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# Efficacy of Sediment Contaminant Remediation of the Benthos in a Segment of the Southern Branch of the Elizabeth River

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EFFICACY OF SEDIMENT CONTAMINANT REMEDIATION OF THE BENTHOS

IN A SEGMENT OF THE SOUTHERN BRANCH OF THE ELIZABETH RIVER

by

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# ABSTRACT

EFFICACY OF SEDIMENT CONTAMINANT REMEDIATION OF THE BENTHOS IN A SEGMENT OF THE SOUTHERN BRANCH OF THE ELIZABETH RIVER

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Old Dominion University, 2021
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The bottom sediment of the Southern Branch of the Elizabeth River, a tributary of Chesapeake Bay, was historically contaminated with hydrocarbons from industrial sources especially wood treatment facilities. The Elizabeth River Project selected a section of the bottom off Money Point in the Southern Branch for a sediment contaminant remediation effort. Prior to initiation of remediation efforts, a survey occurred in summer 2010 to characterize the ecological condition of the benthic communities off Money Point compared to benthic communities of a benthic region across the channel and northwest of Money Point near Blows Creek. That study characterized the benthos of Money Point as significantly different from and degraded compared to that of Blows Creek using the Chesapeake Bay Benthic Index of Biotic Integrity. After the 2010 benthic community collection, the remediation effort removed approximately 20,000 cubic yards of contaminated sediment and covered the bottom with a sand cap. This phase of the remediation was completed in 2012. My study characterized the benthic communities of the same two field sampling strata at Money Point and Blows Creek in summer 2013 after the dredging and capping was completed.

The benthic community condition was characterized using the multi-metric Chesapeake Bay Benthic Index of Biotic Integrity (B-IBI), abundance of individuals, biomass, species richness, and informational diversity. In comparing the pre-remediation and post-remediation benthic community condition, I used a fixed 2-factor ANOVA consistent with a BACI design (Before After Comparison

Interaction). The B-IBI and all metrics showed improvements at Money Point, whereas the majority of metrics at Blows Creek showed a decrease. The B-IBI in particular decreased at Blows Creek by the same amount that Money Point increased, changes that would not be significant except when compared directly by the BACI style assessment. Comparison of biological metrics between sample periods at Money Point indicated a change from an opportunist dominated community to a more transitional community. A comparison of ratios of biomass to abundance and species richness to abundance further suggests a shift towards larger bodied organisms in less abundance than before remediation, indicative of an improved condition.

This thesis is dedicated to my mother and father; you generally don't get to choose them in your life, and I'm lucky to have had those that could raise a kid like me.

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# CHAPTER I

# INTRODUCTION

## HISTORY OF AN IMPACTED URBAN ESTUARY EMPHASIZING PAH CONTAMINATION

The Elizabeth River is a tributary of the southern Chesapeake Bay, whose watershed includes the cities of Norfolk, Portsmouth, Chesapeake and Virginia Beach. The Southern Branch of the Elizabeth River is one of the three regions of concern in the Chesapeake Bay (USEPA 1994) characterized by an industrialized watershed with multiple U.S. Naval and commercial shipyards, marinas, coal terminals, and petroleum storages; historically it was also home to five wood treatment facilities (Hawthorne and Dauer 1983, Walker et al. 2005). These facilities operated on petroleum and coal fuel sources but the prime contributor to pollutant deposition was the use of the wood treatment substance creosote, which was released into the water during normal treatment procedures as well as from spills, leaks and ground water contamination (Walker et al. 2005). The influx of creosote to the groundwater and open waters of the watershed greatly increased the levels of polycyclic aromatic hydrocarbons (PAHs) in the bottom sediments. Other sources of PAHs were inputs from latent atmospheric deposition (Dickhut and Gustafson 1995) and to a much lesser extent, from weathered petroleum products (Merril and Wade 1985). PAHs can be toxic in concentrations as low as 1ppm (Long 1992) but lethal concentrations vary directly with the number of aromatic rings of the PAH (Chandler et al. 1997). These different types of PAH are either known or suspected carcinogens and mutagens (Denissenko et al. 1996, Menzie et al. 1992, Phillips and Grover 1994). PAHs are among the most serious anthropogenic stressors to estuarine ecosystems along with pesticides, heavy metals, and polychlorinated biphenals (PCBs) (Kiddon et al. 2003).

The Southern Branch is characterized by concentrated anthropogenic activity, its physiographic shape, its small tidal range and low levels of riverine input, resulting in slow current velocities and poor flushing. These factors result in high depositional rates and therefore benthos characterized by the prevalence of fine, silty sediments, and little transport of sediment-bound contaminants out of the system (Hawthorne and Dauer 1983). These processes are capable of binding and immobilizing contaminants due to the pollutants' high $K_{ow}$ values (water-octanol partitioning coefficient), resulting in a high potential for adsorption to sediment and as well as a high potential for bioaccumulation (the ratio of the concentration of a substance in an organism compared to its surroundings) in the lipids of benthic animals (Arzayus et al. 2001, Chandler et al. 1997, DiToro et al. 1991, Hinga 1988, Karickhoff et al. 1979). Organic content of the sediment is also proportional to the contaminant levels therein, and finer, siltier sediment has naturally higher organic carbon content than coarser sediments due to surface area to volume relationships (Arzayus et al. 2001, Bjørgesæter and Ray 2008). Adsorption and bioaccumulation can temporarily immobilize these toxins; however changes in salinity, pH, water physiochemistry, dissolved oxygen, and redox potential can all remobilize the toxins into the water column (Macfarlane and Booth 2001). Additionally, slight disturbances such as benthic organisms foraging, feeding and burrowing through the sediment can remobilize buried contaminants, or at least mix them into cleaner sediments (Eganhouse and Sherblom 2001). The ease of mobilization makes constant monitoring of these pollutants essential due to their significant risk to alter benthic communities and to harm organisms at higher trophic levels (Kiddon et al. 2003, Zimmerman and Canuel 2000).

SUMMARIZATION OF SEDIMENT CONTAMINANT REMEDIATION EFFORTS AT MONEY POINT

For decades the Money Point peninsula in the Southern Branch of the Elizabeth River has been associated with environmental challenges (Figure 1). In 2006 The Elizabeth River Project announced a plan for restoring Money Point at a cost of more than $6 million. Five million dollars was provided through The Living River Restoration Trust, a mitigation fund authorized by the U.S. Army Corps of Engineers, Norfolk District, and Virginia Department of Environmental Quality, and dispensed by APM Terminals Virginia. Additional support was provided by: the U.S. Environmental Protection Agency's ‘Targeted Watershed Initiative’ and ‘Community Action for a Renewed Environment’ programs, National Oceanic and Atmospheric Administration's (NOAA) Community Based Habitat Restoration Program, the Virginia Department of Environmental Quality, the FishAmerica Foundation, the Virginia Migratory Waterfowl Stamp Grant Program, the Hess Corporation, Luck Stone and the members and donors of Elizabeth River Project (David Koubsky, Elizabeth River Project 2013, personal communication).

The Elizabeth River Project’s goal is to restore livable wetland and aquatic habitats in this degraded environment through replacement or capping of the contaminated sediment. The restoration effort had three phases. Phase 1 was a comparably smaller 750 cy area of dredging with restoration of the associated wetlands, Phase 2 (the phase I focused on in my study) was a much larger dredging of 20,000 cy of contaminated sand north of Phase 1, followed by the

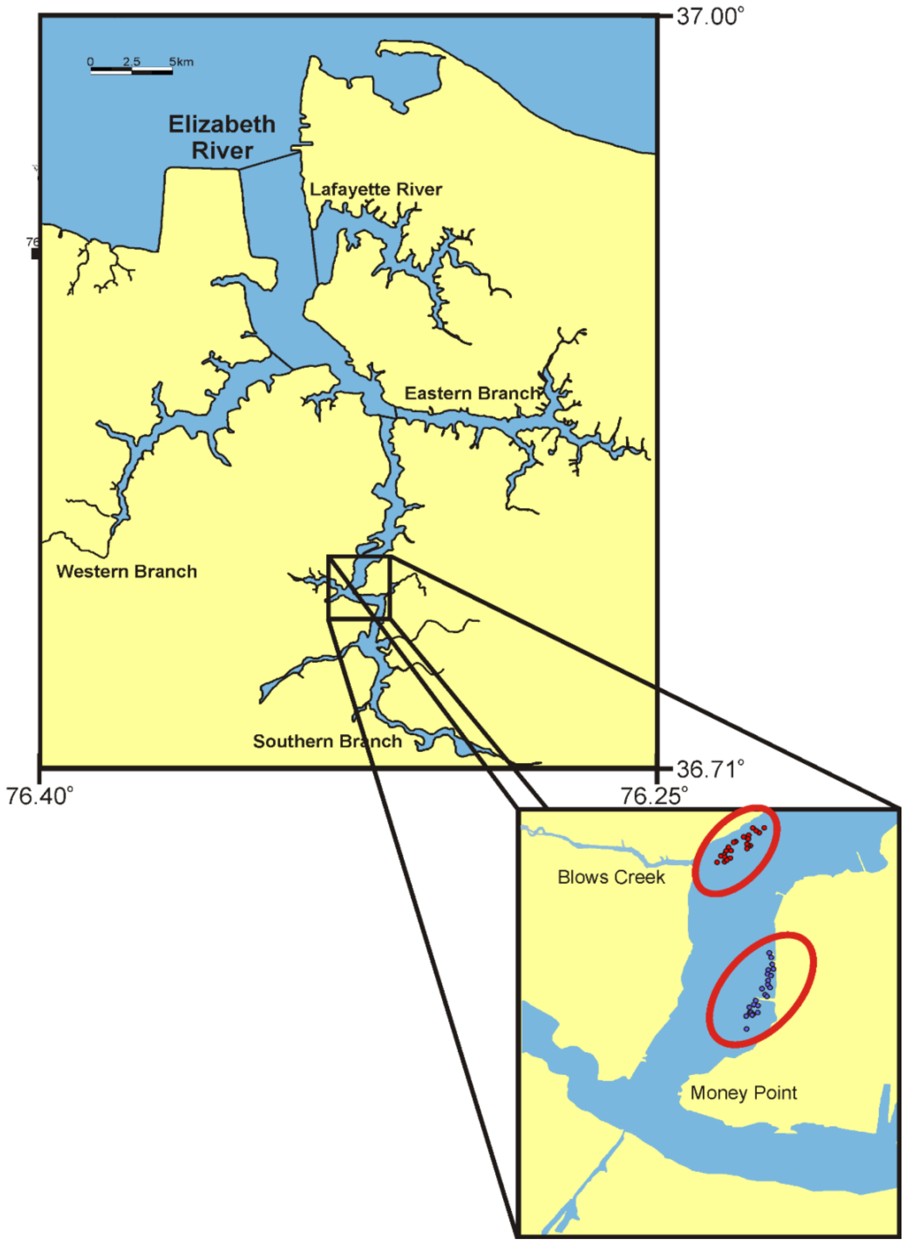



**Figure 1.** Location of the study strata in the Southern Branch of the Elizabeth River in Virginia. Money Point, the stratum of remediation, is located upriver from the reference stratum, Blows Creek.

introduction of clean sands to replace the removed degraded sediment in areas of Phases 1 and 2. Phase 3 consisted of the dredging and replacement of more than 45,000 cy of sediment. Phase 1 restoration was completed in 2009, Phase 2 was completed in 2012 and Phase 3 was completed in 2013. Prior to the remediation in Phase 2, a 2010 chemical analysis showed an average concentration of 358 ppm at the Money Point stratum (Test America, 2010). Following the remediation in Phase 2, the stratum's concentration dropped to a value of 21.5 ppm (Koubsky, 2013) well below the project goal of 45ppm.

## EFFICACY OF REMEDIATION USING BENTHIC COMMUNITY CONDITION AND ENVIRONMENTAL INDICES

The ecological condition of benthic macrofaunal communities is used internationally to assess estuarine and coastal marine ecosystems (Bilyard 1987, Dauer 1993). Benthic communities consist of species that: (1) are relatively sedentary as adults, (2) have a wide diversity of tolerances/susceptibilities to environmental stresses, (3) function at numerous trophic levels (deposit feeders, suspension feeders, herbivores, predators, etc.), (4) are important food sources for higher trophic levels, (5) exhibit a range of reproductive/dispersal strategies, and/or (6) are directly commercially important, i.e. shellfish, baitfish, etc. (Dauer 1993, Kiddon et al. 2003, Macfarlane and Booth 2001 , MacFarlane and Booth 2001, Warwick 1993). The major indicator of benthic community condition for the Chesapeake Bay is the Benthic Index of Biotic Integrity (B-IBI) (Weisberg et al. 1997; modified by Alden et al. 2002). The B-IBI is calculated by scoring values of quantifiable aspects of the benthic communities (such as abundance and biomass) compared to respective aspects of reference samples that are relatively free of anthropogenic stressors. Selection of metrics and the values for scoring metrics were developed separately for each of seven benthic habitat types in Chesapeake Bay (Weisberg et al.1997). The IBI approach involves scoring each metric as 5, 3, or 1, depending on whether its value at a stratum approximates, deviates slightly, or deviates greatly from conditions at reference conditions (Karr et al. 1986).

The most widely cited benthic community condition model is the Species-Abundance-Biomass (SAB) model of Pearson and Rosenberg (1978). The Pearson and Rosenberg model (Figure 2) shows patterns of the SAB curves as a function of organic input with the primary stressor being low dissolved oxygen levels. However, many benthic community ecologists also use the Pearson and Rosenberg SAB model to represent the spatial patterns at increasing distances from a disturbed/stressed system or the temporal pattern at increasing time after the cessation of the disturbance/stress. Rakocinski et al. (2000) developed analogous SAB models relative to the presence of heavy metals and organic contaminants (Figure 3). The patterns of these curves allow further insight into the recovery of the benthos; each of the metrics display maxima at the lowest organic contaminant conditions, then species richness and abundance decline while biomass increases to a high point during biostimulation, followed by a decline of all three metrics towards a low ecotone point, at which the habitat changes composition from dominance of stable long-lived species to greater numbers of shorter-lived opportunists. For organic chemical contaminants at the highest levels, abundance can increase significantly along with a slight biomass increase but the species richness drops off (Rakocinski et al. 2000).

