ABSTRACT

EFFECTS OF SHORE-PARALLEL STRUCTURES ON MEIOFAUNA IN THE INTERTIDAL FORESHORE OF A SANDY ESTUARINE BEACH, RARITAN BAY, NEW JERSEY, USA

by
Valerie L. Spalding

Field investigations conducted at three sites on the intertidal sandy foreshore at Cliffwood Beach and Keyport Harbor, Raritan Bay, New Jersey reveal the relationship between meiofaunal density, wave and beach characteristics at sites where bulkheads and seawalls are present and at an adjacent site where they are not.

Wave characteristics were gathered at 2 hz over the tidal cycle with a pressure transducer. Three replicate core samples, to a depth of 0.10 m, were gathered at four sampling stations across the foreshore at low tide to determine meiofaunal density. A fourth core sample was used to determine grain size, sorting and moisture content. Net change, depth of sediment activation, and beach elevation were measured at low tide.

At Cliffwood Beach, significant wave heights were 0.05-0.13 m with periods of 5.9 - 7.7 s. Meiofaunal densities ranged from 1 - 309 ind./10cm^2. Sediments are finer (0.29 mm) and better sorted (0.54 ϕ) immediately fronting the seawall resulting in lower meiofaunal densities. One-way analysis of variance revealed differences between meiofaunal densities, within the bottom 0.07 m of the core, immediately fronting the seawall and at a similar elevation at the control site.

At Keyport Harbor, significant wave heights were 0.08-0.27 m with periods of 2.0 s. Meiofaunal densities ranged from 2-207 ind./10cm^2. Sediments are finer (0.4 mm) and better sorted (0.47 ϕ) immediately fronting the bulkheads. One-way analysis of variance revealed differences between meiofaunal densities, within the top 0.03 m of the core, immediately fronting the bulkheads and at a similar elevation at the control site. Depth of activation was 0.23 m at sampling station immediately fronting the bulkhead.

Shore-parallel structures have greatest influence when wave energies are high or when the structure is located bayward of wave breaking at high water.

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by
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EFFECTS OF SHORE-PARALLEL STRUCTURES ON MEIOFAUNA IN THE INTERTIDAL FORESHORE OF A SANDY ESTUARINE BEACH, RARITAN BAY, NEW JERSEY, USA

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To my family and friends

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CHAPTER 1

INTRODUCTION

1.1 Statement of Objectives

Estuarine shorelines are important for the development, growth and sustenance of fauna. The intertidal zone of sandy beaches provides a living habitat for meiofauna, a spawning habitat for macrofauna and marine fishes (Botton et al. 1988; Penn and Brockmann 1994) and a feeding habitat for migratory birds (Myers 1983). Meiofauna are mobile or hapto-sessile benthic invertebrates that are distinguished by their small size (45-500 microns) (Giere 1993). Meiofauna live interstitially between the sedimentary particles of the sand beach matrix. The suitability of the interstitial environment as habitat is a function of hydrodynamics (waves, tides, and currents), sedimentary characteristics (grain size, porosity, and permeability), as well as chemical and physical properties including salinity and temperature of the water, and water content of the sediments (Giere 1993).

Another important resource value of estuarine shorelines is to protect human development from wave attack and flooding. Human development along the coastline of the United States is widespread (Thom et al. 1994). Low-elevation flooding and shoreline erosion caused primarily by storms are the two most threatening processes to development along estuarine shorelines (Jackson 1996). Shore stabilization is employed to protect development and includes hard structures, such as bulkheads, groins, seawalls, and breakwaters as well as soft alternatives including artificial dune creation and beach nourishment. Shore-parallel structures (bulkheads and seawalls) are the most common form of shore protection in estuaries (Ward et al. 1989; Shipman and Canning 1993;

Jackson 1996). Bulkheads are often employed in estuaries, due to low wave energies and gentle offshore gradients, when there is no need for a recreation beach (Nordstrom 1989). Beach nourishment can be used in conjunction with shore-parallel walls (Jackson and Nordstrom 1994) when there is a need to protect the toe of the structure from wave attack.

Bulkheads and seawalls can reflect wave energy, alter nearshore currents and elevate the beach water table (Kraus 1988; 1996). Shore-parallel structures can limit sediment supply to the beach, exacerbate shore erosion, and eliminate vegetation on the backbeach (Thom et al. 1994). The location of a bulkhead or seawall on the intertidal profile will influence the effect that the structure has on local hydrodynamics and changes to the beach fronting the structure (Plant and Griggs 1992). Bulkheads and seawalls that are located seaward of the normal breaker zone are subject to non-breaking waves (Weggel 1988) and scour at the toe of the structure will be minimal (Jackson and Nordstrom 1994). Shore-parallel walls located in the surf and breaker zone can result in impoundment of sediment on the updrift side of the structure, flanking on the downdrift side of the structure and increased scour at the toe of the structure (Kraus 1988). Bulkheads and seawalls are best employed when placed high enough on the intertidal profile so as to not adversely affect beach width through elimination of an upland sand source or through scour of the beach seaward of the structure due to wave reflection (Zabawa et al. 1981; Nordstrom 1989). Shore-parallel structures can indirectly influence the suitability of the beach matrix for meiofauna. Increased energy due to wave reflection at the structure can increase sediment mobilization and eliminate habitat fronting the structure due to scour, alter the sedimentary properties (grain size and sorting) that control porosity and permeability important for oxygen and nutrient cycling, and increase

the elevation of the local beach water table resulting in an increase in moisture content of sediments.

There are numerous studies that investigate meiofauna (Swedmark 1964; Bush 1966) and the significance of sediment size (Jansson 1967; Hockin 1982; McLachlan 1996), seasonal variability and salinity (Dye 1983; Santos et al. 1995), geographical location (Dexter 1992; Soetart et al. 1995), current-speeds (Fegley 1987), sediment disturbance (Sherman and Coull 1980) and morphology (McLachlan and Hesp 1984) on sandy beaches. There are studies that examine changes that occur to beach morphology fronting shore-parallel structures (beach mobility, beach slope, scour) (Schultz and Ashby 1967; Zabawa et al. 1981; Kraus 1988; Weggel 1988; Plant and Griggs 1992; Jackson and Nordstrom 1994). There are also studies that examine the effects of beach nourishment on meiofauna (Naqvi and Pullen 1982; Gorzelany and Nelson 1987; McLachlan 1996) and the long-term effects of shore-parallel structures on coastal ecology and biological resources (Thom et al. 1994; Weis and Weis 1996). But no published studies exist that examine specifically short-term changes of meiofaunal density in developed sandy shorelines where shore-parallel structures are employed. The aim of this study is to examine the potential of shore-parallel structures to alter the interstitial habitat and meiofaunal density in sandy estuarine shorelines.

Field investigations were conducted at two study areas in Raritan Bay, New Jersey to determine the relationship between meiofaunal, wave, and beach characteristics at sites where a shore-parallel structure is present and at adjacent sites where no shore-parallel structure is present. The following research questions were examined:

- Are there differences in meiofaunal density between sites that front a shore-parallel structure and sites that do not?
- What characteristics (hydrodynamic, sedimentary, chemical, and physical) influence meiofaunal densities at sites that front a shore-parallel structure and sites that do not?

Data on meiofaunal density and type were gathered on three cross-shore transects along two sandy shorelines in Raritan Bay, NJ. Variables measured to assess hydrodynamic, sedimentary, chemical and physical properties of sites, include wave height and period, swash width, grain size and sorting, moisture content, beach elevation change, depth of sediment activation, beach slope, and water temperature and salinity,. Longshore differences in meiofaunal density are examined at similar elevations relative to mean sea level between sites fronting a shore-parallel structure and sites that do not. Spatial differences are explained relative to hydrodynamic and sedimentary characteristics of the beach matrix.

