not been conducted before in the estuary. Also, every estuary is different and although some might share the same bio-geoclimatic zone

If I could do this experiment again, I would wait for a year to pass after berm removal before I take the post-berm removal samples for analysis and comparison. Benthic data from studies on benthic availability are often difficult to interpret because of limited knowledge of benthic species and predator-prey relationship (McGreer et al. 1984). Different species respond differently to environmental disturbance; therefore, it might have been useful to combine results from individual samples in the same site and analyzed the changes across sites within the study area (McGreer et al. 1984). A previous study done in the Nanaimo estuary concluded that hyperbenthic species which constitutes a great portion of species that dwell at the sediment water-interfaces are of considerable importance in trophodynamics and usually form a large portion of the recolonization population after sediment disturbance (Sibert 1981). The response of the Sabellidae family taxa which constitutes of hyperbenthic species seems to reinforce this theory.

Chapter 5. Recommendations

5.1. Proposed Monitoring Approaches and Variables

The inclusion of meibenthos in future monitoring studies can serve to improve the overall importance of these organisms as indicators of ecosystem health and establish their importance to juvenile salmonids using the Nanaimo estuary (Alves et al. 2015; McGreer et al. 1984). A more robust study that looks at not just benthic but terrestrial and pelagic invertebrates will give a more comprehensive indication of invertebrate prey availability in the Nanaimo estuary. However, focusing on one or two target indicator species or groups might substantially reduce sample processing and data interpretation (McGreer et al. 1984; Cabral & Murta 2004). If that is the case, concentrating studies on harpacticoid copepods for Chum, insects for Chinook and meioinvertebrates (especially nematodes) for overall ecosystem performance (Miss & Boomer 1986; Alves et al. 2015; David et al. 2016)

The tidal marsh area and dendritic channels close to Holdom Creek a freshwater channel east of the main Nanaimo river were covered in red slime-like biofilm substance upon observation during site inspection for the duration of this study in the summer of 2019 . This area is also affected by berm structures and warrants more investigation to determine if the causes are natural or due to some form of contamination if overall restoration is to be successful. Also investigating benthic community dynamics beyond tidal channels such as those directly on the salt marshes, mudflats and nearshore environments will give an extensive representation of the invertebrate ecosystem dynamics within the Nanaimo estuary. This research was focused on an area leeward of the berm; indirect effects can also occur in the area seaward of the berm (Gregory 2004) . Including these additional areas in a study will be helpful in judging how the overall estuary is responding to berm removal restoration efforts.

Studies have shown that woody debris is important in estuarine environments not just for controlling flow or providing shelter for aquatic organisms but also helps with the long-term contribution of organic matter (Hilderbrand et al. 1997; Lemly & Hilderbrand 2000; Hrodey et al. 2008). Woody Debris can also enhance substrate stability affecting invertebrate community composition and feeding associations over time However, from personal observation through out the research, only one large root wad was spotted in the estuary. A research study looking at how to improve the natural upstream contribution or the effects of deliberate placement of large woody debris in the estuary would be a worthy project and a hypothesis worth testing. Re-establishment of vegetation, especially the *Carex lyngbyei* (Lyngbye's sedge) along the channel edges may help to stabilize the channel edges that have been disturbed by the berm removal and perhaps attract more insect prey (Woo et al. 2019).

Despite the restricted scope and timeframe of this study, it is possible to detect relationships between macroinvertebrate community structure, habitat structure and other environmental conditions. These possible relationships highlight the need for estuarine management efforts to study both conditions of in-stream benthic habitats as well as elements influencing environmental conditions such as freshwater influx, tidal flushing and hydrologic modifications occurring within watersheds(Li et al. 2018). Monitoring of long-term estimates of river flow, runoff, and water quality conditions such as turbidity, pH and dissolved oxygen levels is essential for establishing connections between tidal channel invertebrates, watershed modifications and overall estuarine production (Walton et al. 2013). Differences in macroinvertebrate assemblages among seasons and channels may help to identify the main drivers of channel dynamics which in turn determines invertebrate assemblages in a reciprocal fashion.

Chapter 6. Conclusion

To the best of my knowledge, this has been the first attempt to analyze invertebrate communities in the channels of the tidal marsh area of the Nanaimo estuary since restoration began and the berms were breached. This study was limited by a short timeline and data gathered do not account for seasonality, nor was it possible to collect data prior to previous dike breaches. This study does show that it is possible that the invertebrate communities will respond to the removal of the berm structure with time, just not as fast or immediately in the positive direction as anticipated. I recommend that the Nature Trust of BC put more effort into analyzing the remaining 42 samples gathered from both before and after berm removal in order to gain enough statistical power to see if there is a statistical difference between the channel processes in the impacted sites compared to those in the reference site (Site C). Increasing the effort put into the pre-berm removal samples that I collected but didn't have the budget to process will be very important in establishing the baseline conditions that existed prior to berm removal and will provide necessary insights to future projects monitoring data and restoration planning.

The goal of this study was to provide scientific supplemental data to the ongoing restoration project by providing a record assessing the response of macroinvertebrate communities in the nearby channels of the active restoration site of the Nanaimo estuary. Although there have been yearly surveys on fish populations in the Nanaimo estuary; this study represents the first attempt at looking at the benthic invertebrate community for habitat assessment specifically in tidal channels since a study looked at intertidal hyperbenthic populations in the 1980s in the mudflats area of the estuary. Invertebrates are an important food source for many fish species and they have been moderately surveyed in the Nanaimo estuary as part of salmon population assessment but have not been the focus of any recent surveys or research in the estuary despite their importance as indicators of overall ecosystem health and importance to the diet of juvenile salmonids. Dikes usually have impacts on physical process such as organic matter pathways, freshwater influx, tidal flushing sediment transport/stability; these factors influence invertebrate community composition in estuaries. Therefore, it is necessary to understand the relationship between biotic and abiotic elements to improve ecosystem management(Park et al. 2017).

Current information on macroinvertebrate community reactions to geomorphologic change indicates that macroinvertebrate communities react to physical habitat disturbances, but also recover quickly (Hood 2002; Simenstad et al. 2005). A common instantaneous response is for abundance, density and species richness to decrease in most scenarios(Dernie, Kaiser, Richardson, et al. 2003). The recovery of macroinvertebrates may influence recovery time of other species that are dependent on macroinvertebrates through trophic structures, this should be considered in implications for estuary management plans.(Roark & Podolak 2009). Data from long-term studies is important if consistent changes due to anthropogenic influences are to be interpreted distinctly from natural variation at the ecosystem level. Present information of natural variability of benthic ecosystems suggest the length of time for monitoring is at least several years to sufficiently describe changes in population dynamics, habitat and sediment types but recovery can range from months to years depending on severity of disturbance (McGreer et al. 1984).