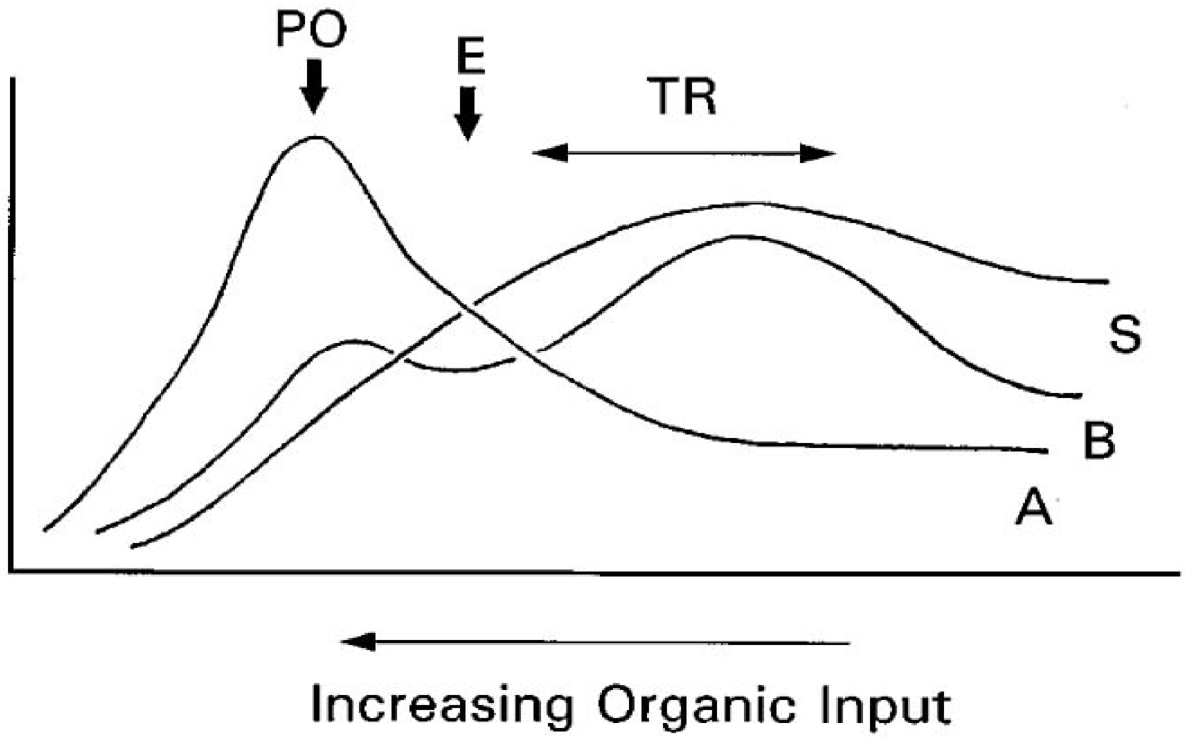



**Figure 2.** Graphical model of SAB responses to an organic enrichment gradient (PO = peak of opportunists; E = ecotone point; TR = transition region; S = species richness; A = total abundance; B = total biomass). (Pearson and Rosenberg, 1978).

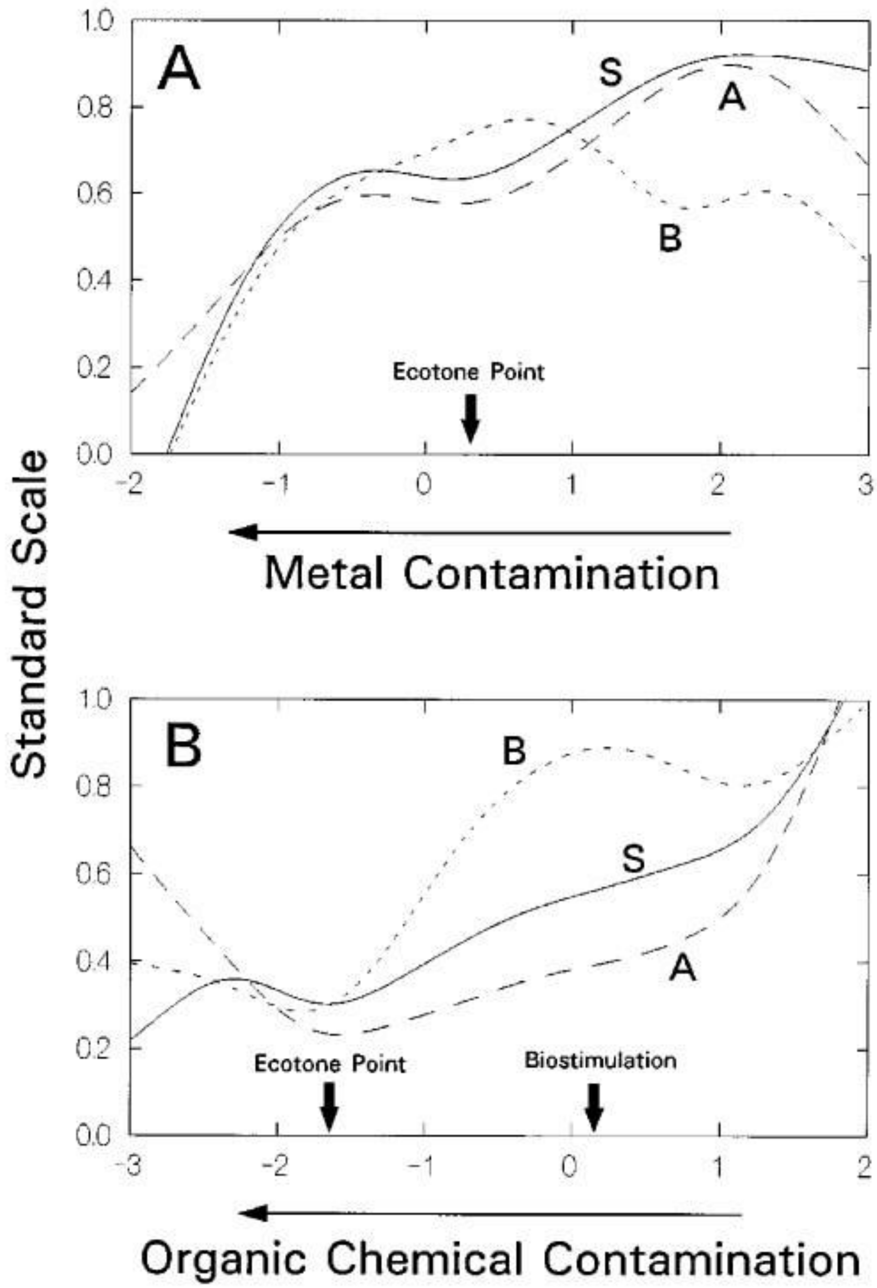



**Figure 3.** SAB responses to metal contamination and organic-chemical contamination. Adjusted for the effects of primary estuarine gradients averaged across 317 estuarine sites distributed throughout the northern Gulf of Mexico. (S = species richness; A = total abundance; B = total biomass) (Rakocinski et al. 2000).

SUMMARIZATION OF BENTHIC COMMUNITY CONDITION AT MONEY POINT PRIOR TO SEDIMENT CONTAMINANT REMEDIATION

Within the Elizabeth River, sediment contamination from heavy metals and polynuclear hydrocarbons has been identified as a major problem (Dauer and Llansó 2003). The Elizabeth River has been analyzed and classified using the B-IBI as largely below reference conditions after a ten-year study of 14 fixed-point stations throughout all branches of the river from 1999 to 2008 (Dauer, 2009). Five of the six fixed-point stations in the Southern Branch were characterized as degraded or severely degraded in benthic community condition while only one met reference conditions (Figure 4). The Southern Branch is the only stratum characterized by severe problems due to levels of heavy metals and sediment organic compounds relative to the other branches of the Elizabeth River (Dauer 1993, Dauer and Llansó 2003). The benthic communities of the Southern Branch are characterized by low species diversity (as used by the Shannon Index) and biomass, with excessive abundances above reference conditions (Dauer 2009). Additionally, the most dominant species (by abundance) was *Mediomastus ambiseta* (Table 1), a capitellid polychaete often considered to be an euryhaline opportunist and a plausible indicator of polluted sediments due in part to high pollution tolerance (Llansó et al. 2016).

Webb conducted a 2010 study to serve as a pre-remediation assessment of the benthic condition at Money Point (Webb 2014). His assessment concluded that several of the same conditions presented by Dauer (2009), including *Mediomastus ambiseta* dominating community abundances, existed at both Money Point and the Blows Creek reference stratum. At the contaminated Money Point stratum the B-IBI, biomass and species richness (as used by Webb 2014) were significantly lower than at the Blows Creek reference stratum (Table 2). Webbs data

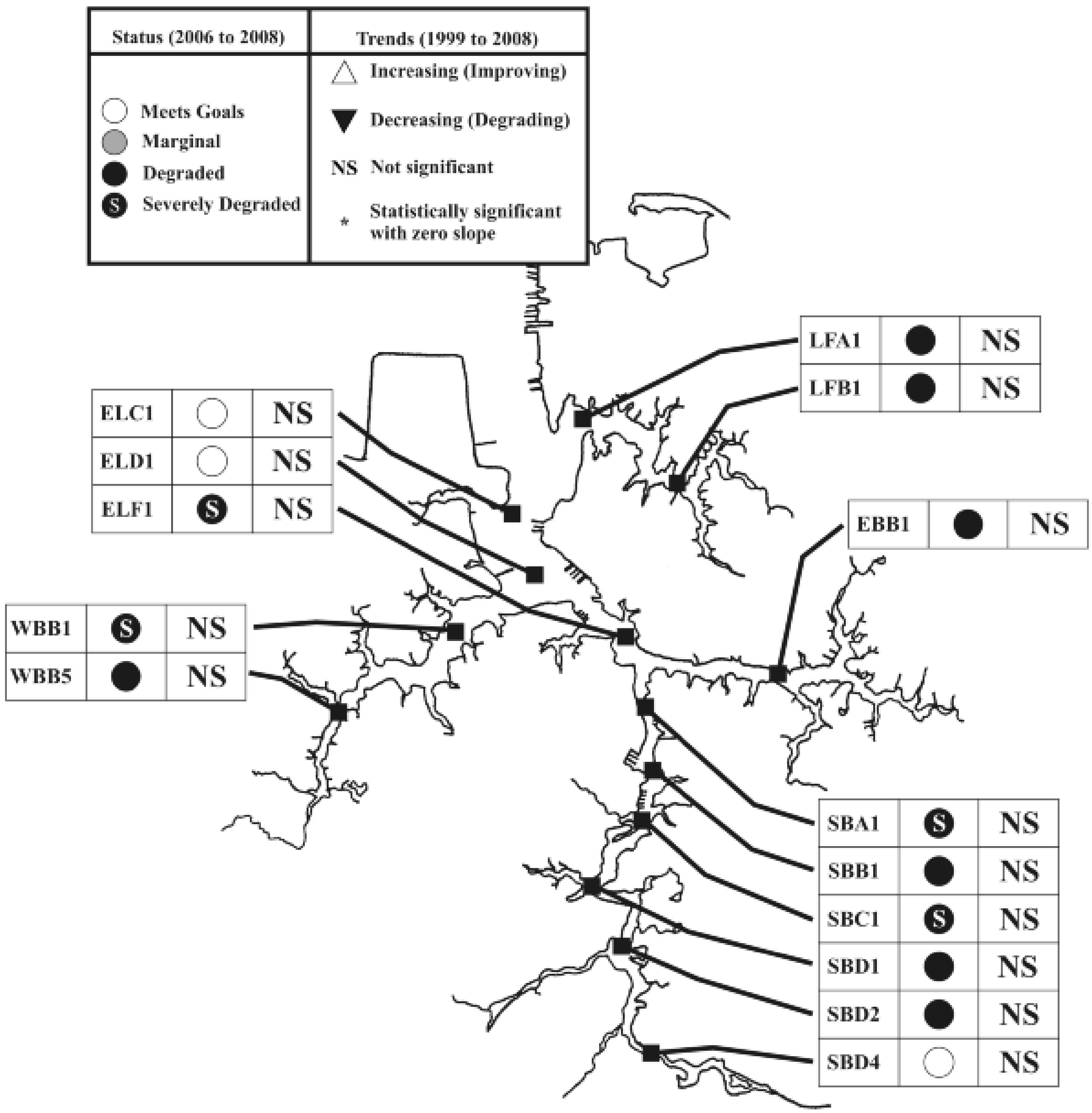



**Figure 4.** Status of and long-term trends in the Benthic IBI for the Elizabeth River Project monitoring stations for the period of 1999 through 2008. All trends shown were significant at p ≤ 0.05. Status is calculated as the mean value for the last three year period (2006-2008) (Dauer 2009)

**Table 1.** Fixed Stations of the Elizabeth River sampled in 2008. Dominant tax by abundance. Taxon code A=amphipod, C = cumacean, N = nemertean, O = oligochaete, P = polychaete, PH =phoronid. (See Table 5 in Dauer 2009)

| Rank | Taxon | Abundance per m$^2$ |
|---|---|---|
| 1 | *Mediomastus ambiseta* (P) | 4,018 |
| 2 | *Streblospio benedicti* (P) | 647 |
| 3 | *Paraprionospio pinnata* (P) | 233 |
| 4 | *Leitoscoloplos* spp. (P) | 202 |
| 5 | *Glycinde solitaria* (P) | 110 |
| 6 | *Leucon americanus (C)* | 104 |
| 7 | *Tubificoides* spp. Group I (O) | 88 |
| 8 | *Phoronis* spp. *(PH)* | 86 |
| 9 | *Caprella penantis (A)* | 57 |
| 10 | *Demonax microphthalmus* (P) | 53 |
| 11 | Nemertea spp. (N) | 50 |
| 12 | *Neanthes succinea* (P) | 49 |
| 13 | *Tharyx* sp. A Doner (P) | 43 |
| 14 | *Podarkeopsis levifuscina* (P) | 35 |
| 15 | *Listriella barnardi (A)* | 25 |

**Table 2.** Webb's 2014 metrics for Chesapeake Bay (CB), Blows Creek (BC), and Money Point (MP) strata, presented as mean values, with associated standard errors (SE in parentheses). B-IBI values were calculated using the methods of Weisberg et al. (1997). Values underscored were not significantly different between strata. (See Table 2 in Webb 2014)

| Metrics | B-IBI | Abundance | Biomass | Species Richness |
|---|---|---|---|---|
| **CB** | <u>2.7(0.1)</u> | 2,705(230) | 1.28(0.16) | 17.0(1.0) |
| **BC** | <u>2.6(0.6)</u> | <u>6,112(526)</u> | 0.83(0.10) | 13.8(0.5) |
| **MP** | 2.0(0.1) | <u>6,011 (96)</u> | 0.35(0.03) | 9.6(0.6) |

serve as the ‘Before’ conditions in my study, and are directly compared to the data I collected during my sampling season in 2013.