CHAPTER 2

CONCEPTUAL MODEL

Meiofauna are an important part of the coastal ecosystem. Micro- and meiofauna are responsible for the purification of large volumes of sea water that flush through the interstitial sedimentary system. (McLachlan 1989). They are also an integral part of the food chain. Laboratory studies document that the presence of meiofauna can increase community metabolism threefold compared to a system depleted of meiofauna (Lee et al., 1974). Thus, knowledge of the effects that human alteration have on interstitial habitat and density of meiofauna is crucial.

2.1 Meiofauna and Beach Morphology

The interstitial sand zone of sandy beaches is characterized by a mobile substratum and the absence of attached plants. McLachlan (1983) describes two habitats suitable for fauna populations in the substratum. These are the macrofauna habitat consisting of the sand surface and upper layer of sediment, and, the interstitial habitat consisting of the porous system of the sand body that is colonized by meiofauna.

The ability for meiofauna to survive is dependent on the structure of the beach matrix and the availability of oxygen and nutrients carried by the movement of water through the sediment. Thus, physical properties of the beach, including grain size and sorting, moisture content and beach slope, are important to assess the viability of a beach matrix as meiofaunal habitat.

The interstitial beach system is the porous area between the sand grains of the beach matrix. Most physical properties of this system are directly determined by the sediment characteristics. These in turn are influenced by wave and current processes as well as the geological history of the area. Movement of water by tides, waves, and currents allows for the infiltration of water to the interstitial zone (Figure 1A). The rate of infiltration is controlled, in part, by the porosity and permeability of the beach sediments (a function of grain size, shape, and sorting). Porosity controls the amount of water that can be held within a sediment deposit while permeability represents the ability of a deposit to transmit water (Dunne and Leopold 1978). Finer grain sediments that are well-sorted will have the highest porosity but lowest permeability. Thus, the sedimentary characteristics of the beach matrix controls moisture content, oxygen and organic input and depth of reduced layers (McLachlan 1983) that influence the suitability of the beach matrix to support meiofauna.

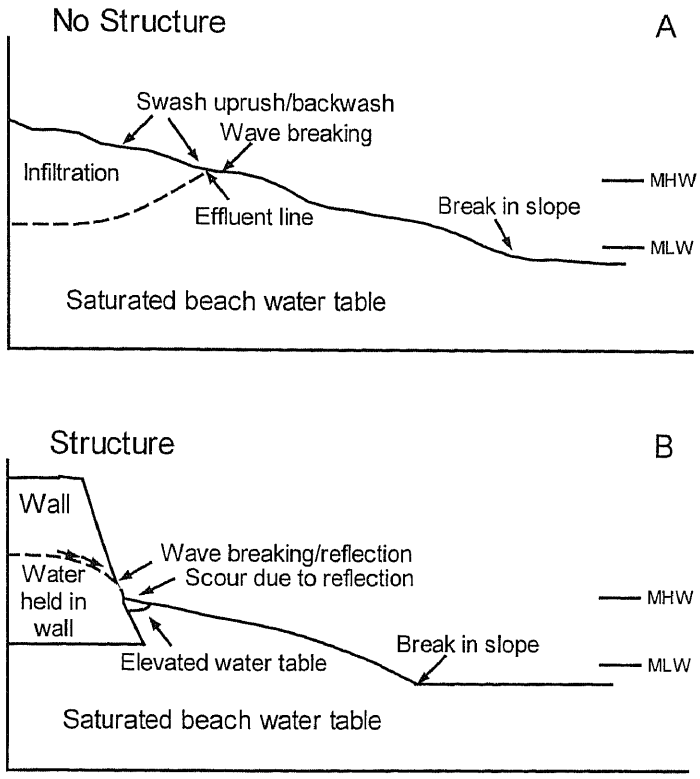

Figure 1: Beach dynamics at high water on: A) shoreline with no structure; and, B) shoreline with shore-parallel structure.

2.2 Shore-Parallel Armoring and Beach Morphology

There exist three alternatives for communities that are threatened by storm wave impact and shoreline recession: emplacing hard protection structures (armoring), widening the beach through artificial nourishment, or relocating buildings away from the beach (Griggs et al. 1991). The decision is usually based on the politics and economics of the different approaches. Historically, seawalls are built to protect development and not beaches (Pilkey 1988). A Shore-parallel structure introduces interactions between waves and sediment that do not exist on the original beach. The nearshore area and neighboring shore in the vicinity of a bulkhead or seawall are expected to undergo different short- and

long-term changes compared to changes that would occur in the absence of the structure (Kraus 1988).

The alteration of sandy beach habitat and ecosystem structure and functioning is exacerbated by the presence of beach armoring technologies. The short-term effects of shore-parallel armoring on beach morphology and processes are depicted in Figure 1B. The length of the swash cycle decreases, wave reflection truncates the uprush portion of the swash cycle, and the duration and velocity of backwash increases (Plant and Griggs 1992). Water held within the rock revetment above beach level does not infiltrate and, thus, feeds the backwash flow (Plant and Griggs 1992). Swash and wave reflection increase activation and scour exacerbating beach erosion (Thom et al. 1994) and could result in a decrease in elevation and sediment volume in front of the structure. Sediments are finer and better sorted due to the constant attack of waves against the structure. Reduced permeability and porosity below beach level due to shore-parallel structures inhibits groundwater flow and increases water table elevation (Plants and Griggs 1992); the result is higher moisture content of beach sediments.

Long-term changes to the beach due to the effects of shore parallel structures are also of importance in determining how, where, and when to use hard structures. Pilkey and Wright (1988) describe three potential effects shore-parallel structures will have on the immediate surroundings. Firstly, impoundment on the updrift side and flanking on the downdrift side occurs when a structure is built seaward of the base of a cliff, bluff or dune, on the intertidal foreshore. The effect is immediate beach loss and the extent of the loss is a function of how far seaward and alongshore the structure extends. Secondly, passive erosion is what occurs when a hard structure is built on an eroding shoreline and

when erosion continues to occur, the shoreline will migrate landward beyond the structure. This will eventually result in the gradual loss of the beach in front of the seawall as the nearshore slope steepens and the beach profile migrates landward. Over time, a sandy beach can be transformed into gravel or cobbles, and may even be scoured down to bedrock or hard clay. The footings of armoring are exposed, leading to destruction and failure (Thom et al. 1994).

Seawalls interrupt longshore sediment transport during high water and prevent natural changes to the beach during swell and winter storm wave conditions. Seawalls can also prevent building of the backbeach and long-term recovery by prohibiting berm formation by wave uprush and dune formation by wind (Kraus and McDougal 1996).

2.3 Research Questions

Shore parallel armoring has the potential to alter or eliminate sandy beaches and the habitat of meiofauna. To determine the effect of shore-parallel structures on meiofauna the following research questions were examined.

- Are there longshore differences in meiofaunal density at a similar elevation relative to mean sea level between sites that employ shore-parallel structures and those that do not?
- Are the differences in meiofaunal density that exist between the sites due to differences in the physical attributes of the intertidal beach?

Two one-day field investigations were conducted on the southern shoreline of Raritan Bay, New Jersey. Raritan Bay was chosen because it is an urban estuary

characterized by extensive development and there exists a range of physical environments and human development. It is an area where numerous beach armoring technologies have been employed over several years (USACOE 1960, 1993).

Two shoreline reaches, located at Cliffwood Beach and Keyport Harbor, were selected for detailed assessment. The reaches were chosen based on wave climate, presence of shore-parallel armoring (bulkheads and seawalls), and the presence of a control site where there are no shore-parallel structures. Collectively, the sites provide valuable information on the effect of shoreline armoring on coastal habitat and meiofauna of the Raritan Bay estuary.