Chapter 7. References

Alves AS et al. (2015) Estuarine Intertidal Meiofauna and Nematode Communities as Indicator of Ecosystem's Recovery following Mitigation Measures. Ecological Indicators 54:184–196

Borja Á et al. (2010) Medium-and Long-term Recovery of Estuarine and Coastal Ecosystems: Patterns, Rates and Restoration Effectiveness. Estuaries and Coasts 33:1249–1260

Cabral HN, Murta AG (2004) Effect of Sampling Design on Abundance Estimates of Benthic Invertebrates in Environmental Monitoring Studies. Marine Ecology Progress Series 276:19–24

Catherine Berris Associates Inc. (2006) Nanaimo Estuary Management Plan. Vancouver

David AT et al. (2016) Wetland Loss, Juvenile Salmon Foraging Performance, and Density Dependence in Pacific Northwest Estuaries. Estuaries and Coasts 39:767–780

Day JH (1964) A Review of the Family Ampharetidae (Polychaeta). Annals of the South African Museum. Annale van die Suid-Afrikaanse Museum. 48:97–120

Dernie KM, Kaiser MJ, Richardson EA, et al. (2003) Recovery of Soft Sediment Communities and Habitats following Physical Disturbance. Journal of Experimental Marine Biology and Ecology 285:415–434

Dernie KM, Kaiser MJ, Warwick RM (2003) Recovery Rates of Benthic Communities following Physical Disturbance. Journal of Animal Ecology 72:1043–1056

Gerhardt RR, Hribar LJ (2019) Chiromidae (Chironomid Midges). In: Medical and Veterinary Entomology. Elsevier.

Glazier GS (2009) Amphipoda. In: Invertebrates. Elsevier, Huntingdon.

Govedich FR, Brinkhurst RO (2010) Reproduction and Life History. In: Ecology and Classification of North American Freshwater Invertebrates. Elsevier.

Gregory HW (2004) Indirect Environmental Effects of Dikes on Estuarine Tidal Channels: Thinking Outside of the Dike for Habitat Restoration and Monitoring. Estuaries 27:273–282

Healey MC (1980) Utilization of the Nanaimo River Estuary by Juvenile Chinook Salmon Oncorhynchu Tshawytscha. Fishery Bulletin

Hilderbrand RH et al. (1997) Effects of Large Woody Debris Placement on Stream Channels and Benthic Macroinvertebrates. Canadian Journal of Fisheries and Aquatic Sciences 54:931–939

Hood WG (2002) Landscape Allometry: From Tidal Channel Hydraulic Geometry to Benthic Ecology. Canadian Journal of Fisheries and Aquatic Sciences 59:1418–1427

Hrodey PJ, Kalb BJ, Sutton TM (2008) Macroinvertebrate Community Response to Large-Woody Debris Additions in Small Warm-Water Streams. Hydrobiologia 605:193–207

Lefcheck J (2012) Sample (Ecology): Random Thoughts on Ecology, Biodiversity and Science in General. WordPress

Lemly AD, Hilderbrand RH (2000) Influence of Large Woody Debris on Stream Insect Communities and Benthic Detritus. Hydrobiologia 421:179–185

Li H et al. (2013) Effect of pH, Temperature, Dissolved Oxygen, and Flow Rate of Overlying Water on Heavy Metals Release from Storm Sewer Sediments. Journal of Chemistry 2013

Li X et al. (2018) Coastal Wetland Loss, Consequences, and Challenges for Restoration. Anthropocene Coasts 1:1–15

Maier GO, Simenstad CA (2009) The Role of Marsh-Derived Macrodetritus to the Food Webs of Juvenile Chinook Salmon in a Large Altered Estuary. Estuaries and Coasts 32:984–998

McGreer ER, Moore DM, Sibert JR (1984) Study of the Recovery of Intertidal Benthos After Removal of Log Booms, Nanaimo River Estuary, British Columbia.

Miss JM, Boomer RS (1986) Feeding Ecology of Juvenile Pacific Salmonids in Estuaries: A Review of Recent Literature. Olympia

Myers AA (2009) Corophiidae. Zootaxa 2260:373–379

Myers AA, Lowry JK (2003) A Phylogeny and a New Classification of the Corophiidea Leach, 1814 (Amphipoda). Journal of Crustacean Biology 23:443–485

Park HJ et al. (2017) Comparative Trophic Structures of Macrobenthic Food Web in Two Macrotidal Wetlands With and Without a Dike on the Temperate Coast of Korea as Revealed by Stable isotopes. Marine Environmental Research 131:134–145

Peart RA, Ahyong ST (2016) Phylogenetic Analysis of the Family Ampithoidae Stebbing, 1899 (Crustacea: Amphipoda), with a Synopsis of the Genera. In: Journal of Crustacean Biology.Vol. 36 Brill Academic Publishers pp. 456–474.

Roark J, Podolak C (2009) Response of Benthic Macroinvertebrate Communities to Increases in Sediment Supply from Dam Removal. AGU Fall Meeting Abstracts

Rotramel G (1975) Filter-Feeding by the Marine Boring Isopod, Sphaeroma Quoyanum H. Milne Edwards, 1840 (Isopoda, Sphaeromatidae). Crustaceana

Schumacher B a (2002) Methods for the Determination of Total Organic Carbon in Soils and Sediments. Carbon 32:25

Seliskar DM, Gallagher JL, National Coastal Ecosystems Team (U.S.) (1983) The Ecology of Tidal Marshes of the Pacific Northwest Coast: A Community Profile. Washington, D.C: The Service

Shaffer JA et al. (2017) Nearshore Fish Community Responses to Large Scale Dam Removal: Implications for Watershed Restoration and Fish Management. Aquatic Sciences 79:643–660

Shaw P (2012) Layers of Change: The Nanaimo River Estuary (Nanaimo, British Columbia, Canada). Boletim do Observatório Ambiental Alberto Ribeiro Lamego 6:173–183

Shreffler DK, Simenstad CA, Thom RM (1992) Foraging by Juvenile Salmon in a Restored Estuarine Wetland. Estuaries 15:204–213

Sibert JR (1981) Intertidal Hyperbenthic Populations in the Nanaimo Estuary. Marine Biology 64:259–265

Sibley PK et al. (1996) Predicting Chronic Toxicity of Sediments Spiked with Zinc: An Evaluation of the Acid-volatile Sulfide Model using a Life-cycle Test with the Midge Chironomus tentans. Environmental Toxicology and Chemistry 15:2102–2112

Simenstad CA et al. (2005) Landscape Structure and Scale Constraints on Restoring Estuarine Wetlands for Pacific Coast Juvenile Fishes. In: Concepts and Controversies in Tidal Marsh Ecology.