## OBJECTIVES OF STUDY

I expected the removal and/or capping of sediments containing potentially toxic levels of PAHs to result in improvements in the benthic community ecological condition. My data were compared to those of Webb (2014), who determined the benthic ecological condition of the same two strata (Money Point and Blows Creek) in 2010 prior to any sediment restoration efforts. I expected to see positive trends in the metrics of Money Point while not seeing changes in the condition of Blows Creek, suggesting a successful remediation at Money Point.

Using a Before-After Control-Impact (BACI) format I tested the relationships and differences between the impacted stratum at Money Point in the Southern Branch of the Elizabeth River and the reference stratum near Blows Creek   Five metrics of benthic community condition were tested using the BACI design: (1) the multimetric B-IBI, (2) the Shannon-Weiner diversity index, (3) richness of species, (4) the abundance of individuals, and (5) the biomass of the benthic community. Additionally, ratios of biomass to abundance (B/A) and species richness to abundance (S/A) were examined to test for average body size and relative dominance of species respectively, alongside comparisons of volatile organic content and silt-clay percentages to examine organic contaminant presence in the strata. The data for each of these metrics were separately tested, comparing strata, times and potential interactions between strata and times.

# CHAPTER II

# MATERIALS AND METHODS

Samples of bottom sediments and macrobenthic communities were collected from the remediated Money Point stratum and a nearby reference stratum near Blows Creek (Figure 1). The remediated area was 1.47 x$10^3$ $m^2$. The reference stratum of identical area, known to have low PAH concentrations, was designated near Blows Creek 500m downstream of the Money Point stratum (Figure 5).

## SAMPLE COLLECTION

Twenty-five sites per stratum were randomly selected following the Chesapeake Bay Benthic Program's random probability stratum approach (Dauer and Llansó 2003, Llansó et al. 2003). All sampling occurred in the summer index period (July 15 to September 30) for application of the B-IBI (Weisberg et al. 1997). Each site was sampled for benthic community with a modified Young Grab (440 $cm^2$) having a minimum depth of penetration of 7 cm, sieved in the field using a 0.5 mm mesh sized screen and fixed in a 10% formalin-ambient seawater mixture with an added rose bengal stain. A subsample of the surface sediment was collected with a Ponar Grab for determination of percent silt-clay content and for determination of total volatile solids at each station. These samples were put on ice in the field and stored at 0°C in the lab. Instantaneous measurements, such as water depth, bottom temperature, salinity, and dissolved oxygen, were measured at each sampling site with a handheld YSI.

A third dataset representing the Chesapeake Bay was also collected through the long-term Chesapeake Bay Program's probability-based monitoring program data (Dauer and Llansó 2003;

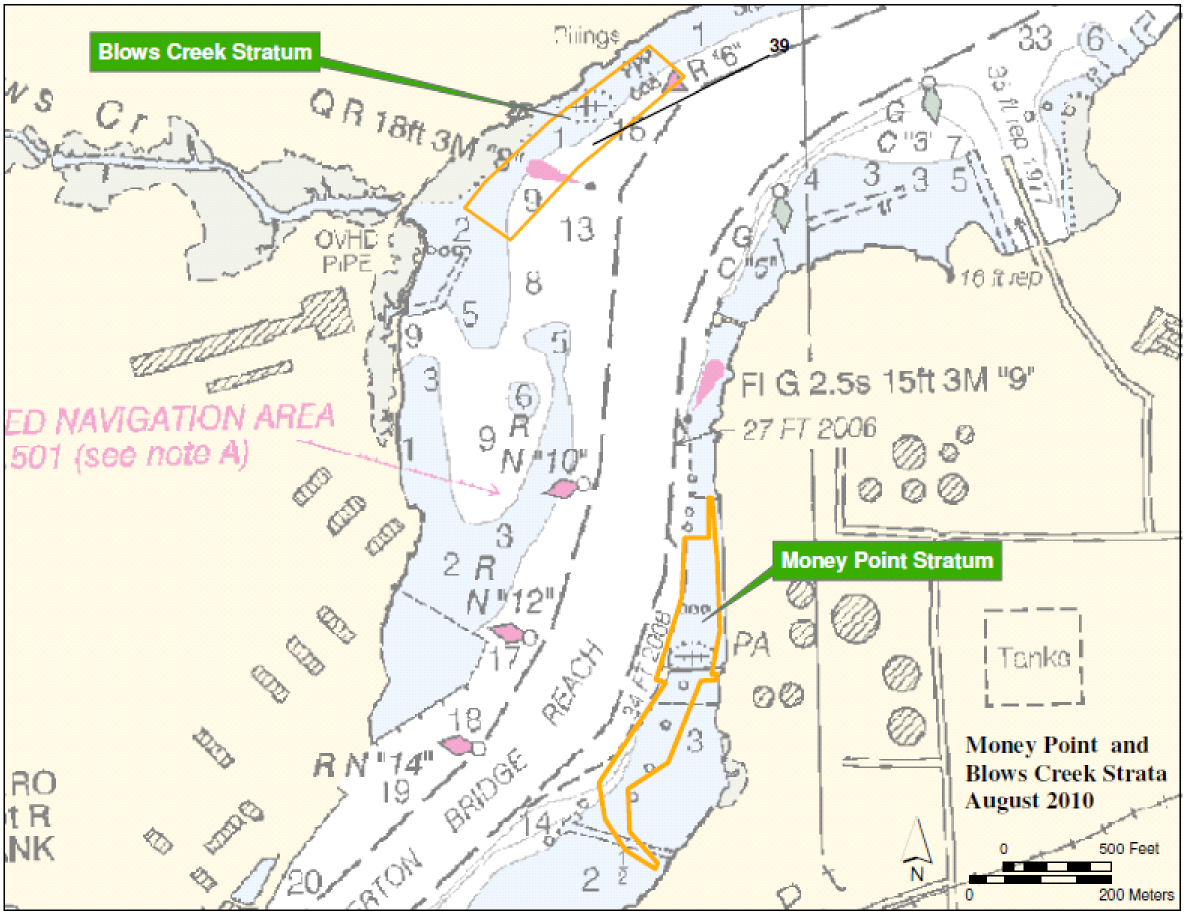



**Figure 5.** The Southern Branch of the Elizabeth River, showing the restoration stratum at Money Point and the reference stratum near Blows Creek.

Llansó et al. 2003). A period of 5 years (2009-2013) was used as the dataset, consistent with Webb (2014) and the same range of years used by Llansó et al. (2009) for impaired water listings in Maryland and Virginia. Using the summer data of two fixed-point stations in the Southern Branch of the Elizabeth River (see stations SBE2 and SBE5 in Dauer et al. 1992), a confidence interval for salinity of 19.82 to 22.52 ppt was generated. Samples from the Chesapeake Bay Program were selected within this salinity range, provided they were not collected from the Rappahannock River where summer anoxia occurs, the York River where periodic hypoxia occurs, or the Elizabeth River as it was the location of the data initially used for the interval. This third dataset included 42 samples and was only used in comparison of total volatile solids to silt-clay percentage values in this data set and Webb's (2014).

LABORATORY ANALYSIS

Each replicate was sorted in the laboratory and all individuals identified to the lowest possible taxon and enumerated. Biomass was estimated for each taxon as Ash-Free Dry Weight (AFDW) by drying to constant weight at $60^{o}$ C and ashing at $550^{o}$ C for four hours. Biomass was expressed as the difference between the dry and ashed weight while abundance was measured by number of organisms. Diversity was calculated afterwards through the Shannon-Weiner index method.

Particle-size analysis was performed as per Folk (1974). Each sediment sample was first separated into a sand fraction (> 63 µm) and a silt-clay fraction (< 63 µm). The sand fraction was dry sieved and the silt clay fraction quantified by pipette analysis. For random stations, only the percent sand and percent silt-clay fraction were estimated. Total volatile solids of the sediment was estimated by the loss upon ignition method, as described in Bale and Kenny (2005) and presented as percentage of the weight of the sediment. Station sediment type was classified as mud when the silt-clay content was > 40%, and as sand when ≤ 40%.

B-IBI CALCULATIONS

The B-IBI was calculated according to Weisberg et al. (1997) and Alden et al. (2002). This index scores several metrics of the benthic community as either 5, 3, or 1, based upon whether value at a site approximates, deviates slightly, or deviates greatly from conditions at the reference conditions. These metrics can include species diversity, abundance, biomass, percentages of pollution sensitive/indicative taxa, and trophic composition. The B-IBI index is only used during a summer sampling period of July 15$^{th}$ through September 30$^{th}$.

The metric scores were then averaged and the final value was used to classify the benthic community condition as: meeting expectations (≥ 3.0), marginal (2.6 - 2.9), degraded (2.1 – 2.5), or severely degraded (≤ 2.0). Threshold values were established as approximately the 5th and 50th (median) percentile values for reference conditions in each habitat. For each metric: values below the 5th percentile were scored as 1, values between the 5th and 50th percentiles were scored as 3, and values above the 50th percentile were scored as 5. Additionally, in regards to the metrics of abundance and biomass, very high values are also considered an indication of degradation. Therefore, for total species abundance and total biomass: a score of 1 is assigned if the value of these metrics for the sample being evaluated is below the 5$^{th}$ percentile or above the 95$^{th}$ percentile of corresponding reference values, a score of 3 is assigned for values between the 5$^{th}$ and 25$^{th}$ or between the 75$^{th}$ and 95$^{th}$ percentiles, and a score of 5 is assigned for values between the 25$^{th}$ and 75$^{th}$ percentiles.

## STATISTICAL ANALYSIS

For each metric, a fixed 2-factor ANOVA was performed. Assumptions of normality were tested using Shapiro Wilk's D test and by examining quantile plot output from SAS's UNIVARIATE procedure. Most parameters violated assumptions of normality and were transformed successfully using either log based 10 or square root transformation with the exception of the B-IBI which could not be successfully transformed. Due to the nature of the B-IBI, results are classified as a 1, 3, or 5; this results in anything but a 'slight deviation from reference conditions' strata displaying non-normal data distribution and would not easily be normalized through transformations. This is accepted and the B-IBI is regarded as sensitive, stable, robust and statistically sound (Alden et al. 2002) and is appropriate for ANOVA procedures (Karr, 1998). Post-hoc Bonferroni corrected Student's t tests were performed on least squared means corrected data (transforming the data instead of the alpha level so as to maintain a significance threshold of $p < 0.05$ for all tests) when required to test for significant differences within strata between years (2010 versus 2013, and between strata (BC vs MP) within years. Table 3 describes the rationale for performing post hoc comparisons which are based on the BACI approach (Underwood, 1992;1994).

Calculations were made from the data collected using individual stratum means of the ratio of biomass to abundance (B/A) to estimate the average size per organism, and individual stratum means of the ratio of the species richness per replicate to total abundance per sample (S/A) to measure dominance. These ratios were then analyzed following the same statistical approach described above.

Volatile organic content and silt-clay percentage from the 2013 strata and the Chesapeake Bay dataset were mapped in a linear regression due to high correlation established in Webb's study (2014). This graph was visually assessed and compared to Webbs graph of the 2010 data to identify trends.

**Table 3.** Stratum comparisons and rationales between Money Point (MP) and Blows Creek (BC) Strata to determine which results from LS Means test were analyzed (Tables 4B, 5B, and 6B)

| Comparisons | Rationale |
|---|---|
| MP (2010) X BC (2010) | Was the MP ecological condition different from the reference condition (BC) before remediation? |
| MP (2010) X MP (2013) | Did the MP ecological condition change after remediation? Improved or degraded? |
| MP (2013) X BC (2013) | Was the MP ecological condition different from the reference condition (BC) after remediation? |
| BC (2010) X BC (2013) | Did the reference stratum (BC) change over time? |

# CHAPTER III

# RESULTS

## B-IBI

The data for the B-IBI was not transformed due to the nature of the data, but still eligible for ANOVA assessment. The stratum-time interaction was significant (Table 4A). Subsequent LS means tests showed that (1) the MP stratum had a lower B-IBI value than the BC stratum in 2010 (Table 4B.1), (2) the MP stratum B-IBI value increased insignificantly after remediation (Table 4B.2), (3) after remediation the MP B-IBI value was not significantly different from the BC stratum (Table 4B.3), and (4) the BC stratum B-IBI was lower in 2013 compared to 2010 (Table 4B.4). Figure 6 summarizes these patterns.

## SPECIES DIVERSITY AND SPECIES RICHNESS

For species diversity, as measured by the Shannon-Wiener index, the stratum-time interaction was significant (Table 4A). Subsequent LS means tests showed that: (1) the MP stratum had a lower species diversity value than the BC stratum in 2010 but it was not significantly so (Table 4B.1), (2) the MP stratum species diversity value significantly increased after remediation (Table 4B.2), (3) after remediation the MP species diversity value was significantly larger than the BC stratum (Table 4B.3), and (4) the BC stratum species diversity values did not change significantly between 2010 and 2013 (Table 4B.4). Figure 7 summarizes these patterns.

For species richness (SR), the stratum-time interaction was significant (Table 4A). Subsequent LS means tests showed that: (1) the MP stratum had a lower species richness value than the BC stratum in 2010 (Table 4B.1), (2) the MP stratum species richness value significantly increased after remediation (Table 4B.2), (3) after remediation the MP species richness value was not significantly different than the BC stratum (Table 4B.3), and (4) the BC stratum species richness value was lower in 2013 than 2010, but not significantly so (Table 4B.4). Figure 8 summarizes these patterns.

## ABUNDANCE

For community abundance (A), the data required a log 10 transformation to meet assumptions of variance.  The stratum-time interaction was not significant (Table 4A). The main effects of both time and stratum were both significant however (Table 4A).

The top ten species by abundance were organized in relation to Money Point 2013 (Table 7). Across the strata and times polychaete species dominated in abundance with the polychaete *Mediomastus ambiseta* the top dominant; however at MP after the restoration its abundance decreased substantially, with the polychaete  *Hermundura americana* being present as the second most abundant species in the 2013 sites and MP 2010 and the third most abundant in BC 2010. In 2013 the third most plentiful organism was the polychaete *Paraprionospio pinnata*, while the polychaete *Streblospio benedicti* was the second and third most abundant species at MP 2010 and BC 2010 respectively.