Data on characteristics of meiofauna (density and diversity), beach (elevation and slope), waves (height and period), sediments (size, sorting and activation), and water (temperature, salinity and moisture content) were gathered along three transects at each study area over one tidal cycle during spring tide conditions.

CHAPTER 3

METHODOLOGY

3.1 Study Areas

The study was conducted along the southern shoreline of Raritan Bay, New Jersey (Figure 2). Raritan Bay is a funnel-shaped estuary located within the New York Bight. Tides in the estuary are semi-diurnal with a mean range of 1.5 m and a spring range of 1.8 m (NOAA 1998). The dominant energy reworking beach sediments is from locally-generated waves although some segments of the shoreline are exposed to ocean waves that enter to the north of Sandy Hook spit. Locally-generated waves during non-storm conditions are less than 0.14 m in height with periods less than 3.0 s (Jackson and Nordstrom 1992).

Two shoreline reaches, Cliffwood Beach and Keyport Harbor, were selected for detailed assessment. The reaches were chosen based on wave climate, presence of shore-parallel armoring structures (bulkheads or seawalls), and the presence of a control site where there are no shore-parallel armoring structures.

3.1.1 Cliffwood Beach

The shoreline reach at Cliffwood Beach is 2.3 km long and is bounded by Matawan Creek to the southeast and by Whale Creek to the northwest. An erosion and flood control project including a seawall, beach nourishment and artificial dune was completed in 1982 (USACOE 1993). The seawall is constructed of stone with a concrete cap. The

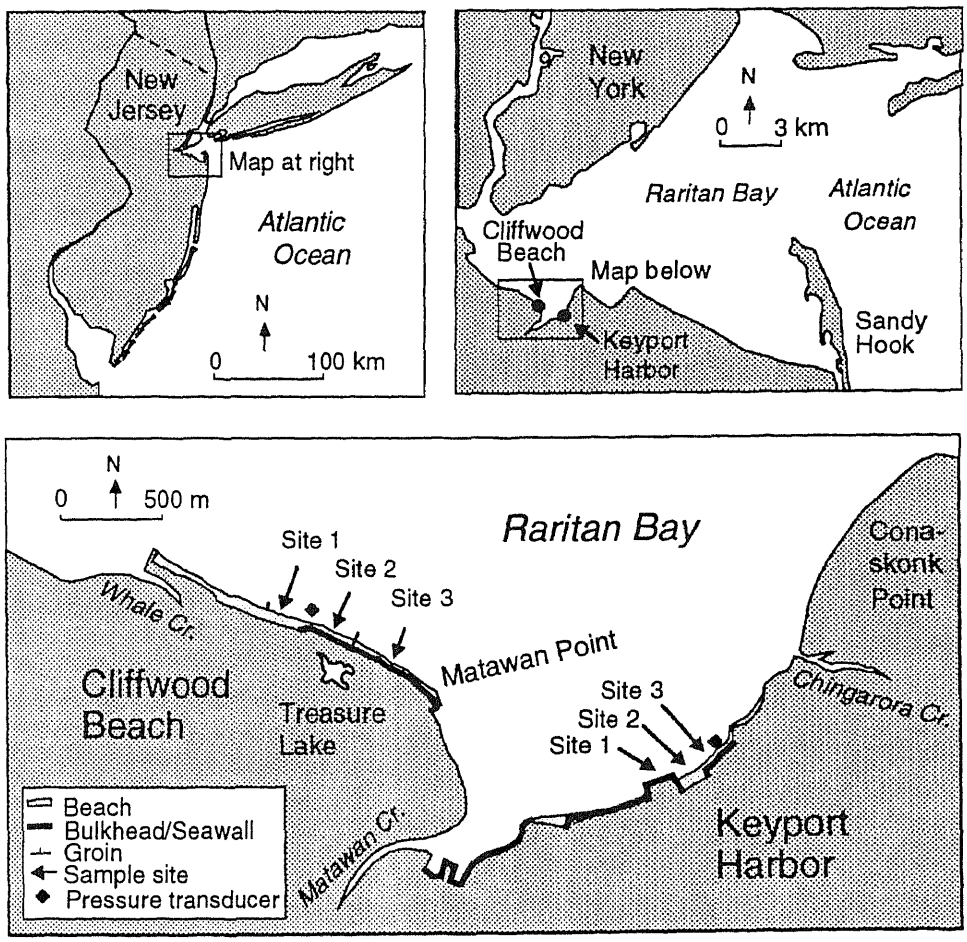

Figure 2: Location map showing Raritan Bay, study areas, and study sites.

seawall is backed by a vegetated cliff-face slope with a layer of gabions at the base of the slope. The nourishment operation included emplacement of sediment in front of the seawall and between the west end of the seawall and Whale Creek (Figure 2) (Jackson and Nordstrom 1994). Fill sediments are moderately well sorted medium sand (0.35 mm diameter); the sediments are finer than grain sizes reported on the foreshore prior to the nourishment operation but coarser than sediments reported on the low tide terrace (USACOE 1960). Dominant waves reworking beach sediments are locally-generated within Raritan Bay but the northwest end of the reach can be influenced by ocean waves during off-shore winds or northeast storms (Jackson and Nordstrom 1994). Net longshore currents are to the west from Matawan Point to Whale Creek (Jackson and Nordstrom 1994).

Three sites were selected at each study area for detailed assessment (Figure 2). The sites are located on the northwest portion of the reach. Site 1 is 600 m east of Whale Creek and was designated a control site because there is no shore-parallel structures on the profile. Peat outcrops are visible on the low-tide terrace near the break in slope (Jackson and Nordstrom 1994) but are not located within the sampling area. The site is backed by a dune that reaches 2.8 m above mean sea level. Site 2 is 200 m east of Site 1. The site is backed by the seawall. The toe of the wall intersects the profile at an elevation of 1.5 m above mean sea level. The swash uprush limit reaches the toe of the structure during spring high tide under low wave energies. Site 3 is located 300 m east of Site 2. The site is backed by the seawall, but the seawall is located lower on the profile, (the toe of the wall is 0.25 m above mean sea level). Waves break against the toe of the structure at mid-rising and mid-falling tide during spring tides under low wave energies.

3.1.2 Keyport Harbor

The shoreline reach is 1.2 km in length and bounded on the south by Matawan Creek and to the north by Chingarora Creek (Figure 2). Keyport is more densely developed than Cliffwood Beach and has commercial and residential structures located on the shoreline. Over 50 % of the shoreline is protected with shore-parallel armoring. The reach is sheltered from waves generated by northeast storms due to the sheltering of Conaskonk Point (Figure 2). High speed winds from the north-northwest can generate the highest wave heights along the reach. Historical shoreline change along the reach reveals lower rates of change compared to Cliffwood Beach (Jackson 1996).

Three sites, located at the mid-point of the reach, were chosen for detailed assessment. Site 1 is backed by a wooden bulkhead that is located low on the intertidal profile (the toe of the structure is 0.5 m above MSL). Waves reflect against the base of the bulkhead at mid-rising and mid-falling tide. Site 2 is located 100 m north of Site 1. The site was designated a control site because there are no shoreline armoring structures on the profile. The site is backed by a low elevation dune. Site 3 is located 100 m north of Site 2. The site is backed by a cement bulkhead protecting a street end but the structure is located higher on the profile than the bulkhead at Site 1, the toe of the structure is 1.0 m above MSL. The swash limit reaches the base of the bulkhead at spring high water. Rubble, extending 3.0 m landward from the base of the bulkhead, protects the toe of the structure.

3.2 Sampling Methodology

The same sampling methodology was followed in both field investigations. The cross-shore limits of the investigations extend from the upper limit of swash at high water or the base of the shore-parallel structure bayward to the break in slope (Figures 3 and 4). Data were gathered during a spring tidal cycle on August 22, 1997 at Cliffwood Beach and during a spring tidal cycle on September 21, 1997 at Keyport Harbor. Spring tidal cycles were selected because there is the greatest interaction between waves and shore-parallel structures.