Sket B, Bruce NL (2003) Sphaeromatids (Isopoda, Sphaeromatidae) from New Zealand Fresh and Hypogean Waters, with Description of Bilistra n. gen. and Three New Species. Crustaceana 76:1347–1370

Stocks K, Grassle J (2003) Benthic Macrofaunal Communities in Partially Impounded Salt Marshes in Delaware: Comparisons with Natural Marshes and Responses to Sediment Exposure. Estuaries 26:777–789

Swartz RC et al. (1990) Toxicity of Fluoranthene in Sediment to Marine Amphipods: A Test of the Equilibrium Partitioning Approach to Sediment Quality Criteria. Environmental Toxicology and Chemistry 9:1071–1080

Thorp JH, Martin D (2019) Oligochaeta: Enchytraeida: Enchytraeidae: Lumbricillus: Species. In: Thorp and Covich's Freshwater Invertebrates . Elsevier.

US Geological Survey (2010) Invertebrate lab manual. Unpublished benthic invertebrate sieving and sorting protocols. USGS, Western Ecological Research Center, San Francisco Bay Estuary Field

Vaquer-Sunyer R, Duarte CM (2011) Temperature Effects on Oxygen Thresholds for Hypoxia in Marine Benthic Organisms. Global Change Biology 17:1788–1797

Verdonschot PFM (2015) Introduction to Annelida and the Class Polychaeta. In: Thorp and Covich's Freshwater Invertebrates. Elsevier.

Walton A et al. (2013) Description of the Benthic Macroinvertebrate Communities of Four Tidal Creeks Along the Eastern Shore of Charlotte Harbour. Florida Scientist 76:121

Woo I et al. (2019) A Mosaic of Estuarine Habitat Types with Prey Resources from Multiple Environmental Strata Supports a Diversified Foraging Portfolio for Juvenile Chinook Salmon. Estuaries and Coasts 42:1938–1954

Woo I et al. (2018) Enhanced Invertebrate Prey Production Following Estuarine Restoration Supports Foraging for Multiple Species of Juvenile Salmonids (Oncorhynchus spp.). Restoration Ecology 26:964–975

Wright AL, Wang Y, Reddy KR (2008) Loss-on-Ignition Method to Assess Soil Organic Carbon in Calcareous Everglades Wetlands. Communications in Soil Science and Plant Analysis 39:3074–3083

Chapter 8. Appendices

Appendix A. Invertebrate and Soil Variable Summaries and Models

Table 1. Summary of Simpson's Diversity, Shannon-Wiener Diversity, Total Abundance, Family Richness and Biomass calculated for samples per site for each condition (before and after berm removal) for a restoration project by Nature Trust BC started in 2019 in the Nanaimo estuary, Nanaimo BC.

Sample	Simpson's Diversity	Shannon-Wiener Diversity	Total Abundance	Family Richness	Biomass (g)
A 1	0.67	1.33	1402	12	1.38124
A 2	0.77	1.8	727	12	0.44878
A 3	0.85	2.14	1479	18	1.637996
B 1	0.86	2.23	756	15	0.25818
B 2	0.7	1.45	889	8	0.0972501
B 3	0.46	1.01	845	10	0.215124
C 1	0.9	1.96	365	18	2.61387
C 2	0.73	1.62	108	8	0.04328
C 3	0.74	1.57	108	7	0.00976
AR-A 1	0.62	1.34	962	10	0.298176
AR-A 2	0.38	0.83	1205	8	0.131712
AR-A 3	0.67	1.43	675	11	1.69621
AR-B 1	0.61	1.35	592	10	0.13256
AR-B 2	0.73	1.58	1296	10	0.4416
AR-B 3	0.47	1.03	76	6	0.00884
AR-C 1	0.88	2.37	71	15	0.12974666
AR-C 2	0.8	1.88	159	11	0.0681
AR-C3	0.75	1.8	307	11	0.0811728
Totals			**12022**		**9.69359756**

Table 2. Summary of ANOVA Models for benthic variables including Simpson's Diversity, Shannon-Wiener's Diversity, Total Abundance, Family Richness and Biomass for three samples per site for each condition (before and after berm removal) for a restoration project by Nature Trust BC started in 2019 in the Nanaimo estuary, Nanaimo BC.

Simpson Model

	Df	Sum Sq	Mean Sq	F Value	Pr(>F)	Effect.size	Power
Treatment	2	0.07816	0.03908	2.096	0.204	**0.698668097**	**0.2907269**
Residuals	6	0.11187	0.01864				

Shannon-Weiner Model

	Df	Sum Sq	Mean Sq	F Value	Pr(>F)	Effect size	Power
Treatment	2	1.127	0.5636	2.945	0.128	**0.981707317**	**0.5186838**
Residuals	6	1.148	0.1914				

Total Abundance Model

	Df	Sum Sq	Mean Sq	F Value	Pr(>F)	Effect size	Power
Treatment	2	90134	45067	0.16	0.856	**0.05325218**	**0.051211**
Residuals	6	1692588	282098				

Family Richness Model

	Df	Sum Sq	Mean Sq	F Value	Pr(>F)	Effect size	Power
Treatment	2	49.56	24.78	2.124	0.201	**0.708**	**0.2974685**
Residuals	6	70	11.67				

Biomass Model

	Df	Sum Sq	Mean Sq	F Value	Pr(>F)	Effect size	Power
Treatment	2	0.966	0.4828	0.565	0.596	**0.188340807**	**0.065428**
Residuals	6	5.129	0.8549				

Table 3. Summary of Kruskal-Wallis Rank Sum Test Models for benthic variables including Simpson's Diversity, Shannon-Wiener's Diversity, Total Abundance, Family Richness and Biomass for three samples per site for each condition (before and after berm removal) for a restoration project by Nature Trust BC started in 2019 in the Nanaimo estuary, Nanaimo BC.

Simpson's Model

Kruskal-Wallis Chi-squared	df	p.value	data.name
3.8222222	2	0.1479159	Diff1 by treatment

Shannon-Wiener Model

Kruskal-Wallis Chi-squared	df	p.value	data.name
5.9555556	2	0.05090583	Diff2 by treatment

Total Abundance Model

Kruskal-Wallis Chi-squared	df	p.value	data.name
0.3555556	2	0.8371284	Diff3 by treatment

Family Richness Model

Kruskal-Wallis Chi-squared	df	p.value	data.name
3.38754	2	0.1841736	Diff4 by treatment

Biomass Model

Kruskal-Wallis Chi-squared	df	p.value	data.name
0.8	2	0.67032	Diff5 by treatment

Table 4. Summary of ANOVA and Kruskal-Wallis Models for Organic matter percentages for three samples per site for each condition(before and after berm removal) for a restoration project by Nature Trust BC started in 2019 in the Nanaimo estuary, Nanaimo BC.