BIOMASS

For community biomass (B), the data required a log 10 transformation to meet assumptions of variance.  The stratum-time interaction was significant (Table 4A). LS means tests showed that: (1) the MP stratum biomass was significantly lower than the BC stratum in 2010 (Table 4B.1), (2) the MP stratum biomass significantly increased after remediation (Table 4B.2), (3) after remediation the MP biomass was not significantly different from the BC stratum (Table 4B.3), and (4) the BC stratum biomass was not significantly different between 2010 and 2013 (Table 4B.3). Figure 10 summarizes these patterns.

The top ten biomasses per stratum were sorted by MP2013 first and then BC2013 (Table 8). In MP 2013 the dominant biomass was from *Glycera dibranchiata*, followed by *Nassarius vibex* and *Leitoscoloplos* spp., whereas BC 2013's dominant taxa by biomass was *Leitoscoloplos* spp., followed by *Hermundura americana* and *Glycera dibranchiata*  In the 2010 strata, MP's dominant taxa by biomass was *Mediomastus ambiseta*, followed by *Hermundura americana* and *Leitoscoloplos* spp. respectively, while BC's were *Loimia medusa* as the dominant biomass with *Hermundura americana* and *Glycera dibranchiata* respectively.

VOLATILE ORGANIC CONTENT AND SILT-CLAY PERCENTAGE

For volatile organic content, the stratum-time interaction factor was significant (Table 5A).  Subsequent LS means tests showed that the volatile organic content: (1) was significantly higher at MP than BC in 2010 (Table 5B.1), (2) significantly decreased at MP between the sampling periods (Table 5B.2), (3) at MP was no longer significantly different in 2013 from BC by a small margin (Table 5B.3), and (4) BC increased between 2010 and 2013 but was not significant (Table 5B.4). Figure 11 summarizes these patterns.

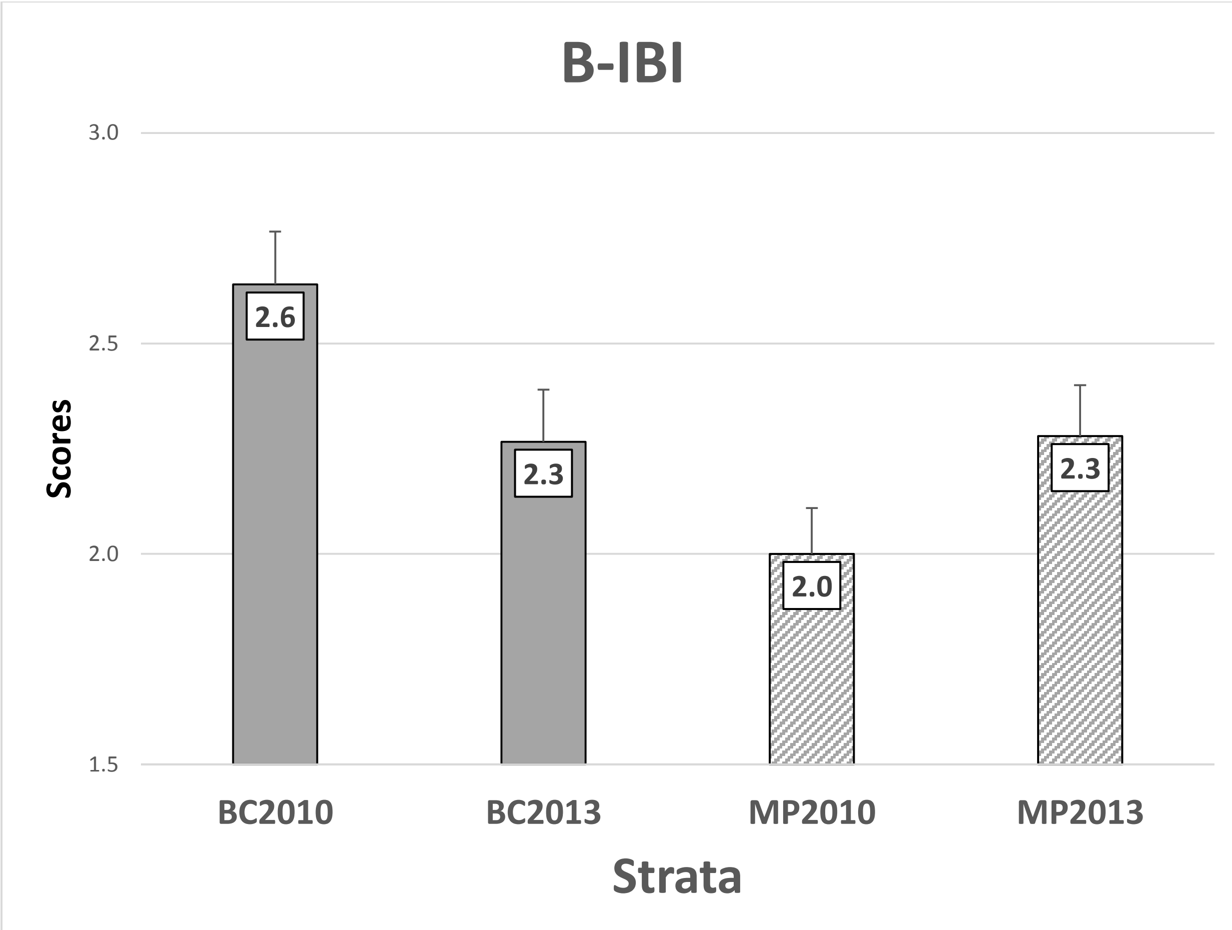
The silt-clay percentage required a square root transformation to meet assumptions of variance. The stratum-time interaction factor was significant (Table 5A). The subsequent LS means tests showed: (1) the percentage was higher at MP than BC in 2010 (Table 5B.1), (2) MP had a non-significant decrease between 2010 and 2013 (Table 5B.2), (3) MP did not differ significantly from BC in 2013 (Table 5B.3), and (4) BC had a non-significant increase between 2010 and 2013 (Table 5B.4). Figure 12 summarizes these patterns.

The linear regression plot of volatile organic content and silt-clay percentage showed all three strata had unique y-intercepts and slopes. The strata had similar y-intercepts; MP's was greater than BC and CB, which were nearer one another. However, the slopes of BC and MP were more similar to one another than CB's slope (Figure 15).

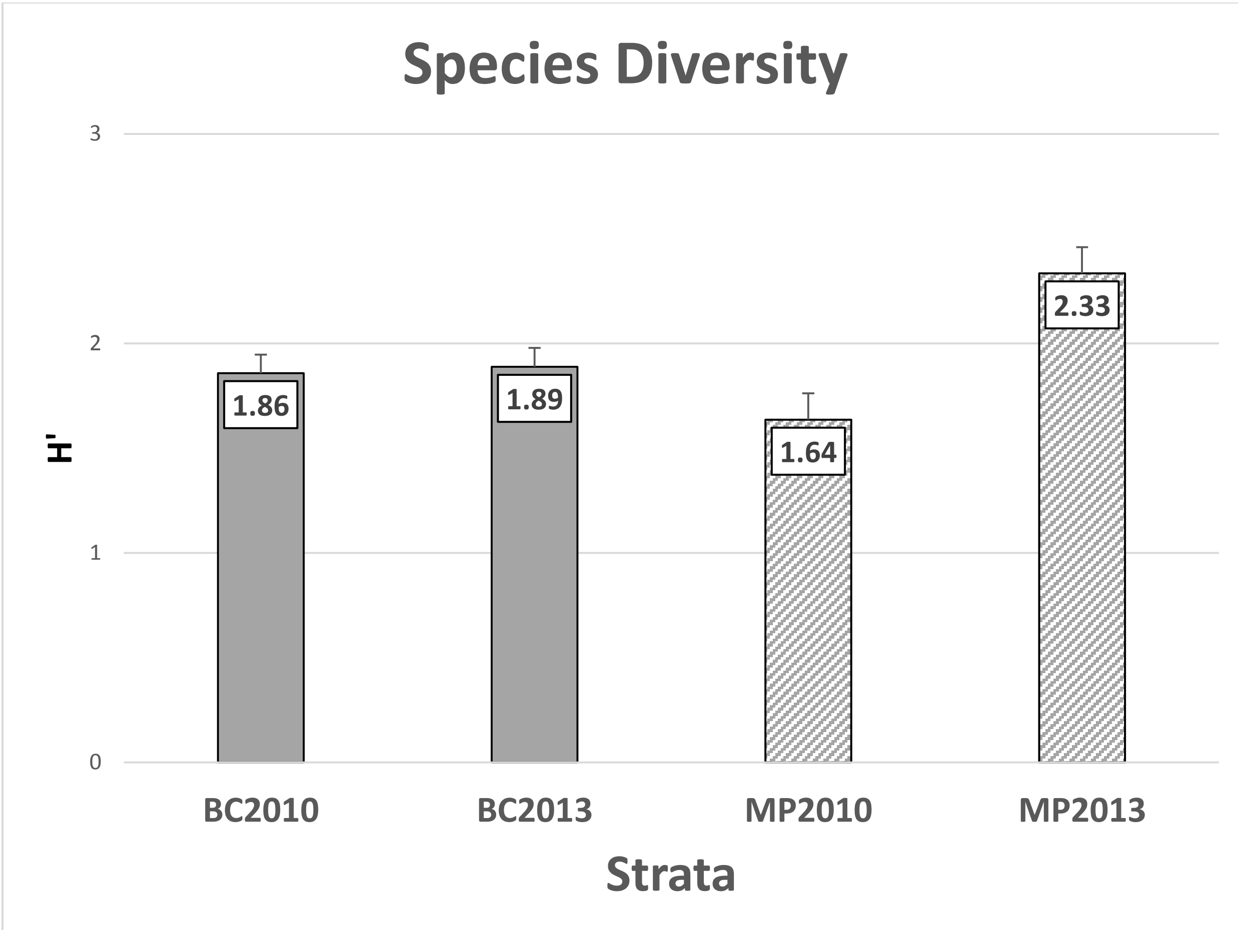
<u>B/A AND S/A RATIOS</u>

For biomass to abundance ratios (B/A) the stratum-time interaction factor was significant (Table 6). Subsequent LS means tests showed that: (1) the MP stratum B/A ratio was lower than the BC stratum in 2010 just below significance ($p > |t| = 0.054$, Table 6B.1), (2) the MP stratum B/A ratio significantly increased after remediation (Table 6B.2), (3) after remediation the MP B/A ratio was significantly higher than the BC stratum (Table 6B.3), and (4) the BC stratum B/A ratio was not significantly different between 2010 and 2013 (Table 6B.3). Figure 13 summarizes these patterns.

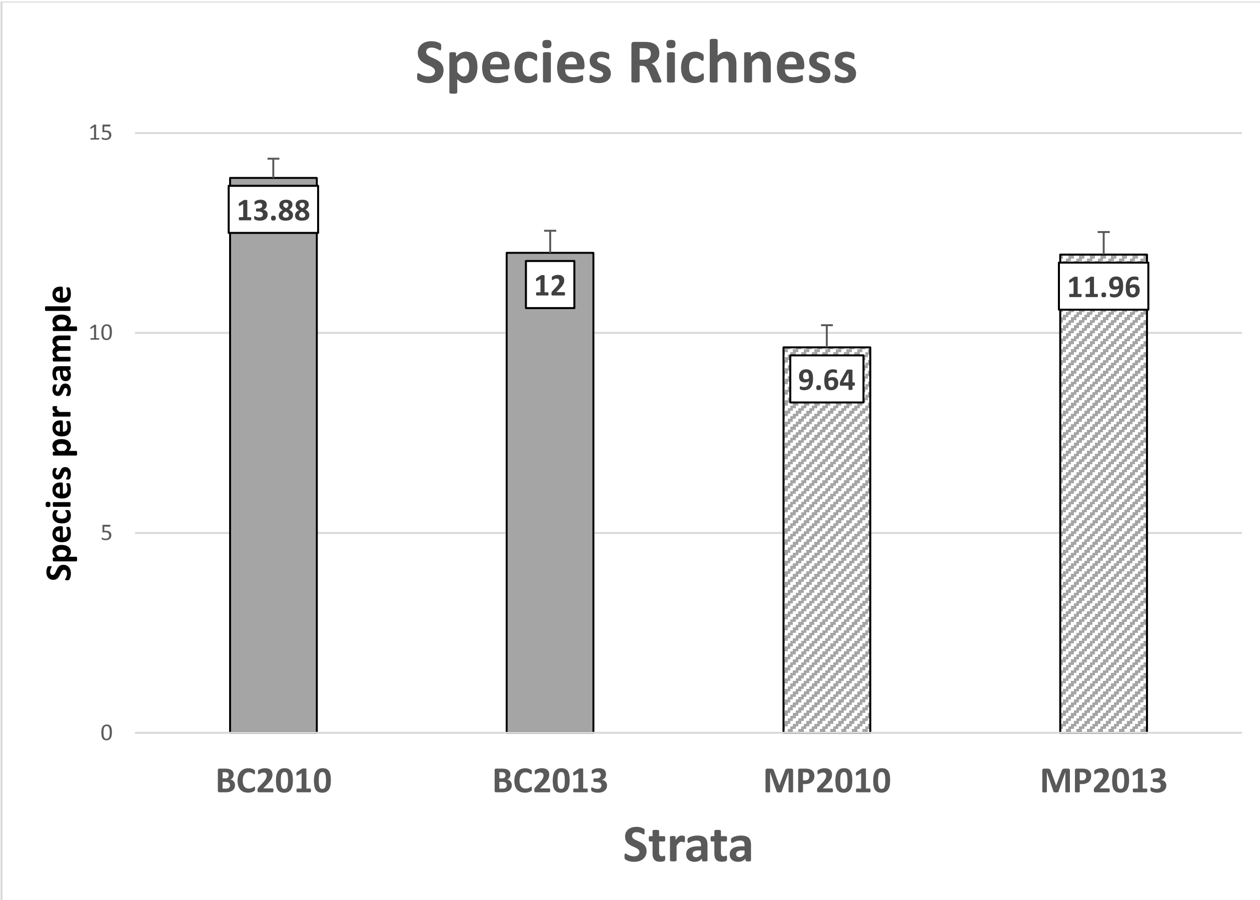
For species richness to abundance ratios (S/A) the stratum-time interaction factor was significant (Table 6). Subsequent LS means tests showed that: (1) in 2010 the S/A ratio of the MP stratum and the BC stratum did not differ significantly (Table 6B.1), (2) the MP stratum S/A ratio significantly increased after remediation (Table 6B.2), (3) after remediation the MP S/A ratio was significantly higher than the BC stratum (Table 6B.3), and (4) that the BC stratum S/A ratio was not significantly different between 2010 and 2013 (Table 6B.3). Figure 14 summarizes these patterns.