Meiofauna and sediment samples were gathered at four sampling stations established across each transect at the upper limit of swash, and the upper-, mid- and lower-foreshore (Figures 3 and 4). Sampling stations were located at similar elevations longshore to allow for comparison between sites.

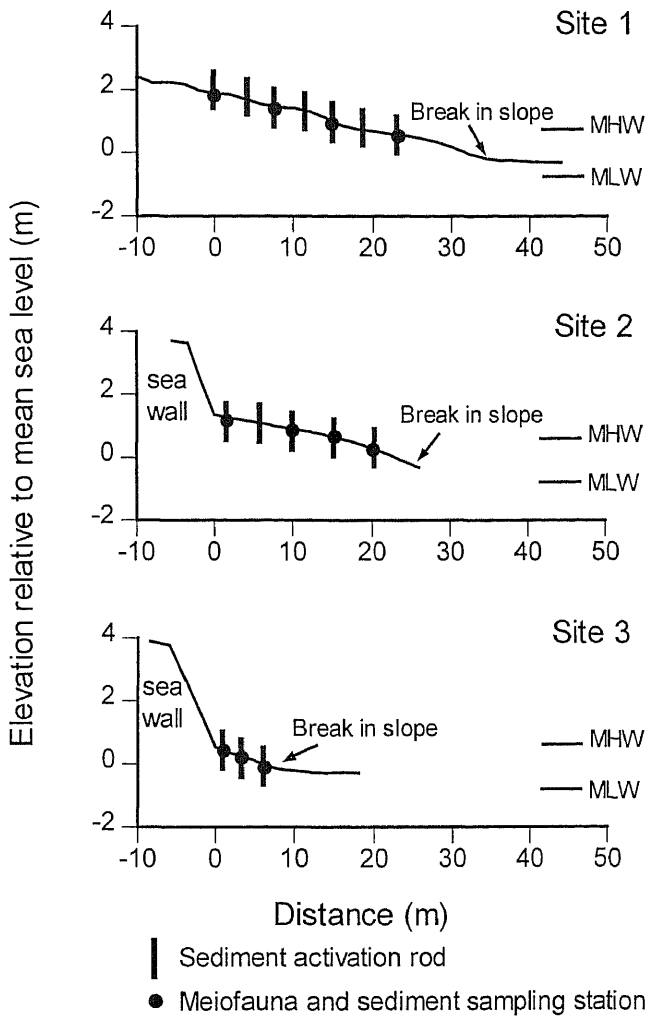

Figure 3: Beach profiles identifying location of sediment activation rods and meiofauna and sediment sampling stations at Cliffwood Beach. 0 m horizontal distance represents upper limit of swash at Site 1. Elevation is based on NGVD.

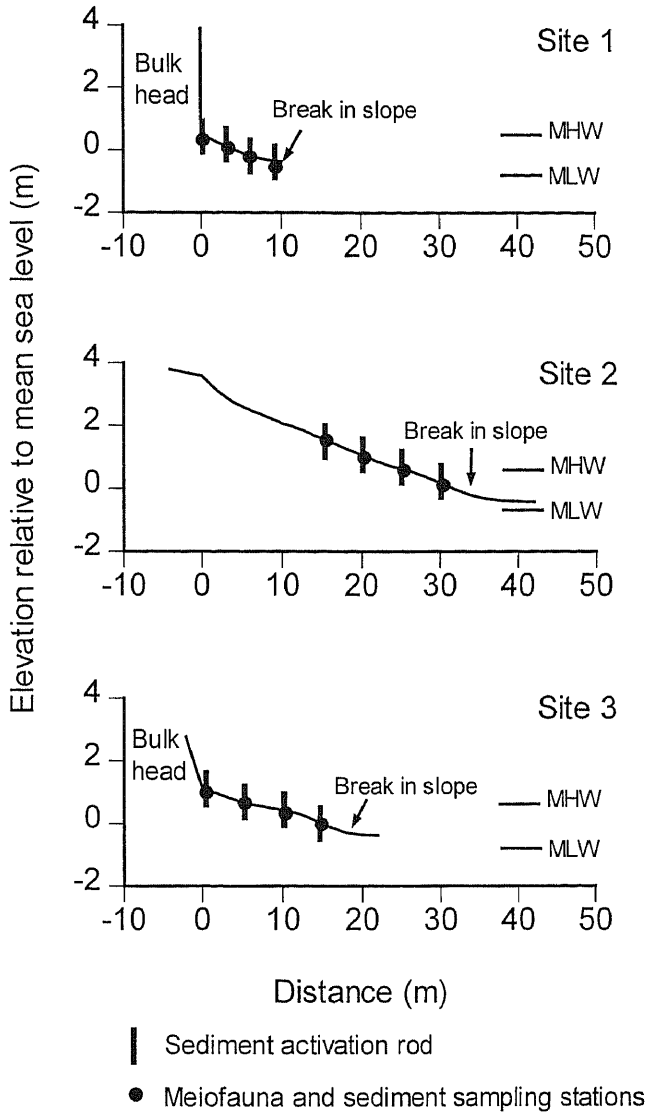

Figure 4: Beach profiles identifying location of sediment activation rods and meiofauna and sediment sampling stations at Keyport Harbor. 0 m horizontal distance represents upper limit of swash at Site 2. Elevation is based on NGVD.

3.2.1 Meiofauna Sampling

Meiofauna were collected at each sampling station from 3 replicate cores with an internal diameter of 0.025 m and a length of 0.10 m. The cores were cut in upper and lower segments to determine distribution of the meiofaunal population with depth. The top

portion of the core samples to a depth of 0.03 m below the sand surface, where the majority of the meiofauna are found. The bottom portion of the core, represents a depth of 0.031 to 0.10 m below the sand surface. Organisms were preserved with Formalin, stained with Rose Bengal solution, and then extracted from the sediment by sieving. Fauna that passed through the 500 micron sieve and retained on the 45 micron sieve are classified as meiofauna. Meiofauna were counted using a monocular microscope at 4X objective. The 3 replicate cores, top and bottom, were used to determine meiofaunal density. Densities were calculated per cm^3 to allow comparison between top and bottom of the core. Organisms in the third replicate sample were identified by taxanomic group to the class level. These were grouped as Nematoda, Copepoda, or Other.

3.2.2 Physical Attributes of the Coastal Habitat

Topographic surveys were conducted at each transect using standard techniques; slope values at each sampling station were determined using a hand level. Net change and depth of sediment activation were determined employing the method of Greenwood and Hale (1980), using 6.4 mm diameter, 0.9 m long rods driven into the sand at 3 m intervals, at Site 3, Cliffwood Beach and at Site 1, Keyport Harbor, where the foreshore is narrower, and 5 m intervals cross-shore at each transect for all other sites. Loose fitting washers were placed on each rod at the beginning of the tidal cycle. Net change was determined from the difference in sand elevation measured from the top of the rod at successive low tides. Depth of activation was determined from the difference between the initial sand elevation and the depth of the washer at the subsequent low tide. Sediment core samples were gathered at each station (Figures 2 and 3) at the surface (top

0.03 m) and at depth (between 0.031 and 0.10 m). Sediment characteristics were not determined from the meiofauna samples to prevent loss of the fine fraction in the extraction process. Samples were washed, dried, and sieved at 0.5 ϕ intervals; mean grain size and sorting were determined using graphic measures (Folk 1974). Gravimetric moisture content was calculated from each of the samples as the percent difference between wet sample weight and dry sample weight.

Water temperature in the swash zone and sand temperature landward of the upper limit of swash were gathered at 1 hr intervals over the tidal cycle. Three water samples were taken at rising, high and falling tide at 9:00, 14:00 and 17:00 and tested for salinity.