ANOVA Model

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	Effect Size	Power
Treatment	2	77.53	38.77	2.191	0.193	**0.73031**	**0.313895**
Residuals	6	106.16	17.69				

Kruskal-Wallis Rank Sum Test

Kruskal-Wallis chi-squared	df	p.value	data.name
2.509804	2	0.285103	diff by treatment

Table 5. Summary of ANOVA Models for Grain Sizes (gravel, very coarse & coarse sand, medium sand, fine sand, very fine sand and silt & clay for three samples per site for each condition(before and after berm removal) for a restoration project by Nature Trust BC started in 2019 in the Nanaimo estuary, Nanaimo BC.

Gravel

	Df	Sum Sq	Mean Sq	F value	Pr (>F)	Effect Size	Power
Treatment	2	0.01695	0.008476	0.82	0.484	**0.273431199**	**0.08317024**
Residuals	6	0.06199	0.010331				

Very Coarse, Coarse Sand

	Df	Sum Sq	Mean Sq	F value	Pr (>F)	Effect Size	Power
Treatment	2	0.006082	0.003041	3.008	0.124	**1.002802968**	**0.536489**
Residuals	6	0.006065	0.001011				

Medium Sand

	Df	Sum Sq	Mean Sq	F value	Pr (>F)	Effect Size	Power
Treatment	2	0.01724	0.008621	0.981	0.428	**0.326824645**	**0.09808619**
Residuals	6	0.05275	0.008791				

Fine Sand

	Df	Sum Sq	Mean Sq	F value	Pr (>F)	Effect Size	Power
Treatment	2	0.01469	0.007344	1.676	0.264	**0.558555133**	**0.1998997**
Residuals	6	0.0263	0.004383				

Very Fine Sand

	Df	Sum Sq	Mean Sq	F value	Pr (>F)	Effect Size	Power
Treatment	2	0.008875	0.004437	3.04	0.123	**1.013243521**	**0.5452762**
Residuals	6	0.008759	0.00146				

Silt & Clay

	Df	Sum Sq	Mean Sq	F value	Pr (>F)	Effect Size	Power
Treatment	2	0.011915	0.005957	17.6	0.00309	**5.866568193**	**1**
Residuals	6	0.002031	0.000339				

Table 6. Summary of Kruskal-Wallis Models for Grain Sizes (gravel, very coarse & coarse sand, medium sand, fine sand, very fine sand and silt & clay for three samples per site for each condition(before and after berm removal) for a restoration project by Nature Trust BC started in 2019 in the Nanaimo estuary, Nanaimo BC

Gravel

Kruskal-Wallis Chi-squared	df	p.value	data.name
1.4222222	2	0.4910982	gravel_Diff by treatment

Very Coarse, Coarse Sand

Kruskal-Wallis Chi-squared	df	p.value	data.name
3.288889	2	0.1931198	Coarse.Sand_Diff by treatment

Medium Sand

Kruskal-Wallis Chi-squared	df	p.value	data.name
1.866667	2	0.3932407	medium.Sand_Diff by treatment

Fine Sand

Kruskal-Wallis Chi-squared	df	p.value	data.name
3.466667	2	0.1766944	fine.sand_Diff by treatment

Very Fine Sand

Kruskal-Wallis Chi-squared	df	p.value	data.name
5.066667	2	0.07939393	very.fine.sand_Diff by treatment

Silt & Clay

Kruskal-Wallis Chi-squared	df	p.value	data.name
6.488889	2	0.03899022	silt.clay_Diff by treatment

Table 7. Summary of Grain Sizes (gravel, very coarse & coarse sand, medium sand, fine sand, very fine sand and silt & clay) as a fraction of a Whole (1) retained on sieves for three samples per site for each condition(before and after berm removal) for a restoration project by Nature Trust BC started in 2019 in the Nanaimo estuary, Nanaimo BC.

Samples	>2mm, (gravel)	0.5mm – 2mm (very coarse and coarse sand)	0.25mm – 0.5mm (medium sand)	0.125mm – 0.25mm (fine sand)	0.063mm – 0.125mm (very fine sand)	<0.063mm (Silt and Clay)
A 1	0.132028254	0.213905146	0.394752775	0.042764884	0.136226034	0.080322906
A 2	0.044736077	0.210445125	0.251045183	0.271837063	0.13130184	0.090634711
A 3	0.253172602	0.161733862	0.20186013	0.231499333	0.097561492	0.054172581
B 1	0.016117151	0.063849848	0.265299508	0.33516014	0.19744247	0.122130882
B 2	0.023192198	0.105217253	0.230574056	0.298287345	0.208333333	0.134395814
B 3	0.006110897	0.091599125	0.331500064	0.338511514	0.147787212	0.084491187
C 1	0.183408275	0.038034735	0.123509756	0.297718741	0.216575224	0.140753269
C 2	0.019617263	0.060373128	0.168188005	0.29986388	0.290415566	0.161542157
C 3	0.176504838	0.092439072	0.169517842	0.281032523	0.188011201	0.092494524
AR-A 1	0.12568845	0.184134813	0.205096589	0.228277846	0.159473901	0.097328401
AR-A 2	0.181190924	0.175973971	0.182032368	0.241915126	0.146242953	0.072644658
AR-A 3	0.100960412	0.178931165	0.192283238	0.295117625	0.15694542	0.075762139
AR-B 1	0.002897879	0.074417526	0.343958889	0.334299293	0.143812063	0.10061435
AR-B 2	0.054416603	0.140122754	0.327353834	0.264964566	0.11968489	0.093457353
AR-B 3	0.100960412	0.178931165	0.192283238	0.295117625	0.15694542	0.075762139
AR-C 1	0.046633077	0.052517377	0.142767828	0.33477989	0.234048031	0.189253797
AR-C 2	0.046342439	0.067003747	0.134589502	0.285438871	0.24335237	0.223273071
AR-C 3	0.081679725	0.058431574	0.157648093	0.323387274	0.204400674	0.174452662