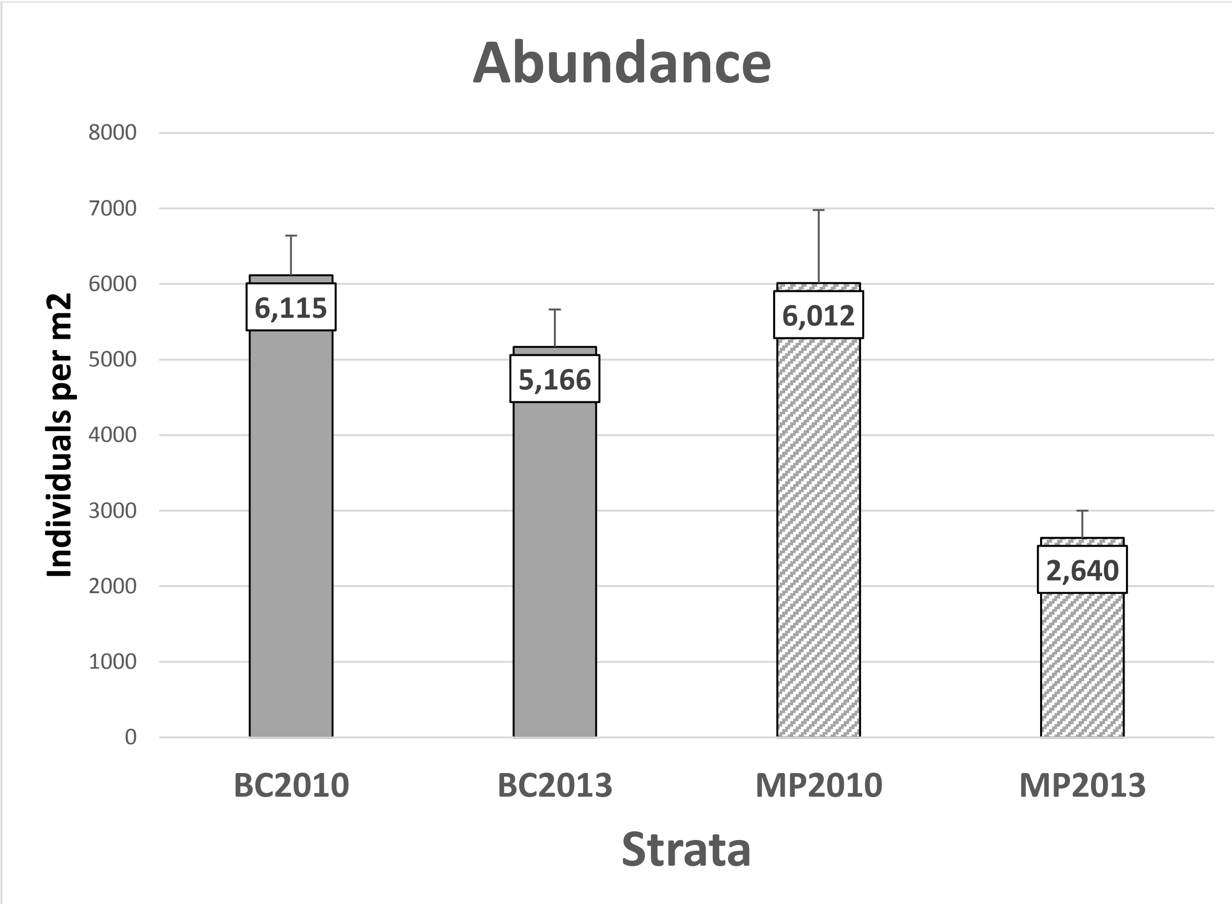

**Graph 1.** Mean B-IBI values (one standard error shown) for the Money Point (MP) and Blows Creek (BC) strata sampled prior to the sediment contaminant remediation (2010) and after the remediation (2013). Mean values indicated at top of each bar. B-IBI values range from 1.0 to 5.0 with 3.0 indicating good quality benthic condition. Ordinate truncated to emphasize pattern.



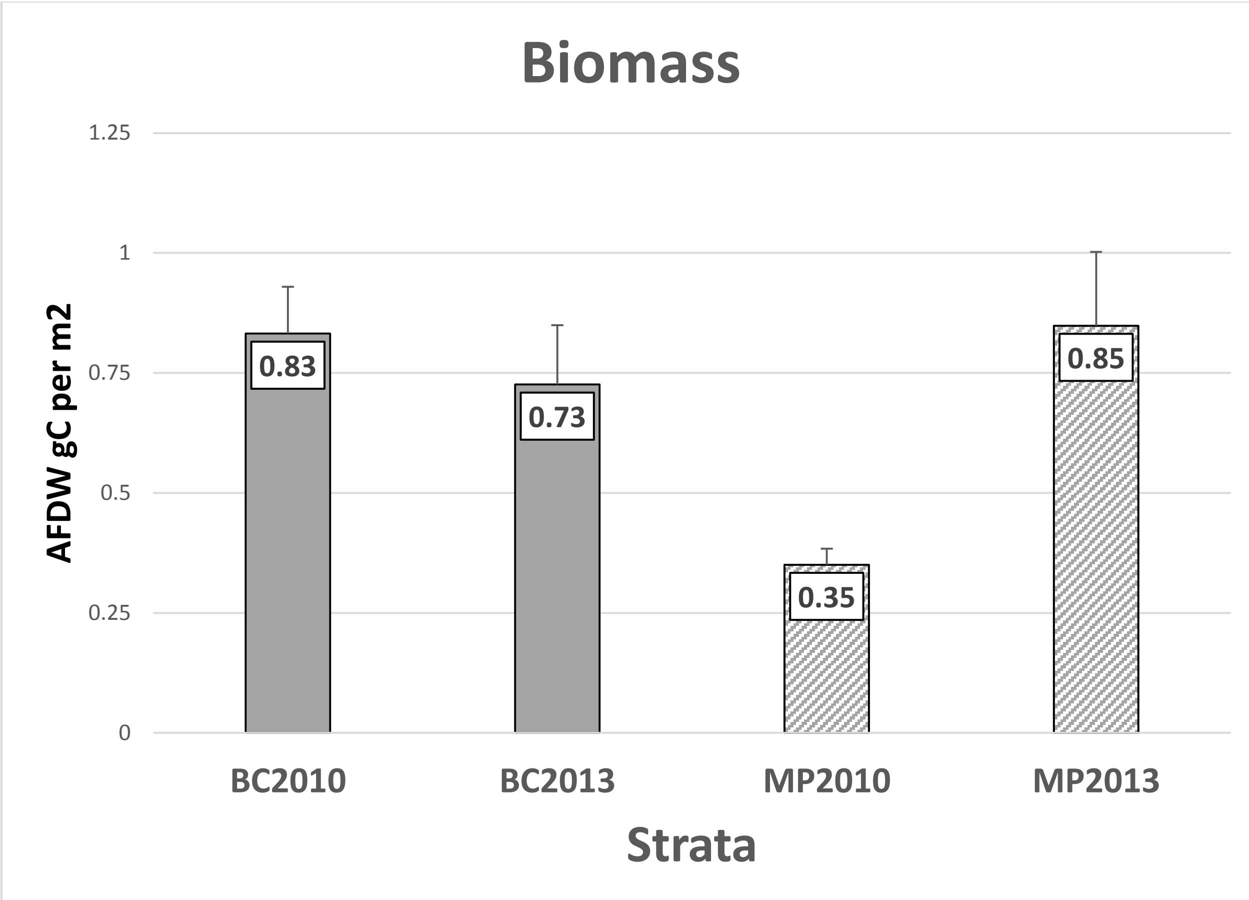

**Graph 2.** Species diversity (H') (one standard error shown) for the Money Point (MP) and Blows Creek (BC) strata sampled prior to the sediment contaminant remediation (2010) and after the remediation (2013). Mean values indicated at top of each bar.



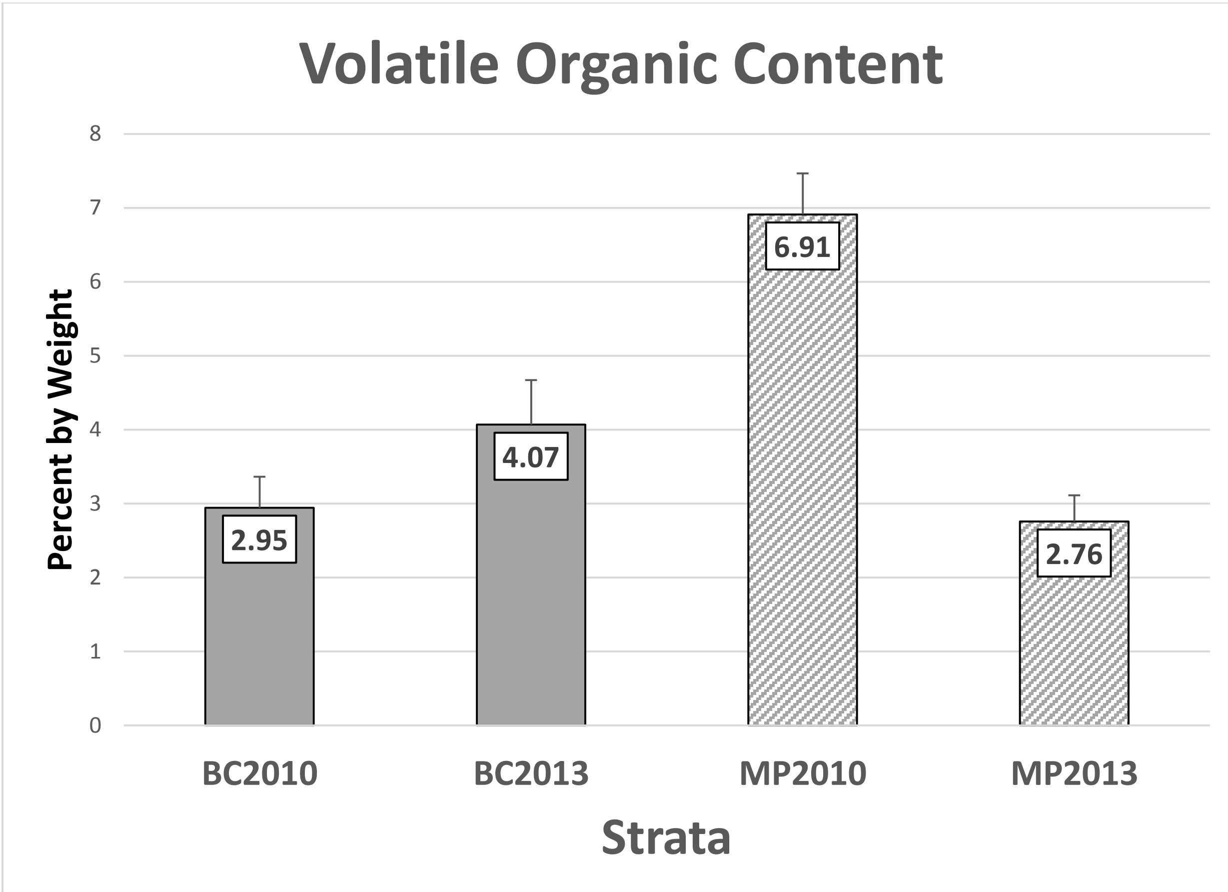

**Graph 3.** Species richness (one standard error shown) for the Money Point (MP) and Blows Creek (BC) strata sampled prior to the sediment contaminant remediation (2010) and after the remediation (2013). Mean values indicated at top of each bar.



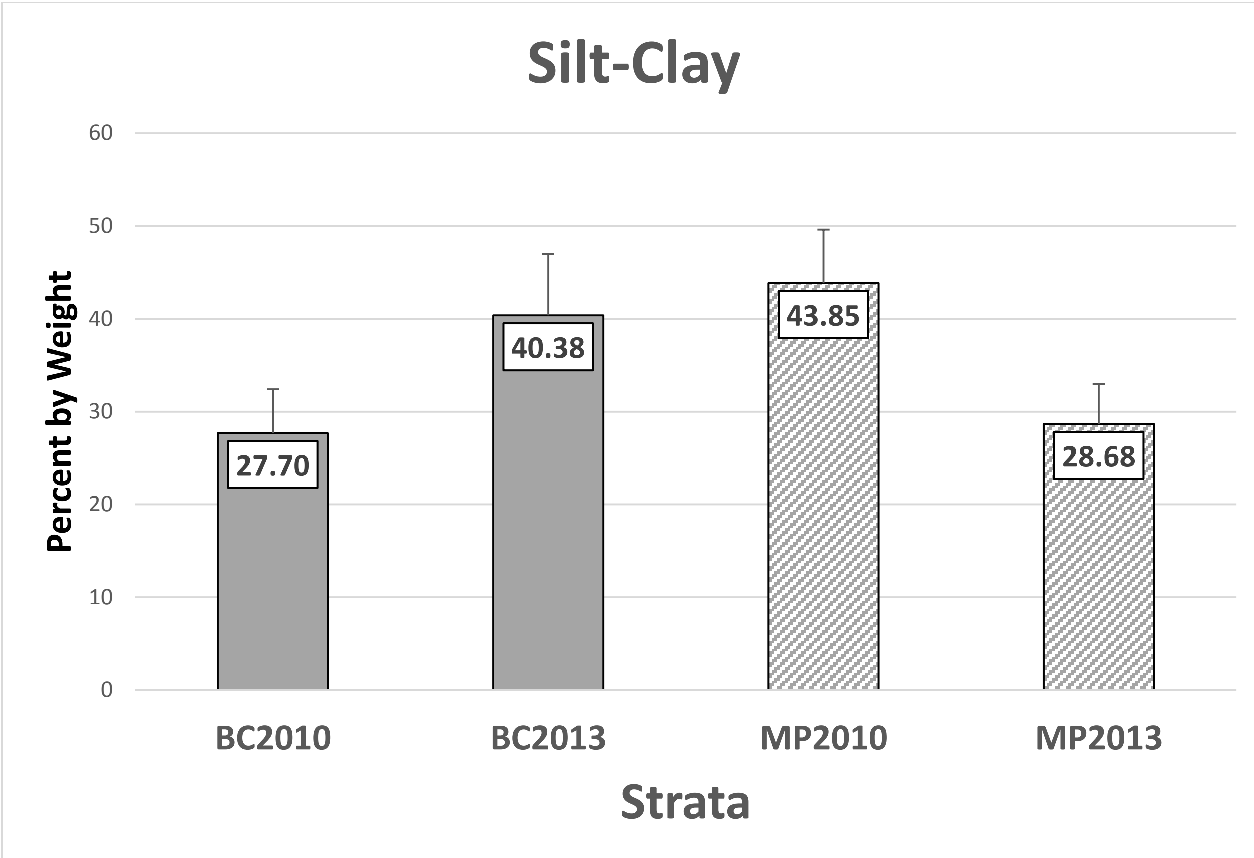

**Graph 4.** Abundance (one standard error shown) for the Money Point (MP) and Blows Creek (BC) strata sampled prior to the sediment contaminant remediation (2010) and after the remediation (2013). Mean values indicated at top of each bar.