Visual observations were made of upper swash limit and breaker location on the profile at 1 hr intervals over the tidal cycle. Visual breaking wave height and wave period were gathered at 1 hr intervals and estimated from an average of 5 wave observations. Significant breaking wave height (H_{bs}) was calculated from visual mean wave heights using Equation 1 (CERC 1984):

Equation 1 $$H_{bs} = 1.598\bar{H}$$

where $\bar{H}$ is the mean wave height.

Wave characteristics and water depth on the low tide terrace over the tidal cycle were gathered with a pressure transducer, located 10 m bayward of the break in slope (Figure 1). The pressure transducer data were gathered at a frequency of 2 hz over the tidal cycle. Data were partitioned into records of 2048 data points (17.1 minutes) to determine water depth, wave height and period over the tidal cycle. Water depth was determined from the average of each data record. Significant wave height (H_s) was

calculated as 4 times the standard deviation of each record. Wave period was determined from the peak frequency of the spectral estimates using Matlab signal processing toolbox (Hegge and Masselink 1996).

Table 1 is a summary of the variables collected and their method of measurement for both field investigations.

Table 1: Variable identification and method of measurement.

Variable	Definition	Measurement
Meiofauna	< 500 um and > 45 um	Preserved, sorted from sediment, counted and identified using a microscope (4X) (density and type)
Beach slope	Incline of the beach	Standard hand level (°)
Beach elevation	Elevation of sand surface (m) relative to mean sea level (MSL)	With stadia rod and transit at 5m intervals from dune crest to low-tide terrace at low tide
Swash limit	Uprush limit of breaking waves	Visual estimate
Grain size and sorting	Mean size and distribution of sediment	Sorted and sieved at 0.5 ϕ intervals
Moisture content	Percent water content in sediment sample	Dry weight- wet weight/ wet weight * 100
Significant wave height	Distance between trough and crest of highest 1/3 of the waves	4 * Standard deviation
Wave period	Peak frequency	Spectral analysis

3.3 Data Analysis

3.3.1 ANOVA

One-way analysis of variance was performed to determine the longshore differences of meiofaunal density between sites at sampling stations with similar elevations relative to mean sea level. The critical value for degrees of freedom (1,4) is 7.71 at the 95 % confidence level. F ratios below the critical value signify that there is no difference between the sites and F ratios that are greater than the critical value signifies that there is a difference between the sites. Post hoc comparisons using a Tukey's HSD test were performed to identify significantly different means among multiple pairs at 95 % confidence interval.

3.3.2 Correlation

The primary purpose of correlation analysis is to measure the strength of a linear association between the physical attributes (mean grain size, sorting, moisture content, depth of sediment activation, and beach slope) and meiofaunal density at each site. For all sites, meiofaunal density for each replicate was used with the corresponding value of the physical characteristics of the sampling stations.

3.3.3 Surf-Scaling Parameter

The surf-scaling parameter, $\in$, is used to determine wave energy dissipation or reflection in the surf/swash zone:

Equation 2 $$\in = a_b\, w^2 / g \tan^2\beta$$

where a_b is breaker amplitude ($H_b/2$), w is incident wave radian frequency ($2\pi/T$; T= period), g is acceleration of gravity, and β is beach/surf zone gradient. Values of $\in < 2.5$ indicate complete reflection, $\in$ values between 2.6-20.0 are intermediate and >20.0 are dissipative (Wright and Short 1983). Wave and slope data used to calculate $\in$, are based on averages across the intertidal profile at each site.

3.3.4 Permeability

Permeability, k, is measured using the formula of Krumbein and Monk (1943) that uses grain size and sorting to determine the rate of water movement through the sediment deposit:

Equation 3 $$k = 760\,(D)^2 \,/\, \exp 1.31\sigma$$

where D is the geometric mean grain diameter (mm), and σ is the sediment sorting (in phi units). Permeability is measured with units of Darcies where 1 Darcy = 9.87×10^{-13} m^2.

3.3.5 Sediment Mixing Depth

The relationship between calculated breaking-wave height (H_b) and the spatially-averaged depth of sediment activation ($\bar{Z}$) for a meso-tidal estuarine beach (Jackson and Nordstrom 1993) is:

Equation 4 $$\bar{Z} = 0.15Hb$$

The calculated values of $\bar{Z}$ are used as a comparison for the average depth of activation measured at Cliffwood Beach and Keyport Harbor to assess the impact of shore-parallel structures.

CHAPTER 4

RESULTS

4.1 Cliffwood Beach

4.1.1 Average Meiofaunal Density and Type at Cliffwood Beach

Figure 5 presents average meiofaunal densities cross-shore for each transect and longshore at similar elevations relative to mean sea level. Standard deviations based on the average of the three replicate samples are shown in parentheses for the top and the bottom of the core samples. The coefficient of variation ($\sigma/\bar{x}$), for the top of the core, ranges from 0.07, on the mid-foreshore at Site 1, to 0.70, at the toe of the seawall at Site 2, with an average of 0.39. The results for the bottom of the core, indicate a coefficient of variation from 0.05, on the mid-foreshore at Site 1, to 1.25, on the lower foreshore at Site 2, with an average of 0.40.

Average densities are greater in the top 0.03 m than the bottom 0.07 m. The average of all densities for the top 0.03 m is 18.9 ind. cm^{-3} with a standard deviation of 6.9 and the average of all densities for the bottom of the core is 5.9 ind. cm^{-3} with a standard deviation of 1.3. On average, 67.3 % of the total meiofaunal densities are found in the top 0.03 m of the beach. The percent meiofaunal density found in the top 0.03 m, increases in the bayward direction, ranging from 31.2% just landward of wave breaking at high water at Site 1 to 88.7% on the lower foreshore at Site 2.