Appendix B. Extra Figures

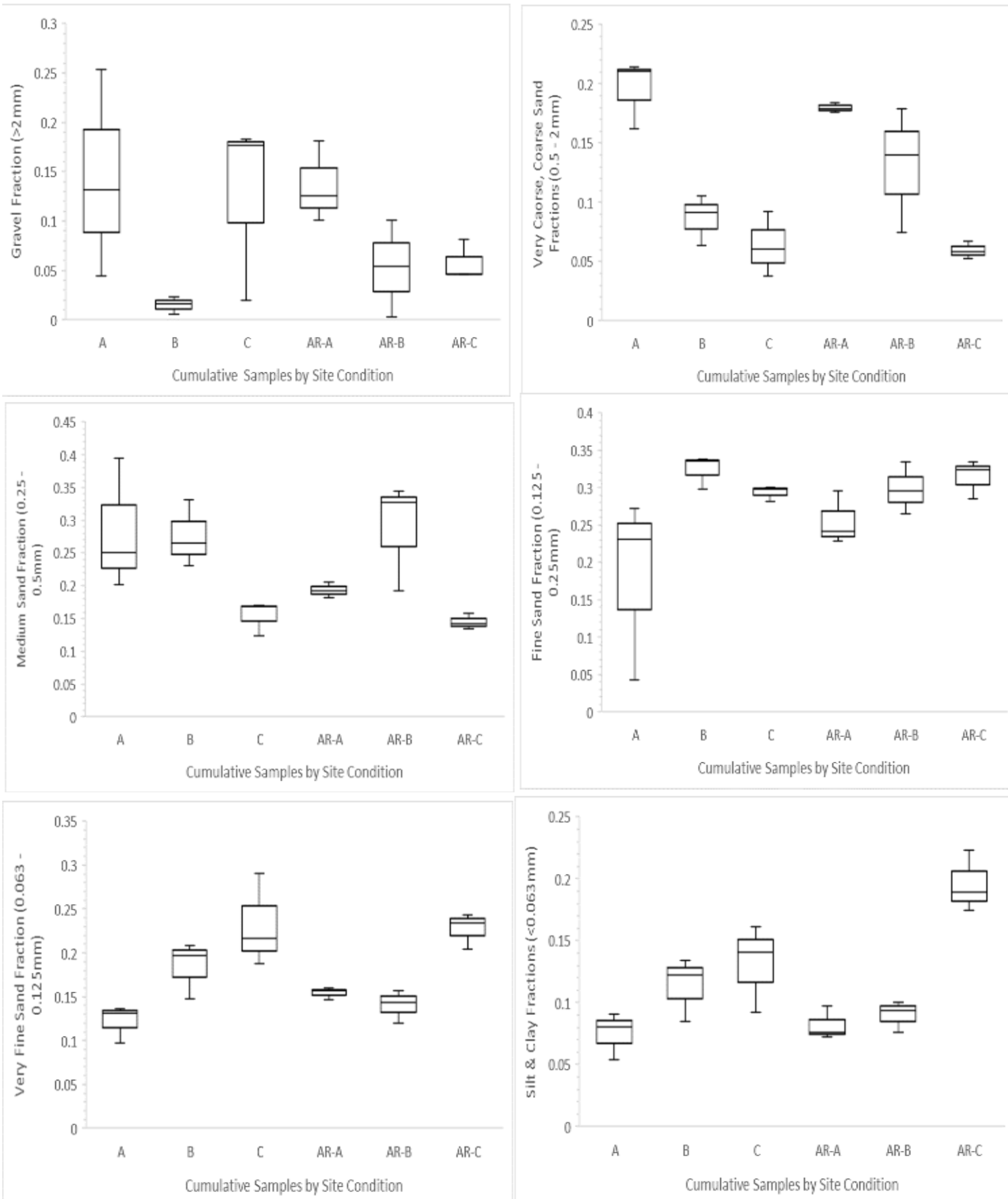

Figure 18. Boxplots of Grain sizes (gravel, very coarse & coarse sand, medium sand, fine sand, very fine sand and silt & clay) represented as a fraction of a Whole (1) of sediment samples collected from 3 sites before and after berm removal in Nanaimo estuary, Nanaimo, BC. Three samples per site and condition were collected and percentages are shown as a fraction of 1. Median ±Standard error is shown including medians (horizontal line), the lower and upper 25th and 75th percentiles (boundaries of the box) and minimum and maximum values(whiskers).

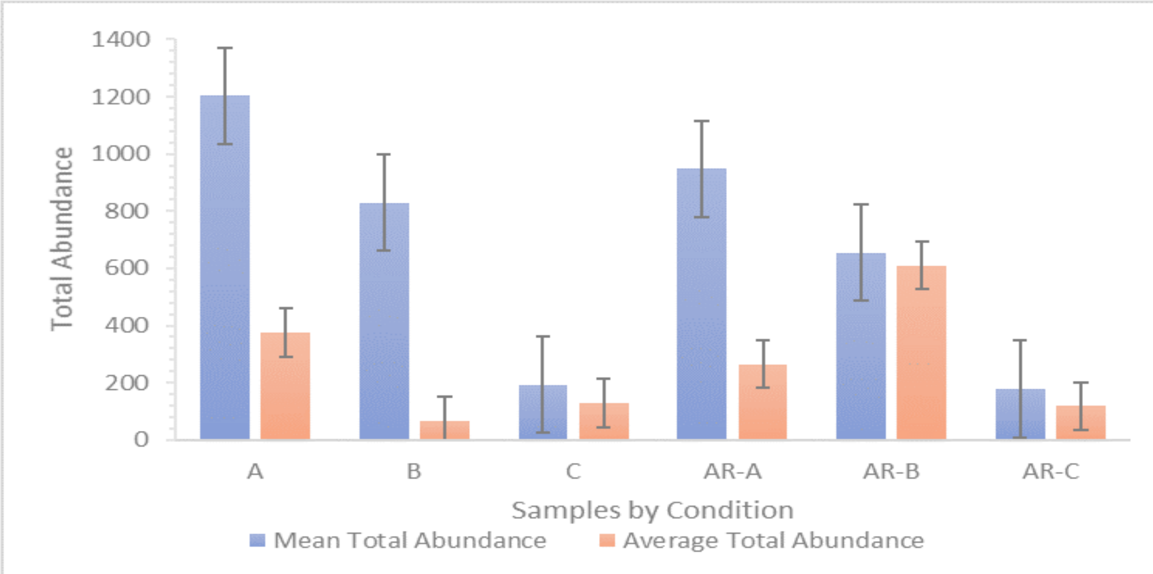

Figure 19. Bar chart showing mean Total Abundance and average Total Abundance of the benthic samples by site condition. The Total Abundance from three benthic samples were combined separately at each site by condition (before berm removal and after berm removal) for a restoration project by Nature Trust BC started in 2019 in the Nanaimo estuary, Nanaimo BC. Standard error is shown.

Appendix C. Pictures

Figure 20. Photo of PVC corer used to extract sediment containing benthic invertebrate samples and soil samples for a study done on behalf of the Nature Trust of BC during a restoration project started in 2019 at the Nanaimo estuary, Nanaimo, BC.

Figure 21. Photo of a 0.5mm sieve and a typical soil core extracted for benthic invertebrate samples and grain size analysis for a study done on behalf of the Nature Trust of BC during a restoration project started in 2019 at the Nanaimo estuary, Nanaimo, BC.

Figure 22. Photo of Site A (berm impacted Ahead channel) located approximately 49°08'12" N 123°53'42" W for a study done on behalf of the Nature Trust of BC during a restoration project started in 2019 at the Nanaimo estuary, Nanaimo, BC. This was before berm removal.

Figure 23. Photo of Site C(control channel) located approximately 49°08'14'' N 123°53'48"W on Oak Island for a study done on behalf of the Nature Trust of BC during a restoration project started in 2019 at the Nanaimo estuary, Nanaimo, BC.