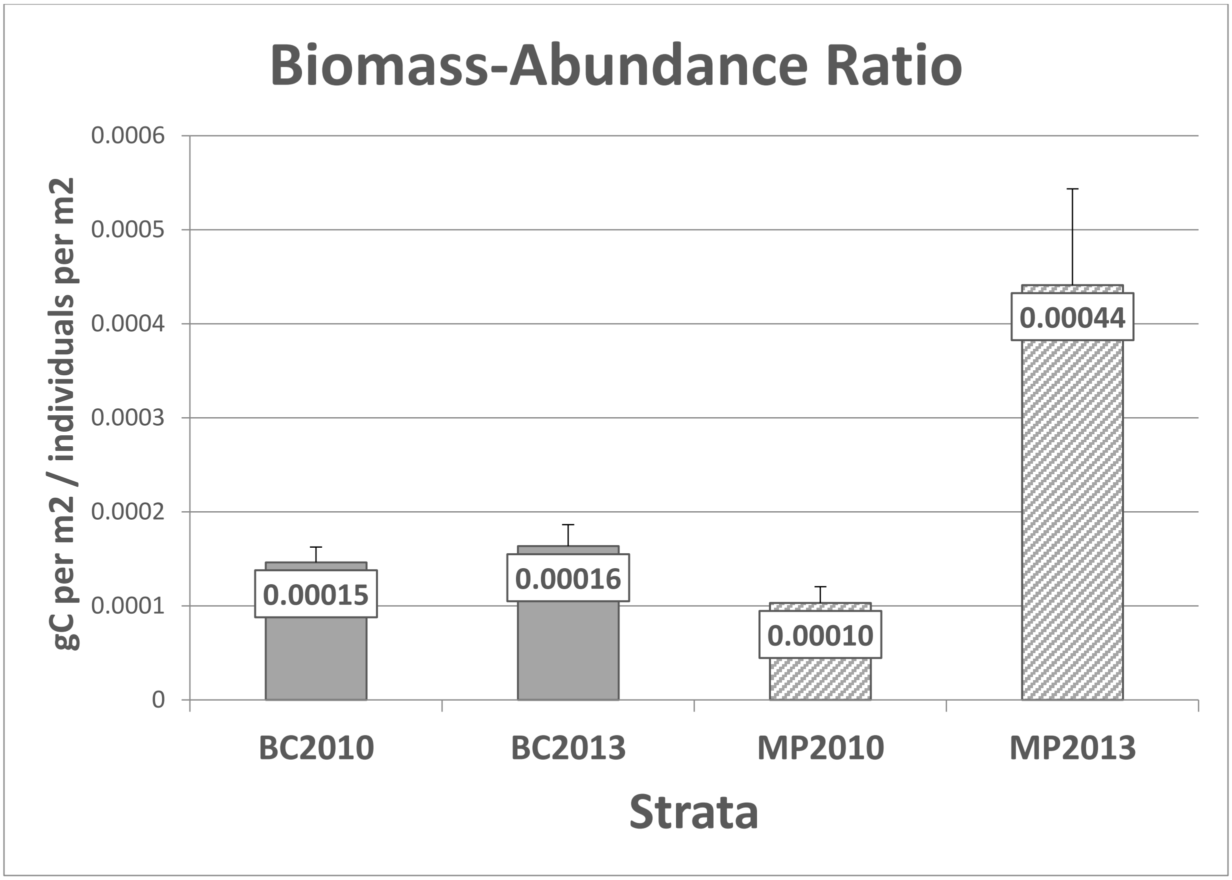

**Graph 5.** Biomass (ash-free dry weight/AFDW) (one standard error shown) for the Money Point (MP) and Blows Creek (BC) strata sampled prior to the sediment contaminant remediation (2010) and after the remediation (2013). Mean values indicated at top of each bar.



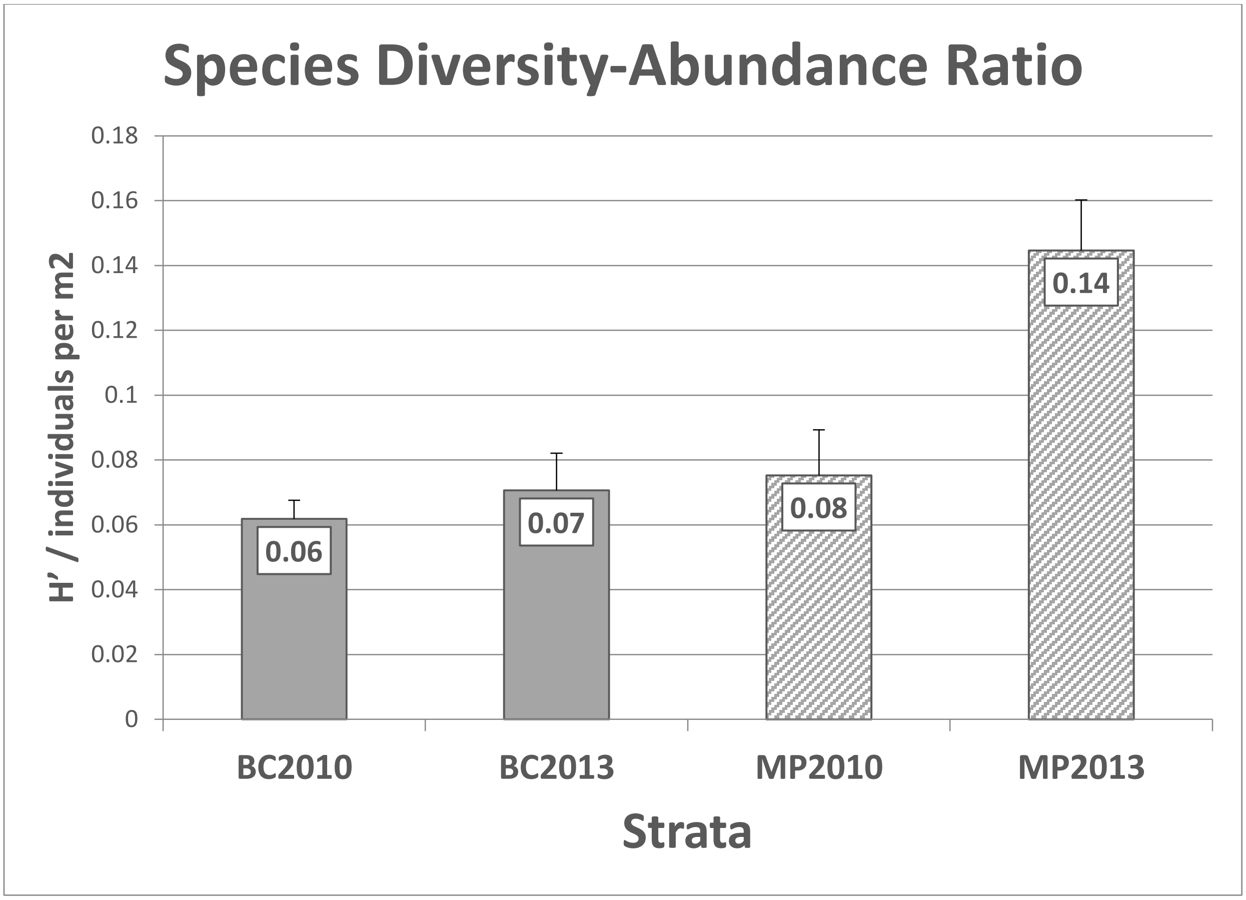

**Graph 6.** Volatile organic content (percent by weight, one standard error shown) for the Money Point (MP) and Blows Creek (BC) strata sampled prior to the sediment contaminant remediation (2010) and after the remediation (2013). Mean values indicated at top of each bar.



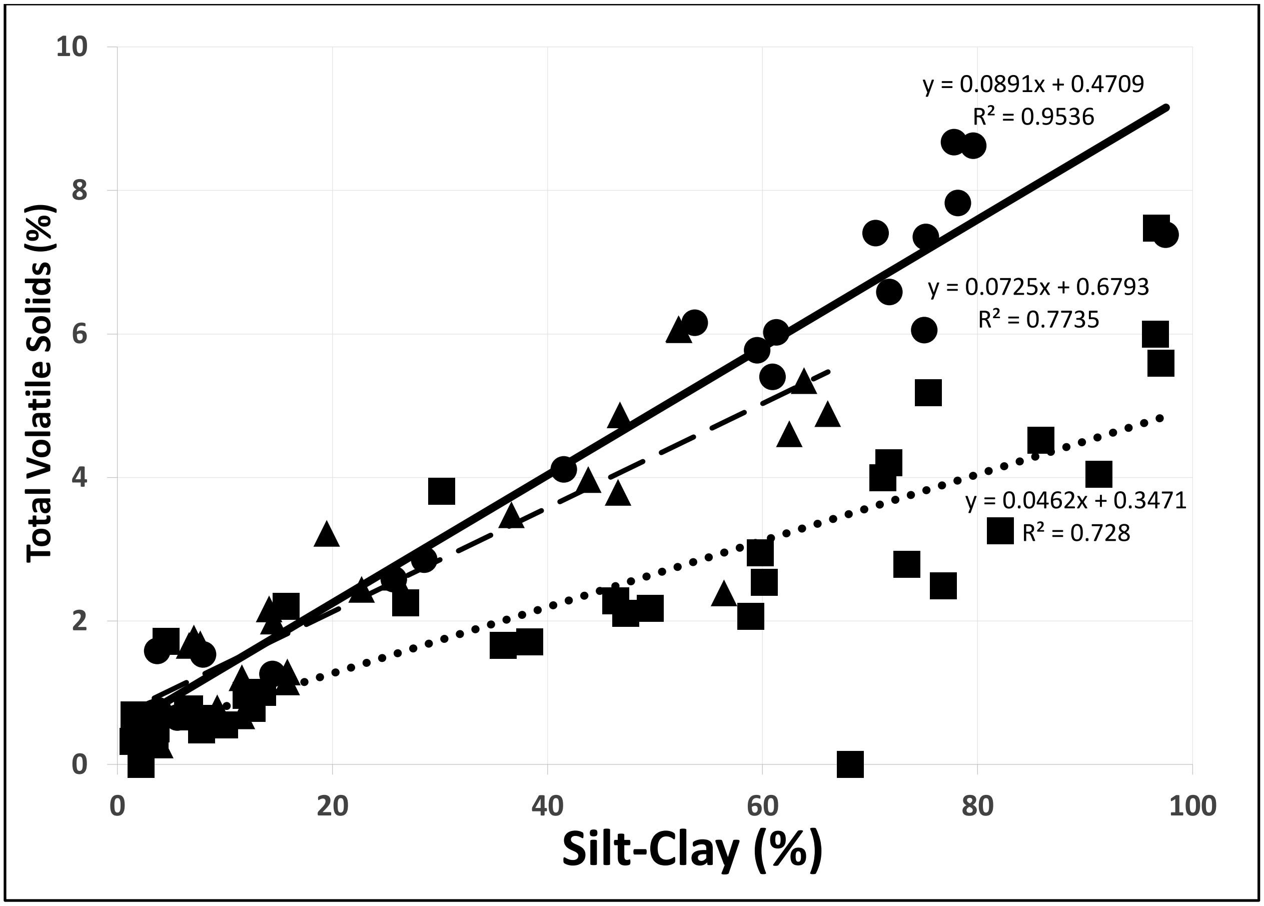

**Graph 7.** Silt-clay percentage (percent by weight) (one standard error shown) for the Money Point (MP) and Blows Creek (BC) strata sampled prior to the sediment contaminant remediation (2010) and after the remediation (2013). Mean values indicated at top of each bar.




**Graph 8.** Biomass (AFDW gC per m2) to abundance (individuals per m2) ratio (one standard error shown) for the Money Point (MP) and Blows Creek (BC) strata sampled prior to the sediment contaminant remediation (2010) and after the remediation (2013). Mean values indicated at top of each bar.




**Graph 9.** Species diversity (H') to abundance (individuals per m2) ratio (one standard error shown) for the Money Point (MP) and Blows Creek (BC) strata sampled prior to the sediment contaminant remediation (2010) and after the remediation (2013). Mean values indicated at top of each bar.




**Graph 10.** Total volatile solids values as a function of silt-clay percentage comparing Money Point, Blows Creek, and Chesapeake Bay strata. Money Point stratum values as triangles and linear regression shown as dashed line. Blows Creek stratum shown as solid circles and linear regression shown as solid line. Chesapeake Bay stratum shown as solid squares and linear regression shown as dotted line.