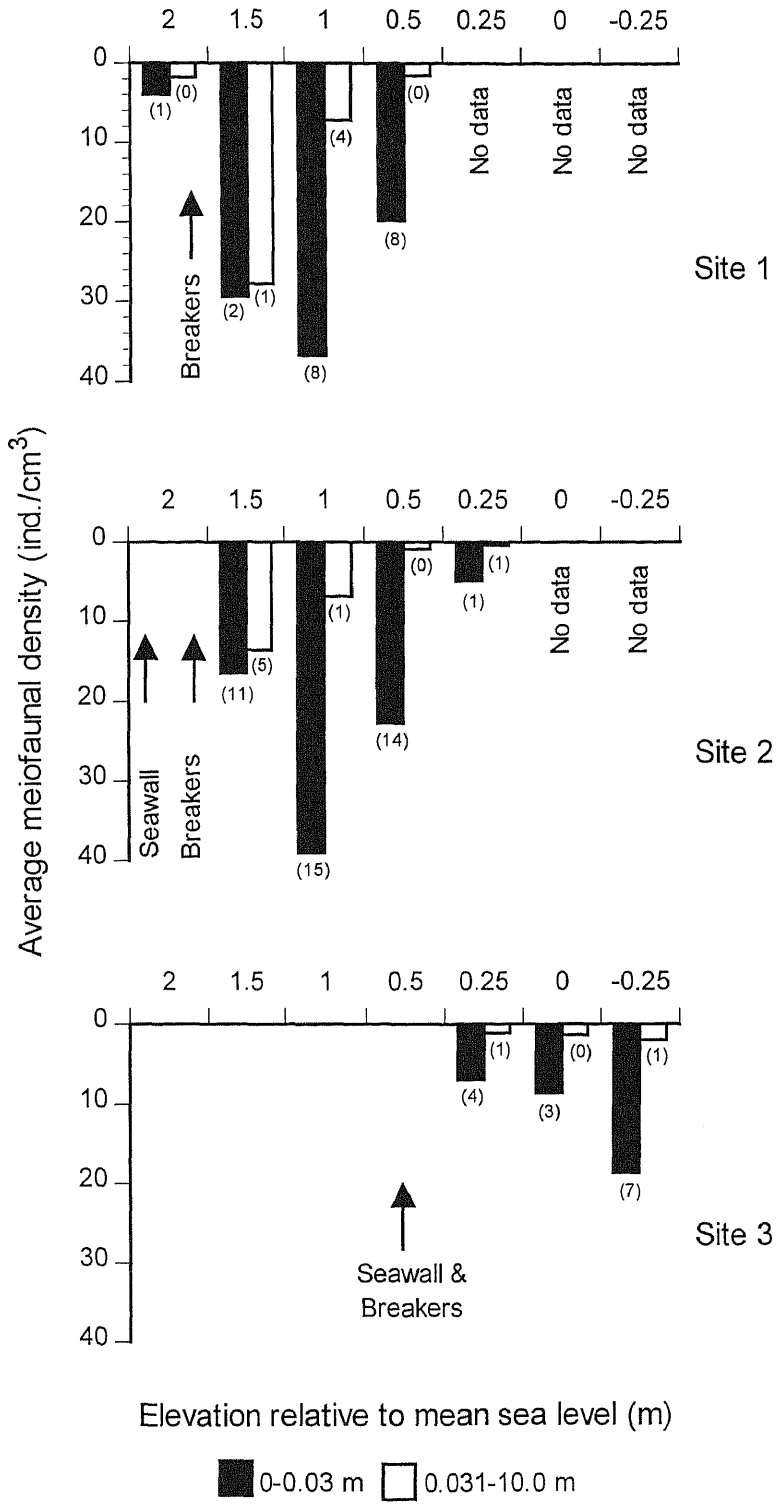

Figure 5: Average meiofaunal densities (ind. cm^{-3}) relative to mean sea level (m) at Cliffwood Beach. Breakers represent location at high water. Standard deviations are in parentheses for top and bottom of the core.

Sites 1 and 2 show similar cross-shore patterns of meiofaunal density distribution. There is a low average density in the swash zone. Average densities increase bayward to an elevation of 1.0 m relative to mean sea level, and progressively decrease at lower elevations on the profile. Site 3 illustrates a generally lower average density than the other two sites and a reverse in the cross-shore trend; densities increase with distance from the seawall to the break in slope.

Nematodes account for 84.7 % of the meiofauna in the top and bottom of the core for all sites and sampling stations (Table 2). Copepods make up 11.7 % of the top of the cores and 13.6 % of the bottom of the cores. Other types of meiofauna account for 3.6 % of the top of the cores and 1.5 % of the bottom of the cores. Nematodes are exclusively found at the highest intertidal elevation at all three sites where moisture is low and in areas which are more prone to sediment activation, at the toe of the seawall. The greatest diversity occurs at the sampling stations that are at least 10 m bayward of the seawall at Sites 2 and 3, and at Site 1 where there is no shoreline armoring.

Table 2: Classification of meiofauna by type at Cliffwood Beach.

Location	Elevation -MSL (m)	Nematoda		Copepoda		Other	
		Top	Bottom	Top	Bottom	Top	Bottom
Site 1	2.0	60	71	0	0	0	0
	1.5	345	750	4	8	100	7
	1.0	311	335	100	50	11	0
	0.5	118	54	52	8	37	4
Site 2	1.5	107	589	0	0	0	0
	1.0	264	176	18	54	1	5
	0.5	195	21	180	17	0	0
	0.25	49	2	16	1	0	0
Site 3	0.25	62	21	0	0	0	0
	0	80	48	1	1	0	0
	-0.25	321	72	0	15	0	0

4.1.2 Site Characteristics at Cliffwood Beach

Wind conditions were offshore and calm and no precipitation occurred during the field investigation. Table 2 presents hourly data on water temperature, sand temperature, significant wave height, wave period and swash width. Mid-day air temperature was 26.4°C. Water temperature increased over the rising tide from a low of 22.5 °C in the morning to a high of 25.1 °C at high tide, and remaining between 24 ° and 25 °C during falling tide. Sand temperature followed a similar pattern with a low of 22.2 °C, at 8:56, and a high of 25.2 °C at 12:05. Water salinity, from samples taken at mid-rising and mid-falling tide, was 24 ‰.

Visual breaking wave heights on the foreshore were between 0.05 m and 0.13 m. The lowest and highest waves were breaking at Site 1. Visual wave periods ranged from 1.5 s to 3.7 s, both recorded at Site 2. Swash widths were less than 5.0 m at all sites. The

upper limit of swash reached the toe of the seawall at Site 2 during high water. Wave breaking occurred on the toe of the seawall at Site 3, beginning 3.0 hrs after low water on the rising tide and ending 3 hrs before low water on the falling tide.

Changes in water depth, wave height, and wave period on the low tide terrace over the tidal cycle from data gathered with the pressure transducer are presented in Figure 6. Significant wave height ranged from 0.10 m at high water to 0.25 m during rising tide. Peak wave periods recorded on the low tide terrace are longer than visual estimates. Figure 7 presents the spectral estimate from data gathered near high water (11:23). The greatest energy is concentrated at frequencies lower than the locally-generated wave and ranges from 0.17 to 0.13 hz (5.9 - 7.7 s). These wave periods are similar to the period of ocean waves (Thompson 1977) and are common on beaches that are close to or oriented toward the mouth of an estuary (Jackson 1995). The locally-generated wave (Figure 7), has a peak frequency of 0.27 hz (3.7 s) and is similar to visual estimates of waves on the foreshore at 12:50 at Site 2 (Table 2) where the pressure transducer was located.

Table 3: Hourly visual site observations during the tidal cycle at Cliffwood Beach on August 22, 1997.

Site	Time	Water temp. (°C)	Sand temp. (°C)	Significant Wave height (m)	Wave period (s)	Swash width (m)
1	08:56	22.6	22.2	0.21	1.7	5.0
	10:04	23.1	22.5	0.13	1.9	2.5
	11:04	23.8	23.7	0.16	2.6	4.0
	12:05	24.4	25.2	0.13	3.3	5.0
	13:04	25.4	24.3	0.18	2.1	4.0
	14:03	25.3	23.7	0.11	2.5	2.0
	15:03	24.4	23.9	0.13	1.6	2.5
	16:03	24.7	23.9	0.11	1.6	2.0
	16:56	24.6	23.4	0.08	1.8	8.0
2	09:15	22.8	22.3	0.16	1.7	2.0
	10:12	23.1	22.5	0.13	1.6	2.0
	11:12	24.4	24.9	0.19	2.1	5.0
	12:14	25.0	24.9	0.13	3.7	5.0
	13:11	24.5	24.5	0.18	2.3	2.0
	14:08	24.1	23.7	0.11	1.6	3.0
	15:09	24.4	23.4	0.13	2.0	3.0
	16:09	24.4	23.6	0.14	1.9	3.0
	17:24	24.7	23.6	0.10	1.5	4.0
3	09:20	22.5	n.d.	n.d.	n.d.	0.0
	10:20	waves	breaking	on	seawall	0.0
	11:20	waves	breaking	on	seawall	0.0
	12:20	waves	breaking	on	seawall	0.0
	13:20	waves	breaking	on	seawall	0.0
	14:15	24.4	n.d.	n.d.	n.d.	0.0
	15:18	24.4	n.d.	0.18	3.2	1.0
	16:15	24.4	24.0	0.14	2.1	2.0
	17:15	25.2	23.9	0.10	1.6	4.0