'Figure 24. Photo of Site B(berm impacted channel) located approximately 49°08'12" N 123°53'45" W for a study done on behalf of the Nature Trust of BC during a restoration project started in 2019 at the Nanaimo estuary, Nanaimo, BC.

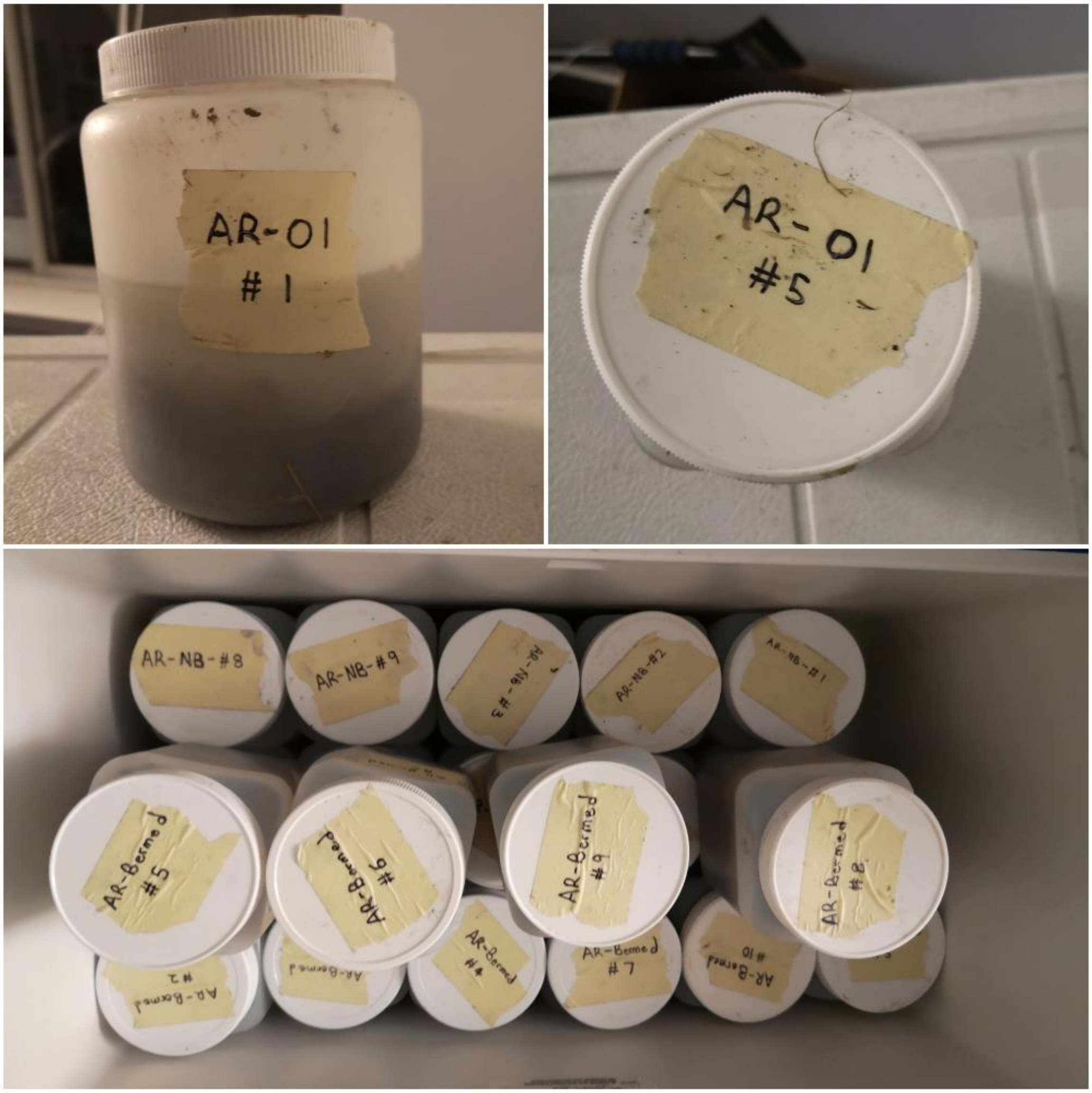

Figure 25. Benthic samples stored in formalin solution for lab analysis for a study for a study done on behalf of the Nature Trust of BC during a restoration project started in 2019 at the Nanaimo estuary, Nanaimo, BC.