**Table 4.** Analysis of the B-IBI and it component metrics - Shannon index, species richness, abundance, and biomass. A. Two-way ANOVAs. B. Results of post-hoc Bonferonni corrected contrasts (t tests) to test for significant differences between individual stratum and year combinations as per Table 3. Comparisons are labeled as combinations of stratum Money Point (MP) and Blows Creek (BC) and sampling years 2010 (_10) and 2013 (_13). Provided are test statistics (F values for ANOVAs, t values for contrasts) and p values for all comparisons. Significant comparisons at $p < 0.05$ are highlighted in bold text.

| | B-IBI | | Shannon Index | | Species Richness | | Abundance | | Biomass | |
|---|---|---|---|---|---|---|---|---|---|---|
| A. Two-way ANOVAs | | | | | | | | | | |
| Factor | F | P | F | P | F | P | F | P | F | P |
| Stratum | 6.81 | **0.011** | 1.05 | 0.307 | 17.74 | **<0.001** | 13.67 | **<0.001** | 11.26 | **0.001** |
| Time | 0.16 | 0.691 | 11.16 | **0.001** | 0.62 | 0.432 | 9.30 | **0.003** | 6.28 | **0.014** |
| Stratum x Time | 7.40 | **0.008** | 9.39 | **0.003** | 17.03 | **<0.001** | 1.15 | 0.123 | 14.23 | **<0.001** |
| B. Stratum X Time Contrasts | | | | | | | | | | |
| Comparison | *t* | *p* > \|*t*\| | *t* | *p* > \|*t*\| | *t* | *p* > \|*t*\| | *t* | *p* > \|*t*\| | *t* | *p* > \|*t*\| |
| 1. MP_10 X BC_10 | 3.770 | **0.002** | 1.441 | 0.917 | 5.570 | **<0.001** | / | / | 5.034 | **<0.001** |
| 2. MP_10 X MP_13 | -1.649 | 0.614 | -4.529 | **<0.001** | -3.048 | **0.018** | / | / | -4.433 | **<0.001** |
| 3. MP_13 X BC_13 | -0.079 | 1.000 | -2.893 | **0.028** | 0.052 | 1.000 | / | / | -0.294 | 1.000 |
| 4. BC_10 X BC_13 | 2.199 | 0.181 | -0.195 | 1.000 | 2.470 | 0.092 | / | / | 0.901 | 1.000 |

**Table 5.** Analysis of sediment and hydrographic data - volatile organic content and silt/clay ratio, A. Two-way ANOVAs. B. Results of post-hoc Bonferonni corrected contrasts (t tests) to test for significant differences between individual stratum and year combinations as per Table 3. Comparisons are labeled as combinations of stratum Money Point (MP) and Blows Creek (BC) and sampling years 2010 (_10) and 2013 (_13). Provided are test statistics (F values for ANOVAs, t values for contrasts) and p values for all comparisons. Significant comparisons at p < 0.05 are highlighted in bold text.

| | Volatile Organic Content | | Silt-Clay Percentage | |
|---|---|---|---|---|
| A. Two-way ANOVAs | | | | |
| Factor | F | P | F | P |
| Stratum | 7.25 | **0.008** | 0.64 | 0.724 |
| Time | 9.45 | **0.003** | 0.12 | 0.426 |
| Stratum x Time | 28.60 | **<0.001** | 4.46 | **0.037** |
| B. Stratum X Time Contrasts | | | | |
| Comparison | *t* | *p* > \|*t*\| | *t* | *p* > \|*t*\| |
| 1. MP_10 X BC_10 | -5.686 | **<0.001** | -2.107 | 0.2264 |
| 2. MP_10 X MP_13 | 5.955 | **<0.001** | 1.979 | 0.3039 |
| 3. MP_13 X BC_13 | 1.877 | 0.381 | 1.527 | 0.7798 |
| 4. BC_10 X BC_13 | -1.608 | 0.666 | -1.655 | 0.6071 |

**Table 6.** Analysis of comparative ratios of biomass to abundance (B/A Ratios) and species diversity to abundance (S/A Ratios). A. Two-way ANOVAs. B. Results of post-hoc Bonferonni corrected contrasts (t tests) to test for significant differences between individual stratum and year combinations as per Table 3. Comparisons are labeled as combinations of stratum Money Point (MP) and Blows Creek (BC) and sampling years 2010 (_10) and 2013 (_13). Provided are test statistics (F values for ANOVAs, t values for contrasts) and p values for all comparisons. Significant comparisons at p < 0.05 are highlighted in bold text.

| | B/A Ratio | | S/A Ratio | |
|---|---|---|---|---|
| **A. Two-way ANOVAs** | | | | |
| Factor | F | P | F | P |
| Stratum | 4.75 | **0.032** | 12.61 | **0.001** |
| Time | 10.89 | **0.001** | 10.07 | **0.002** |
| Stratum x Time | 8.90 | **0.004** | 6.05 | **0.016** |
| **B. Stratum X Time Contrasts** | | | | |
| Comparison | *t* | *p* > \|*t*\| | *t* | *p* > \|*t*\| |
| 1. MP_10 X BC_10 | 2.667 | 0.054 | 0.528 | 1.000 |
| 2. MP_10 X MP_13 | -6.886 | **<0.001** | -4.635 | **<0.001** |
| 3. MP_13 X BC_13 | -3.918 | **0.001** | -3.850 | **0.001** |
| 4. BC_10 X BC_13 | -0.301 | 1.000 | -0.258 | 1.000 |

**Table 7.** The 10 most dominant species by mean abundance per $m^2$ per stratum in 2013 and 2010, rounded to whole individuals. Species are oriented by most dominant in Money Point, and the top ten species abundances in each stratum are in bold. Major taxonomic groups are in parentheses: (a) Amphipoda, (c) Cumacea, (n) Nemertea, (o) Oligochaeta, (p) Polychaeta, (ph) Phoronida.

**Dominant Species by Mean Abundance per $m^2$**

| Species | MP2013 | BC2013 | MP2010 | BC2010 |
|---|---|---|---|---|
| *Mediomastus ambiseta* (p) | **1145** | **3491** | **3696** | **4072** |
| *Hermundura americana* (p) | **382** | **527** | **514** | **661** |
| *Paraprionospio pinnata* (p) | **283** | **228** | **104** | **120** |
| *Grandidierella* sp (a) | **180** | **77** | 7 | **68** |
| *Leucon americanus* (c) | **113** | **167** | **42** | **52** |
| *Streblospio benedicti* (p) | **100** | **71** | **1260** | **525** |
| *Nemertea* spp (n) | **92** | 15 | 6 | 15 |
| *Leitoscoloplos* spp (p) | **73** | **186** | **59** | **170** |
| *Demonax microphthalmus* (p) | **35** | 8 | 0 | 0 |
| *Glycinde solitaria* (p) | **34** | **59** | **51** | **37** |
| *Eteone heteropoda* (p) | 23 | 22 | **85** | 31 |
| *Spiochaetopterus costarum* (p) | 15 | **60** | 0 | 0 |
| *Phoronis* spp (ph) | 0 | **104** | 2 | **41** |
| *Tubificoides* spp. Group I (o) | 0 | 13 | **34** | 0 |
| *Gitanopsis* spp (a) | 0 | 0 | **25** | **42** |

**Table 8.** The 10 most dominant species by mean Biomass per $m^2$ per stratum in 2013 and 2010, rounded to whole individuals. Species are oriented by most dominant in Money Point, and the top ten species abundances in each stratum are in bold. Major taxonomic groups are in parentheses: (a) Amphipoda, (c) Cumacea, (d) Decapoda, (g) Gastropoda, (n) Nemertea, (o) Oligochaeta, (p) Polychaeta, (ph) Phoronida.

**Dominant Species by Mean mg C per $m^2$**

| Species | MP2013 | BC2013 | MP2010 | BC2010 |
|---|---|---|---|---|
| *Glycera dibranchiata* (p) | **179** | **122** | 1 | **104** |
| *Nassarius vibex* (g) | **84** | 0 | 0 | **37** |
| *Leitoscoloplos* spp. (p) | **64** | **141** | **48** | **80** |
| *Hermundura americana* (p) | **61** | **125** | **51** | **108** |
| *Paraprionospio pinnata* (p) | **50** | **29** | 0 | **28** |
| *Alpheus heterochaelis* (d) | **49** | 11 | 0 | 0 |
| *Loimia medusa* (p) | **40** | 0 | 1 | **132** |
| *Nemertea* spp. (n) | **36** | 7 | 0 | 0 |
| *Glycera Americana* (p) | **35** | 0 | 0 | 0 |
| *Mediomastus ambiseta* (p) | **29** | **71** | **53** | **63** |
| *Phoronis* spp (ph) | 0 | **38** | 2 | **21** |
| *Spiochaetopterus costarum* (p) | 9 | **20** | **10** | **37** |
| *Ampelisca* spp (a) | 0 | **19** | 0 | 0 |
| *Glycinde solitaria* (p) | 10 | **19** | **15** | 15 |
| *Streblospio benedicti* (p) | 14 | **19** | **28** | **24** |
| *Leucon americanus* (c) | 15 | 14 | **14** | 12 |
| *Eteone heteropoda* (p) | 0 | 11 | **12** | 15 |
| *Haminoea solitaria* (g) | 0 | 0 | **9** | 0 |

# CHAPTER IV

# DISCUSSION

## BIOLOGICAL METRICS AND EFFICACY OF REMEDIATION

The ecological condition of the benthic communities of the remediated Money Point location changed significantly after sediment contaminant remediation, with improved B-IBI, species diversity, species richness and biomass (Table 4). These findings are consistent with an improving ecological condition. Although the B-IBI did not show significant improvement following remediation at Money Point, an increasing trend in B-IBI was observed from 2010 to 2013. Conversely, no clear increase in the above metrics was observed at Blows Creek from 2010 to 2013 (Table 9). Indeed, the condition at Blows Creek showed an overall degradation between 2010 and 2013. The B-IBI decreased significantly, while species richness, diversity and biomass showed no significant changes. The contrast between the two strata indicate that the remediation effort had a significant ecological impact of improved ecological condition at Money Point while the B-IBI decreased significantly at the reference stratum of Blows Creek.

Abundance did not show a significant interaction but its changes were still positive at the remediated stratum. Abundance did show a significant change in both its main effects, suggesting that there was still a significant difference in the two strata between years, and between the two strata regardless of year. While both BC and MP indicated a loss of abundance, this still suggests an improvement in the B-IBI according to the reference parameters established by Weisberg et al. (1997) and Alden et al. (2002). Abundance's relation to the quality of the benthos is parabolic (Pearson and Rosenberg 1978), and the highest percentiles indicate degraded conditions in the B-IBI rankings (Alden et al. 2002). Money Points decrease in abundance was of a greater magnitude than that of Blows Creek (a difference in averages of 3373 as opposed to 949, Figure 9), but a non-significant interaction factor in the 2-way ANOVA means this change cannot be claimed to have come predominantly from the remediation effort.

When comparing the metrics of the strata (Table 11) to the SAB curves constructed by Pearson and Rosenberg (1978) and Rakocinski et al. (2000), the 2010 strata exhibited conditions indicative of a 'peak of opportunists' stage at Money Point and of moderate toxicity at Blows Creek (Figure 16). The changes in the metrics between 2010 and 2013 would ideally have indicated a shift towards the reference condition for Money Point and little to no change at Blows Creek. However, Blows Creek actually exhibited a decrease in conditions and shift towards higher organic contamination (Figure 16). The changes at Money Point indicated that there was a transition reflective of a reduction of organic contaminants and general organic input, a decrease in abundance coupled with an increase in species richness and biomass, that suggests a shift of the stratum away from the 'peak of opportunists' stage towards an ecotone point (Figure 16). Rakocinski et al. (2000) emphasized that at high organic contaminant levels the ratio of abundance to number of species (A/S) is high and that of biomass to abundance is low (B/A) reflecting benthic communities with high dominance and small body size. At lower levels of sediment organic contaminants A/S should decrease and B/A should increase; thus reflecting decreased dominance (greater evenness of the distribution of individuals among species) and increased body size as the community composition changes to include more long-lived, larger body size and pollution-sensitive species (Dauer 1993, Weisberg et al. 1997). My study considered S/A as opposed to A/S for consistency with Webb's 2014 study, with lower values denoting higher dominance. The observed increase B/A and S/A at the Money Point stratum between 2010 and 2013 indicates a clear shift toward a community with larger, stable animals and improved evenness. These increases, together with the absence of significant changes in these ratios at Blows Creek through time (Table 10) provide further support for ecological improvements following remediation efforts.

## SPECIES COMPOSITIONS AND QUALITY OF THE BENTHOS

A broad array of lifestyles, susceptibilities and functional morphologies make macrobenthic community composition and trends in community metrics ideal for identifying and quantifying environmental stresses and ecological conditions (Bilyard 1987, Dauer 1993). Based on the depth of the sediment cap added on top of the dredging in the Money Point stratum (6-24in: see Koubsky 2013) I had hoped that the species composition would reflect more deep dwelling organisms in 2013, but this was not the case (Tables 7-8). The habitats abundances were still numerically dominated by the capitellid polychaete *Mediomastus ambiseta*, and the spionid polychaetes *Streblospio benedicti* and *Paraprionospio pinnata*, all of which are classified as pollution-indicative taxa in the Chesapeake Bay BIBI (Weisberg et al. 1997). While the biomass dominants were different, belonging to *Glycera dibranchiata, Nassarius vibex,* and *Leitoscoloplos* spp.(Table 8), this was due to the presence of a few of these large bodied organisms, which contributed to the large standard deviation seen in Money Point 2013 (MP2013 Biomass: 0.84, St Dev: 0.77). The presence of these species in the remediated habitat was a positive trend, but no one species' presence or absence directly contributed a large enough change to account for the entirety of the observed changes in the strata. *Mediomastus ambiseta's* great reduction in abundance could have been indicative, if the interaction effect of abundance between the two strata had been significant. *Glycera dibranchiata*'s presence in the dominant species by biomass is heartening and likely contributed to the biomass improvements between

2013 and 2010 at Money Point; however, its carnivore/omnivore nature, absence in the abundance dominants and low proportional contribution to the biomass average (when compared to all other top biomass contributors) muddy the potential interpretations of its presence. The changes in species composition do follow the trends of an improving condition, but the improvements cannot specifically be attributed to any few species.