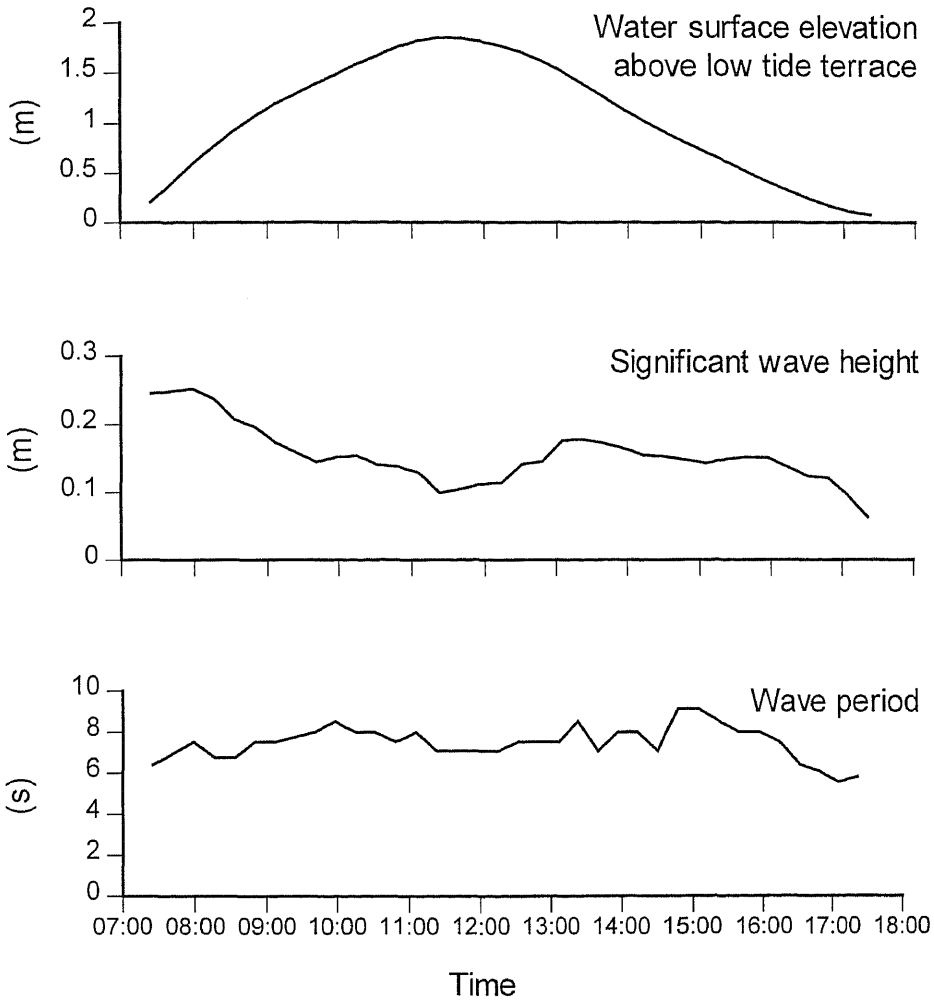

Figure 6: Changes in water depth, wave height, and wave period over a tidal cycle at Cliffwood Beach, August 22, 1997.

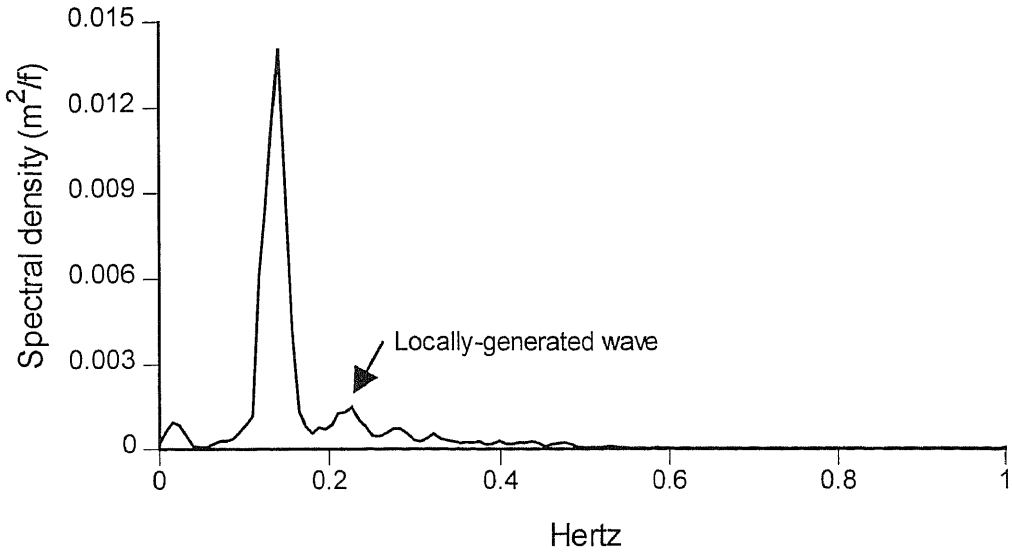

Figure 7: Spectral estimate of pressure transducer data gathered near high water (11:23).

4.1.3 Sediment Characteristics at Cliffwood Beach

4.1.3.1 Top of Core: Mean grain size of the top 0.03 m of the sediment core samples is in the range of medium to coarse sand (Table 4). At Site 1, mean grain size increases bayward, from 0.32 mm in the location under the influence of the swash zone at high water to 0.67 mm, on the lower foreshore near the break in slope. Sediments are more poorly sorted in the bayward direction, characteristic of an estuarine beach foreshore (Nordstrom and Jackson 1993). At Site 2, mean grain size increases bayward, and the sediments change from moderately well sorted to poorly sorted, except at the lowest elevation where it is again, moderately well sorted. At Site 3, mean grain size increases bayward, and the material is increasingly poorly sorted, except at the lowest elevation (0.25 m MSL) where a decrease in grain size occurs and the material is moderately sorted.

Mean grain size for the sediments in the swash zone at high water is similar (medium sand) for Sites 1 (2.0 m MSL) and 2 (1.5 m MSL). Mean grain size is slightly finer at the toe of the seawall at Site 3 compared to mean grain size at a similar elevation at Site 2, 20m bayward of the toe of the seawall. That is, at an elevation of 0.25 m relative to mean sea level, mean grain size is 0.59 mm (coarse sand) at Site 2 and 0.29 mm (fine sand) at Site 3.

Table 4: Sediment characteristics for the top of the core at Cliffwood Beach.

Location	Elevation -MSL (m)	Mean Grain Size (mm)	Mean Grain Size (ϕ)	Sorting (ϕ)
Site 1	2.0	0.32	1.64	0.35
	1.5	0.48	1.06	0.60
	1.0	0.52	0.93	0.97
	0.5	0.67	0.58	1.07
Site 2	1.5	0.33	1.60	0.54
	1.0	0.57	0.80	1.04
	0.5	0.59	0.77	1.06
	0.25	0.59	0.75	0.70
Site 3	0.25	0.29	1.80	0.58
	0	0.43	1.23	1.35
	-0.25	0.33	1.60	0.94

4.1.3.2 Bottom of Core: Mean grain size of the bottom 0.07 m of the sediment core samples are in the range of medium to coarse sand (Table 5) similar to the sediments in the top 0.03 m of the samples. At Site 1, the sediments at the upper limit of swash are finer and well sorted. Sediment characteristics at the remainder of the sampling stations

are similar: coarse mean grain size (0.51mm) and moderately sorted sand (0.99 ϕ). At Site 2, sediments directly in front of the wall are medium sand (0.35mm) and moderately well sorted (0.57 ϕ). At the sampling station on the profile, -0.25 m relative to MSL, mean grain size is larger at 0.73 mm and well sorted at 0.40 ϕ. At Site 3, mean grain size (medium sand) decreases bayward. The most poorly sorted sand is located at mean sea level.

Mean grain sizes are slightly finer at the toe of the seawall at Site 3 compared to mean grain size at a similar elevation at Site 2, 20 m bayward of the toe of the seawall. That is, at 0.25 m above mean sea level, mean grain size is 0.73mm (coarse sand) at Site 2 and 0.35mm (medium sand) at Site 3.