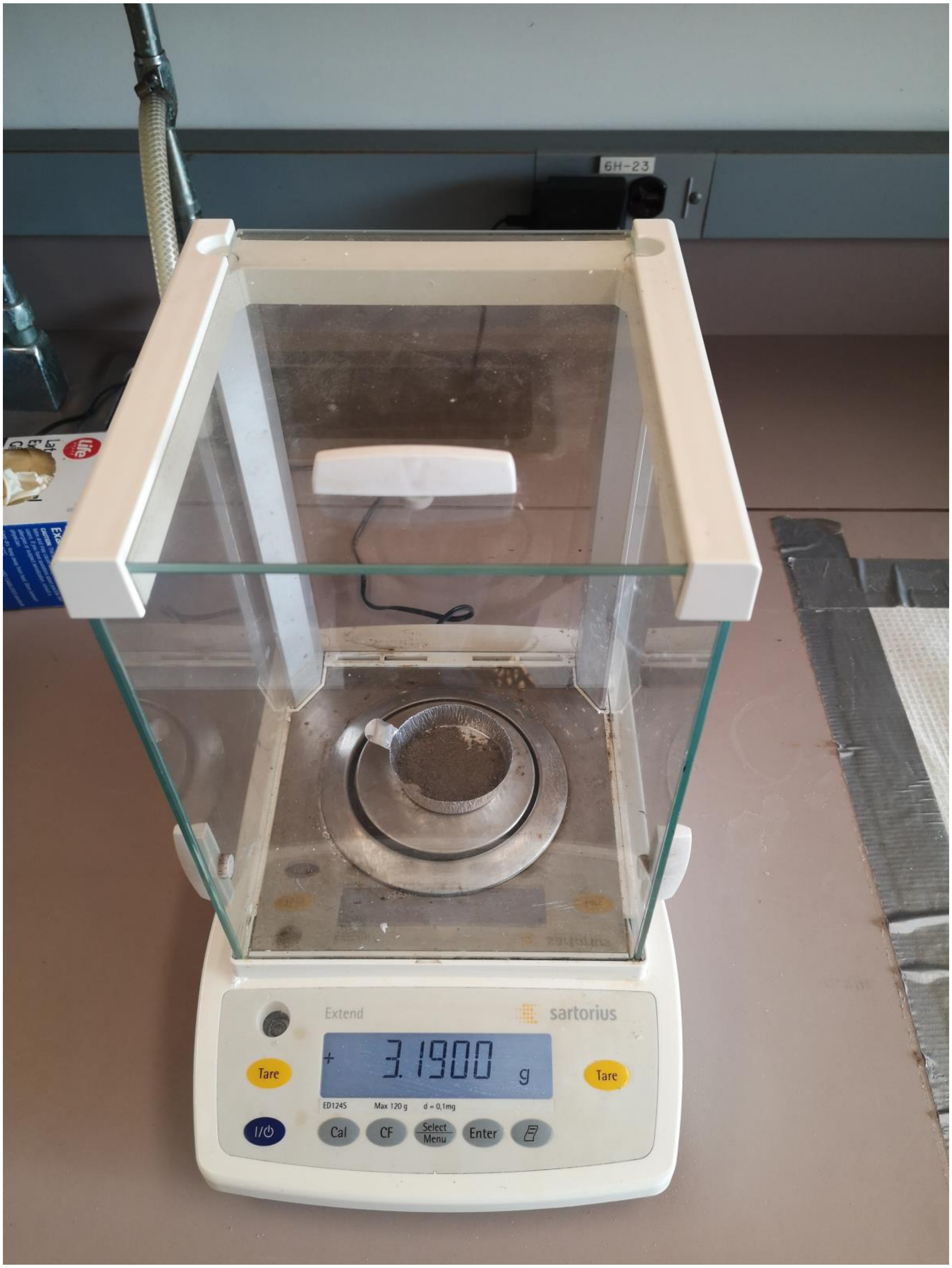

Figure 26. Photo of measuring the weight of the remaining sediment particles after drying and burning the soil samples to remove water content and organic matter respectively analysis for a study for a study done on behalf of the Nature Trust of BC during a restoration project started in 2019 at the Nanaimo estuary, Nanaimo, BC

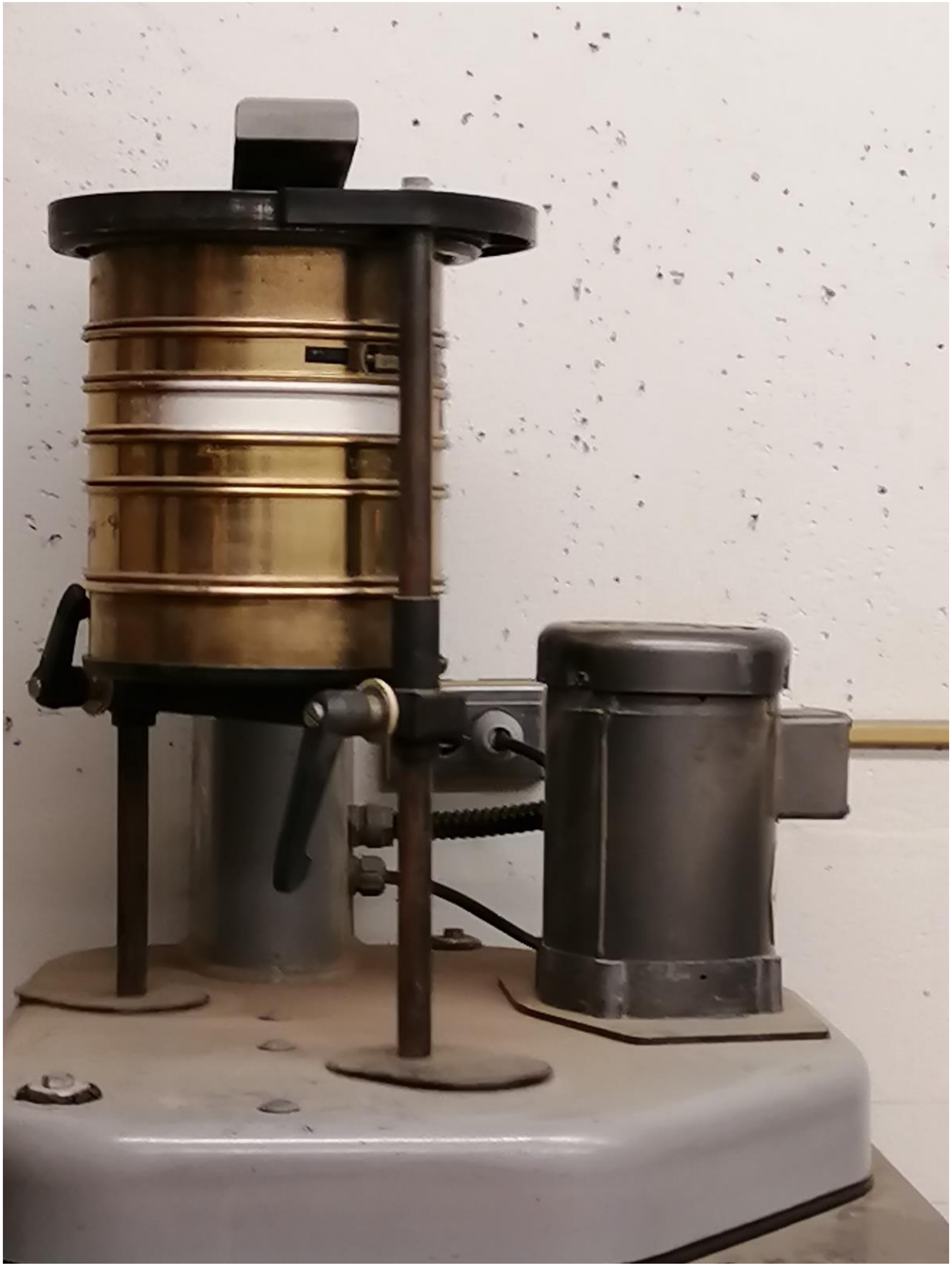

Figure 27. Photo of the sieve shaker sorting the grain sizes of a typical sample through sieve classes >2mm, (gravel),) 0.5mm – 2mm (very coarse and coarse sand), 0.25mm – 0.5mm (medium sand), 0.125mm – 0.25mm (fine sand, 0.063mm – 0.125mm (very fine sand) and <0.063mm (silt and clay) for 5 minutes for a study for a study done on behalf of the Nature Trust of BC during a restoration project started in 2019 at the Nanaimo estuary, Nanaimo, BC

Appendix D. Biologica Raw Data

Table 8. Total Taxa of Benthic Invertebrates extrapolated from subsample raw counts by Phylum, Class, Order and Family done by Biologica Environmental Services Ltd. for a study sponsored by Nature Trust of British Columbia in the Nanaimo Estuary, Nanaimo, BC in 2019.