**Table 9.** Biological data means per sample with standard error in parentheses. B-IBI – Chesapeake Bay Benthic Index of Biotic Integrity. Abundance – individuals per $m^2$. Biomass – Ash-free dry weight grams per $m^2$. Species Diversity – Shannon Index. Species richness – number of species. Strata: BC (Blows Creek) and MP (Money Point) in collection years 2010 and 2013.

| Metrics | B-IBI | Abundance | Biomass | Species Diversity | Species Richness |
|---|---|---|---|---|---|
| **BC2010** | 2.6(0.1) | 6,114(527) | 0.8(0.09) | 1.86(0.09) | 13.9(0.5) |
| **BC2013** | 2.3(0.1) | 5,165(496) | 0.7(0.09) | 1.89(0.09) | 12.0(0.6) |
| **MP2010** | 2.0(0.1) | 6,012(966) | 0.3(0.03) | 1.63(0.13) | 9.6(0.5) |
| **MP2013** | 2.3(0.1) | 2,639(360) | 0.8(0.15) | 2.33(0.12) | 11.96(0.6) |

**Table 10.** Biological data ratios means per sample with standard error in parentheses. B/A ratio – biomass to abundance ratio, S/A ratio – species richness to abundance ratio. Strata: BC (Blows Creek) and MP (Money Point) in collection years 2010 and 2013.

| Metrics | B/A Ratio | S/A Ratio |
|---|---|---|
| **BC2010** | 0.0001(1.62E-05) | 0.0618(5.73E-03) |
| **BC2013** | 0.0002(2.30E-05) | 0.0706(0.01) |
| **MP2010** | 0.0001(1.72E-05) | 0.0752(0.01) |
| **MP2013** | 0.0004(1.02E-04) | 0.1446(0.02) |

**Table 11.** Hydrographical Data Averages. Volatile Organic Content - %, Silt/Clay Ratio – amount of Silt sediments (≥63 microns) to Clay sediments (<63 microns Strata BC (Blows Creek) and MP (Money Point) From 2010 and 2013. Standard Errors in parentheses.

| Metric | Volatile Organics | Silt-Clay Percentage |
|---|---|---|
| **BC2010** | 2.9(0.4) | 27.7(4.7) |
| **BC2013** | 4.1(0.6) | 40.4(6.6) |
| **MP2010** | 6.9(0.5) | 43.8(5.7) |
| **MP2013** | 2.8(0.3) | 28.7(4.3) |

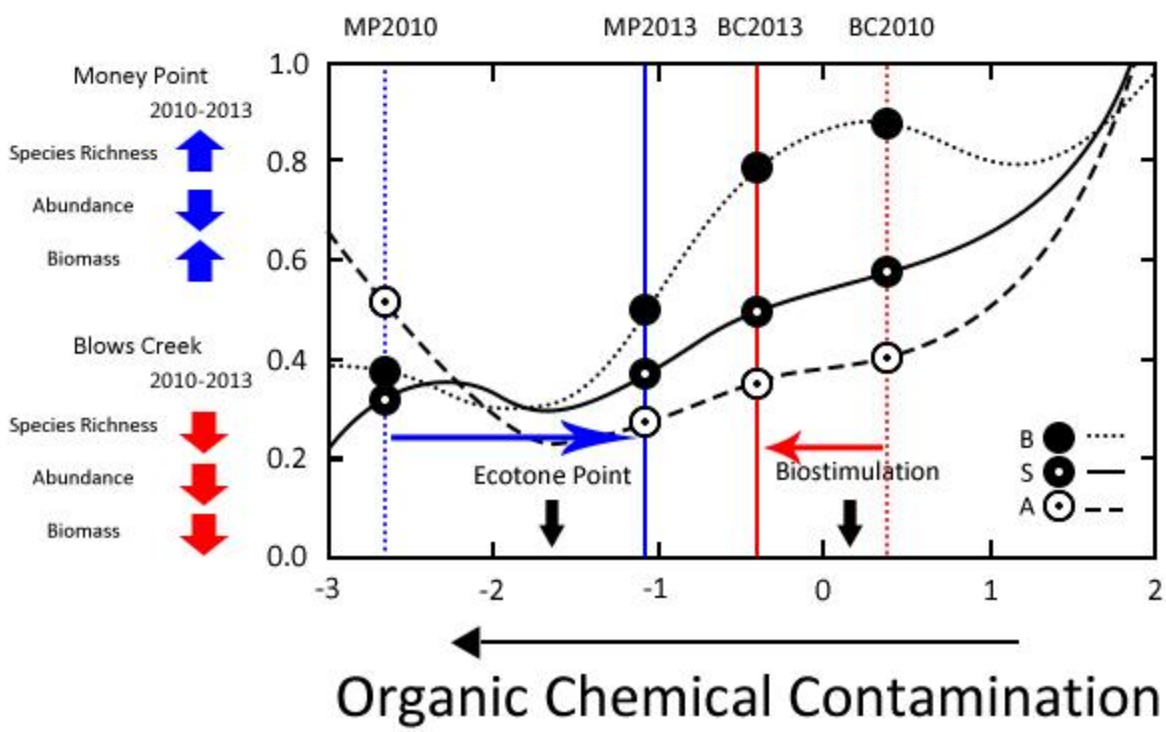



**Figure 6.** Rakocinski et al. (2000) organic chemical contamination species-abundance-biomass (SAB) trend curve with this study's trends superimposed. Metric values shown in Table 11.

HYDROGRAPHICAL TRENDS

Volatile organic content and silt-clay ratios are also relevant for assessment of remediation. Volatile organic content decreased significantly with time at Money Point, indicating the remediation was effective (Table 11). The observed trend ($p = 0.037$) in lower silt-clay percentages was also significant (Table 5) and a reduction of the silt-clay percentage at the Money Point stratum in 2013 relative to 2010 helps explain the significant decrease in volatile organic content. Higher silt-clay percentages result in higher organic contents due largely to the greater amount of fine sediments, which provide more surface area and allow greater adsorption of organic material (Arzayus et al. 2001, Bjørgesæter and Ray 2008); therefore, a reduction in the silt-clay percentages should decrease adsorption and reduce organic load. Webb (2014) compared the relationships across the strata in his study, applying lines of best fit to the 2010 data. Differences in the best-fit curves derive from higher ambient eutrophication of the Elizabeth River in comparison to the Chesapeake Bay as a whole, and the increased organic contamination experienced by Money Point in relation to Blows Creek. However, when the same comparison was made between the three strata in my study using 2013 data, the lines of best fit between Blows Creek and Money Point were much more closely related and both were linear in nature (as opposed to the exponential line of best fit for Money Point in the 2010 sampling period). This similarity of the conditions between the two strata in 2013 and the change in the Money Point stratum between 2010 sampling and 2013 sampling (Figure 17) is expected in a stratum that had a large amount of organic pollutants removed.

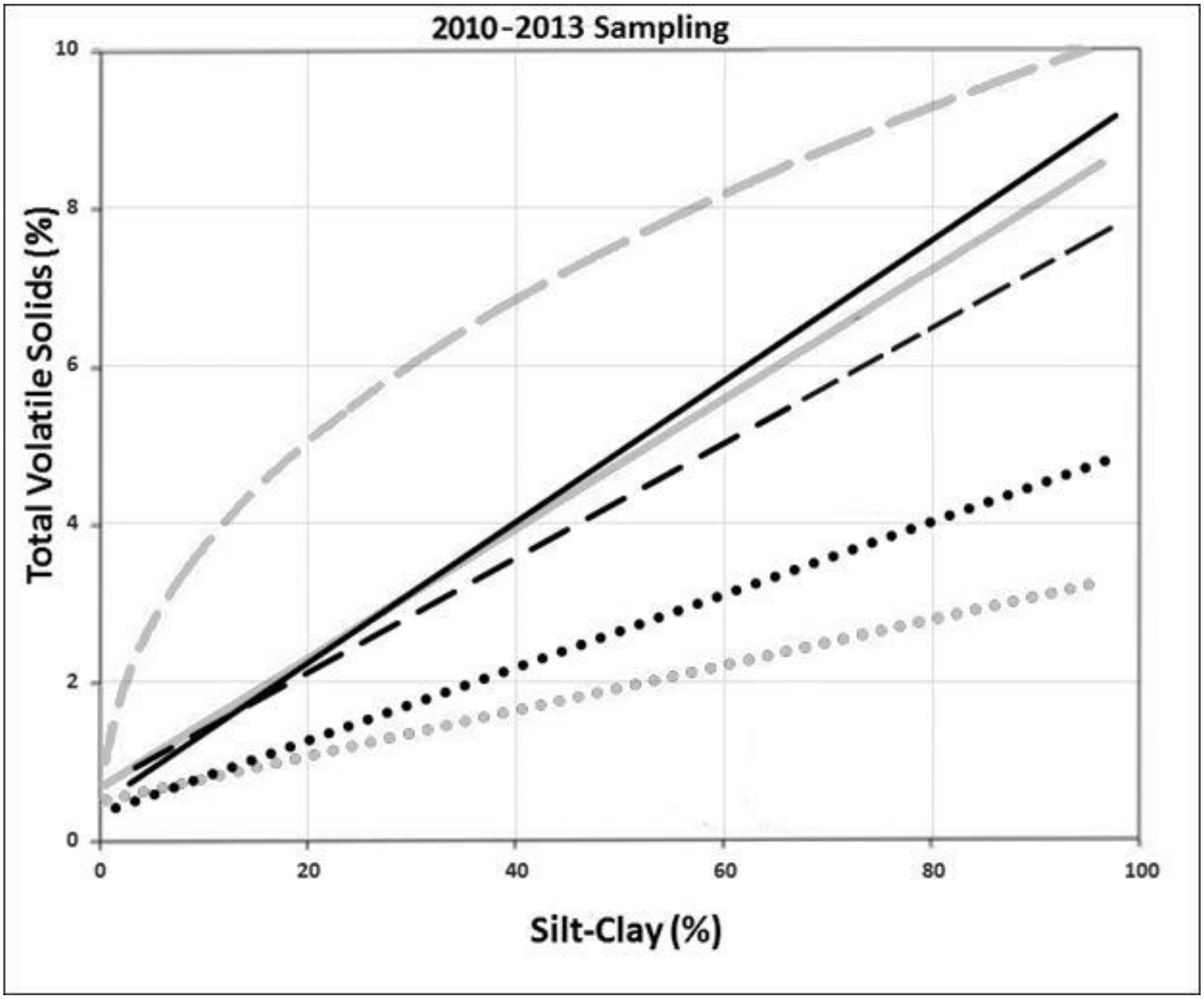



**Figure 7.** Conceptual view of natural, eutrophic (organic chemicals) and organic contamination effects upon concentrations of relative levels of sediment silt-clay (%) to total volatile solids (%) between Money Point (dashed line), Blows Creek (solid line), and the Chesapeake Bay (dotted line). Trends from Webb (2014) in gray and this study's 2013 results in black.

DREDGING AND CAPPING AS A REMEDIATION

The restoration of marine ecosystems from anthropogenic stressors varies greatly depending upon the specific stressor (Borja et al. 2010). Recovery of macrobenthic communities after dredging takes approximately two years to return to prior conditions when natural processes alone drive the restoration of the benthic communities to their original conditions (Powillet et al. 2006, Wilber et al. 2007, Borja et al. 2009). In my study, sediment was dredged from the habitat and replaced with sediment with minimal organic content to facilitate recovery. Dredging alone is a major ecological disturbance that results in dramatic changes to sediment characteristics and the abundance and diversity of benthic communities (Desprez 2000, Kelaher et al. 2003). My results indicate significant improvement, if not total recovery, of benthic community structure and ecological condition is possible in less than two years. The sediment cap of clean sand**s** likely promoted successful recruitment into the Money Point region and accelerated the recovery process.

Hawthorne and Dauer (1983) sampled the Southern Branch of the Elizabeth River quarterly from fall 1977 through summer 1978. Between the second and third quarterly sampling, maintenance dredging of the channel caused the sediment types at all five stations to change from generally <20% to >70% sand yet the dominant species remained quite similar. They concluded that because the Southern Branch was dominated by euryhaline opportunistic species, detection of anthropogenic stresses or their removal may be difficult to assess. This assessment further suggests that it was the introduction of the cap of clean sands that had a significant impact on the macrobenthic condition, as prior examples of dredging alone or simple removal of said stresses did not result in improvements in the benthic communities.

Dredging literature and perspective in the scientific community is largely focused on the notion of dredging as a stressor to an environment, and much of the literature focuses on a recovery to pre-dredged conditions as a measurement of its impact. In addition to the various articles referenced by Borja et al. (2010), there are many articles and discussions surrounding regular maintenance dredging (McCauley et. Al 1977, Rehitha et al. 2017), dredging as an impact on macrobenthic communities (Ceia et al. 2013), and financial feasibility of dredging (Cooper et al. 2013); very few articles treat dredging as a remediation. Capping also tends to play a small part in most dredging studies, if any part at all. Capping is instead implemented as: the passive mechanism for the return to prior conditions after the impact of dredging (Foyle and Norton 2007), a method of recovery used in lieu of dredging efforts (Simpson et al. 2002), or as a landfill-styled method of disposing of degraded sediment off site from the dredging locations (Qian et al. 2003, Chung et al 2015). It is worth mentioning that in the last two approaches, the referenced texts list capping as an effective method of suppressing heavy metal contaminants. The use of dredging and capping together as a remediation effort is very poorly explored, and the results of my study speak to the merit of further investigation.

# CHAPTER V

# CONCLUSIONS

The remediation effort of the Money Point stratum in the Southern Branch of the Elizabeth River has had a profound effect on the composition and quality of the benthos, significantly improving it in all but one recorded metric between 2010 and 2013: diversity, species richness, abundance, community biomass, B/A (biomass/abundance), and S/A (diversity/abundance). Additionally, while the B-IBI did not significantly improve between 2010 and 2013 at Money Point, the use of the BACI format resulted in a significant interaction factor, indicating that its improvement was significant when compared to the changes in the ambient condition. Furthermore, the timeframe of improvement was half the average recovery timeframe of dredging as a disturbance. These positive changes were not present in the reference conditions of Blows Creek, which showed either no change or significant decreases in the supporting metrics. The shifts in the metrics are concordant with Rakocinski et al. (2000)'s organic contaminant SAB curve model, suggesting that the stratum has left its prior 2010 'peak of opportunist' condition and is in a transitional zone, nearing or passing an ecotone point of changing species composition. The reference conditions of Blows Creek suggest a decrease in quality and shift towards a state indicative of higher organic contamination. Volatile organics and silt-clay percentages both showed significant or noticeable improvements at the impacted Money Point stratum and therefore, also support the recovery of the benthic condition post remediation. Much of the existing literature on the effects of dredging and sediment disposal treat such actions strictly as anthropogenic stressors and therefore, look only for a return to the prior conditions as a benchmark for recovery. My study has shown that the efforts taken by the Elizabeth River Project to replace degraded sediments with non-contaminated sediment can not only facilitate a habitat's return to its prior condition, but also improve and exceed the prior condition in as little as one year. Additional testing over time at even greater magnitudes of remediation will provide greater understanding of the transition and provide more insight as to whether or not we are witnessing a true shift of species composition structure or a temporary shift before a more permanent return to prior states. Although continued monitoring of the results of this remediation will provide additional insight into its efficacy, these early results are overwhelmingly positive and present an exciting outlook for the future.

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## Publications/Presentations

2021-Master's Thesis: **Efficacy of Sediment Contaminant Remediation of the Benthos in a Segment of the Southern Branch of the Elizabeth River**

2021-Master's Thesis Defense: **Efficacy of Sediment Contaminant Remediation of the Benthos in a Segment of the Southern Branch of the Elizabeth River**

2014-Atlantic Estuarine Research Society (oral presentation): **Efficacy of Sediment Contaminant Remediation of the Benthos in a Segment of the Southern Branch of the Elizabeth River**