taxcode	grpcode	Phylum	Class	Order	Family	Taxon Name
ANNE	ANOL	Annelida	Clitellata	Enchytraeida	Enchytraeidae	Enchytraeidae indet.
ANNE	ANOL	Annelida	Clitellata	Haplotaxida	Naididae	Naididae indet.
ANNE	POER	Annelida	Polychaeta	Phyllodocida	Nereididae	Nereididae indet.
ANNE	POSE	Annelida	Polychaeta	Sabellida	Sabellidae	Sabellidae indet.
ANNE	POSE	Annelida	Polychaeta	Spionida	Spionidae	Spionidae indet.
ANNE	POSE	Annelida	Polychaeta	Terebellida	Ampharetidae	Ampharetidae indet.
ANNE	POSE	Annelida	Polychaeta		Capitellidae	Capitellidae indet.
ARTH	CHAR	Arthropoda	Arachnida	Trombidiformes	Halacaridae	Halacaridae indet.
ARTH	CRAM	Arthropoda	Malacostraca	Amphipoda	Ampithoidae	Ampithoidae indet.
ARTH	CRAM	Arthropoda	Malacostraca	Amphipoda	Anisogammaridae	Anisogammaridae indet.
ARTH	CRAM	Arthropoda	Malacostraca	Amphipoda	Aoridae	Aoridae indet.
ARTH	CRAM	Arthropoda	Malacostraca	Amphipoda	Corophiidae	Corophiidae indet.
ARTH	CRAM	Arthropoda	Malacostraca	Amphipoda	Hyalidae	Hyalidae indet.
ARTH	CRAM	Arthropoda	Malacostraca	Amphipoda	Melitidae	Melitidae indet.
ARTH	CRAM	Arthropoda	Malacostraca	Amphipoda	Pontogeneiidae	Pontogeneiidae indet.
ARTH	CRAM	Arthropoda	Malacostraca	Amphipoda	Talitridae	Talitridae indet.
ARTH	CRAM	Arthropoda	Malacostraca	Amphipoda		Amphipoda indet.
ARTH	CRDE	Arthropoda	Malacostraca	Decapoda	Varunidae	Varunidae indet.
ARTH	CRIS	Arthropoda	Malacostraca	Isopoda	Sphaeromatidae	Sphaeromatidae indet.
ARTH	CRMY	Arthropoda	Malacostraca	Mysida	Mysidae	Mysidacea indet.
ARTH	CRMY	Arthropoda	Malacostraca	Mysida	Mysidae	Mysidae indet.
ARTH	CRTA	Arthropoda	Malacostraca	Tanaidacea	Tanaididae	Tanaididae indet.
ARTH	INCM	Arthropoda	Collembola	Collembola	Entomobryidae	Entomobryidae indet.
ARTH	INCM	Arthropoda	Collembola	Collembola	Hypogastruridae	Hypogastruridae indet.
ARTH	INDI	Arthropoda	Insecta	Diptera	Ceratopogonidae	Ceratopogonidae indet.
ARTH	INDI	Arthropoda	Insecta	Diptera	Chironomidae	Chironomidae indet.
ARTH	INDI	Arthropoda	Insecta	Diptera	Dolichopodidae	Dolichopodidae indet.
ARTH	INDI	Arthropoda	Insecta	Diptera	Muscidae	Muscidae indet.
ARTH	INDI	Arthropoda	Insecta	Diptera	Tabanidae	Tabanidae indet.
ARTH	INDI	Arthropoda	Insecta	Diptera	Tipulidae	Limoniidae indet.
ARTH	INLE	Arthropoda	Insecta	Lepidoptera	Crambidae	Crambidae indet.
MISC	CNHY	Cnidaria	Hydrozoa	Anthoathecata	Bougainvilliidae	Bougainvilliidae indet.
MISC	CNHY	Cnidaria	Hydrozoa	Anthoathecata	Cordylophoridae	Cordylophoridae indet

MISC	NTEA	Nemertea	Hoplonemertea	Hoplonemertea indet.
MOLL	MOGA	Mollusca	Gastropoda	Gastropoda indet.
Incidental Taxa:				
MEMO	MEMO	Arthropoda		Acari indet. (terrestrial)
MEMO	MEMO	Arthropoda		Arthropoda indet.
MEMO	MEMO	Arthropoda		Copepoda indet.
MEMO	MEMO	Arthropoda		Insecta indet. (terrestrial)
MEMO	MEMO	Arthropoda		Ostracoda indet.
MEMO	MEMO	MEMO		Egg/egg mass
MEMO	MEMO	Nematoda		Nematoda indet.

Table 9. Abbreviations & Definitions of terminology for Benthic Invertebrates used by Biologica Environmental Services Ltd. for a study sponsored by Nature Trust of British Columbia in the Nanaimo Estuary, Nanaimo, BC in 2019.

biologica	
Abbreviations & Definitions	
MEMO	Incidental taxa/fragments not included in data, or whose abundance is not generally captured accurately by 1.0mm screen.
Total Number of Taxa	Number of unique taxa (=species richness), not including higher-order taxa for which there exists a lower-order identification (e.g. not including Lumbrineris sp. if there exists Lumbrineris cruzensis in the data)
Total Number of Organisms	Total Abundance, not including incidental taxa
Biologica Coding	
Major Taxonomic Groups:	
Miscellaneous	
BRAC	Brachiopoda
BRYO	Bryozoa
CNAN	Cnidaria Anthozoa
CNHY	Cnidaria Hydrozoa
CNXX	Cnidaria
ENTO	Entoprocta
EURA	Echiura
HEMI	Hemichordata
KINO	Kinorhyncha
NTEA	Nemertea

PHOR	Phoronida
PIXX	Pisces
PLTY	Platyhelminthes
PORI	Porifera
PRIA	Priapulida
SIPN	Sipuncula
TARD	Tardigrada
URAS	Ascidiacea
Annelida	
ANHI	Annelida Hirudinea
ANOL	Annelida Oligochaeta
POER	Polychaeta Errantia
POSE	Polychaeta Sedentaria
POLY	Polychaeta
POXX	Polychaeta indet.
Arthropoda	
CHPY	Chelicerata Pycnogonida
CHAC	Chelicerata Arachnida
CRAM	Crustacea Amphipoda
CRCI	Crustacea Cirripedia
CRCO	Crustacea Copepoda
CRCU	Crustacea Cumacea
CRDE	Crustacea Decapoda
CRIS	Crustacea Isopoda
CRLE	Crustacea Leptostraca
CRMY	Crustacea Mysidacea
CROS	Crustacea Ostracoda
CRTA	Crustacea Tanaidacea
CRXX	Crustacea
Echinodermata	
ECAS	Echinodermata Asteroidea
ECCR	Echinodermata Crinoidea
ECEC	Echinodermata Echinoidea
ECHO	Echinodermata Holothuroidea
ECOP	Echinodermata Ophiuroidea
Mollusca	
MOAP	Mollusca Aplacophora
MOBI	Mollusca Bivalvia
MOCE	Mollusca Cephalopoda
MOGA	Mollusca Gastropoda
MOPO	Mollusca Polyplacophora
MOSC	Mollusca Scaphopoda