Table 5: Sediment characteristics for the bottom of the core at Cliffwood Beach.

Location	Elevation -MSL (m)	Mean Grain Size (mm)	Mean Grain Size (ϕ)	Sorting (ϕ)
Site 1	2.0	0.36	1.49	0.34
	1.5	0.51	0.98	0.99
	1.0	0.52	0.95	0.96
	0.5	0.51	0.97	0.99
Site 2	1.5	0.35	1.53	0.57
	1.0	0.53	0.92	0.40
	0.5	0.39	1.37	1.01
	0.25	0.73	0.45	0.40
Site 3	0.25	0.35	1.50	0.59
	0	0.31	1.70	1.03
	-0.25	0.26	1.92	0.65

4.1.4 Depth of Sediment Activation at Cliffwood Beach

Depth of sediment activation and net change over the tidal cycle are presented in Figure 8. Maximum sediment activation, at all sites, occurred 1.375 m bayward of the seawall at Site 3, (0.036 m). At Site 2, maximum sediment disturbance occurred at a distance of 10 m from the toe of the seawall. Maximum sediment activation occurred 17 m bayward of the upper limit of swash at high water for Site 1, the control site.

Elevation change across the profile was minimal at all sites. Net change did not exceed 0.04 m. Sites 1 and 2 reveal erosion of the upper foreshore and deposition of sediment lower on the foreshore. Net change at Site 3 shows deposition of sediment across the entire profile.

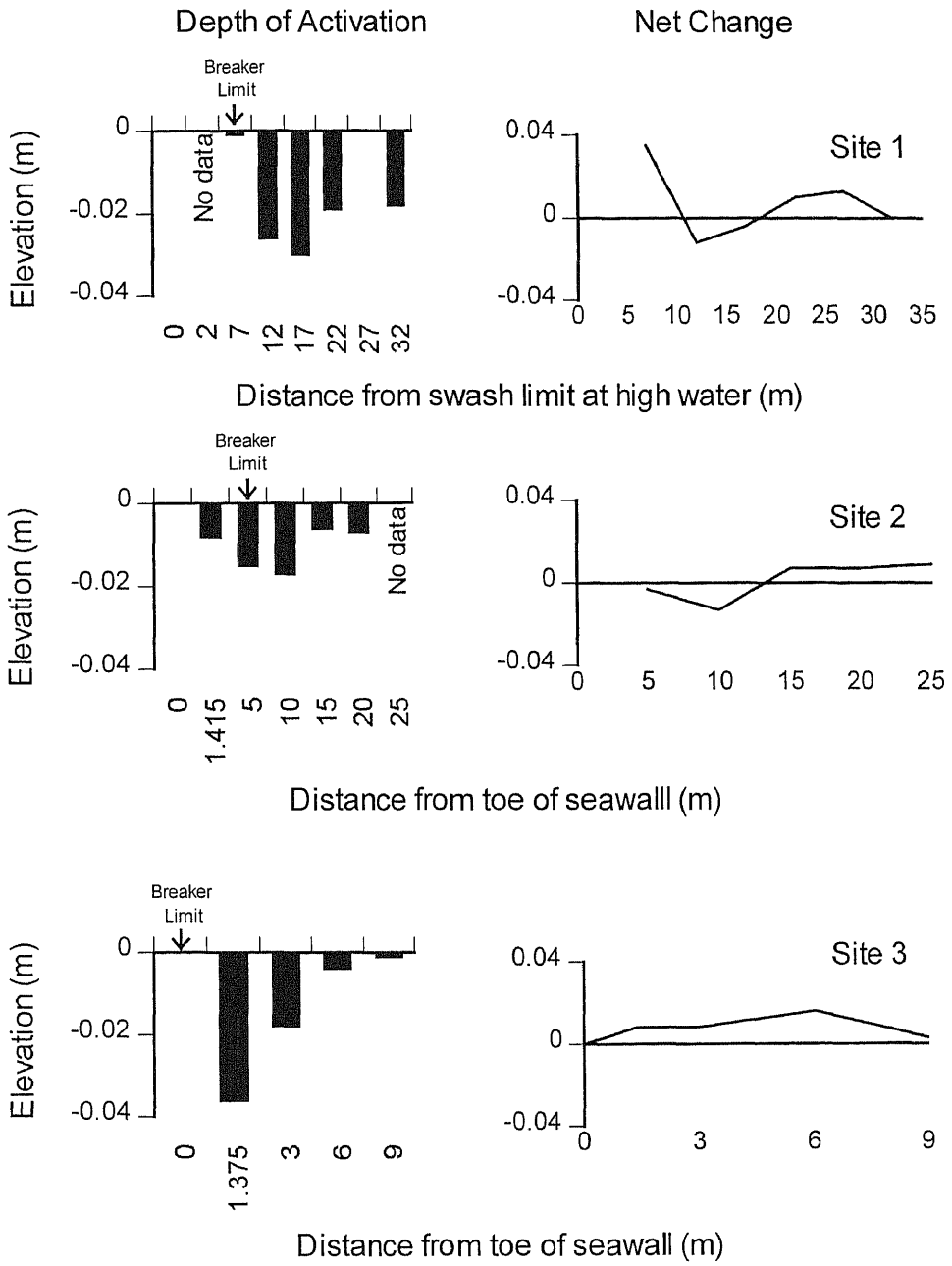

Figure 8: Depth of activation and net change for Cliffwood Beach.

4.1.5 Moisture Content at Cliffwood Beach

Moisture content, calculated from the sediment core samples, are presented in Table 4. For the top and the bottom of the core, the lowest moisture content values (3.28 % and 4.44 %) were found at the highest elevation (2.0 m MSL) at Site 1. For the top of the core, the highest value (18.51 %) was recorded at mean sea level at Site 3. For the bottom of the core, the highest value (18.96 %) is also located at Site 3, 0.25 m above MSL. The highest moisture contents are lower than the moisture content for fully saturated sand (24.0 %).

Table 6: Moisture content for the top and bottom of the core at Cliffwood Beach.

Location	Elevation -MSL (m)	Moisture Content (%)	
		0 - 0.03 m	0.03 - 0.10 m
Site 1	2.0	3.28	4.44
	1.5	8.33	11.24
	1.0	16.18	15.00
	0.5	15.58	14.81
Site 2	1.5	5.58	6.69
	1.0	14.72	15.78
	0.5	15.93	18.57
	0.25	17.87	16.30
Site 3	0.25	18.02	18.96
	0	18.51	17.75
	-0.25	17.70	16.08

Moisture content in the bottom of the core at the toe of the seawall at Site 2 is much lower (6.69%) compared to moisture content at a similar elevation at Site 1

(14.81%) at low tide. The moisture content values at Site 3 are all relatively high where the toe of the seawall inundated by wave and swash action for the majority of the tidal cycle, not allowing the beach to drain.

4.1.6 Time of Inundation at Cliffwood Beach

The period of inundation due to waves and tide was estimated for each sampling station at all sites and is presented in Table 7. At similar elevations (1.0 m and 0.5 m MSL), inundation times are longer at Site 1, 360 min. and 495 min., compared to Site 2, 280 min. and 390 min. At 0.25 m (MSL), inundation times are similar at Site 2 and Site 3, at 510 min. and 495 min., respectively.

Table 7: Period of inundation for the intertidal zone over a spring tidal cycle.

Location	Elevation -MSL (m)	Inundation time (min.)
Site 1	2.0	10
	1.5	180
	1.0	360
	0.5	495
Site 2	1.5	80
	1.0	280
	0.5	390
	0.25	510
Site 3	0.25	495
	0	555
	-0.25	645

4.1.7 Beach Slope at Cliffwood Beach

Beach slopes, measured at each sampling station, are presented in Table 8. At Site 1, the average slope of the transect is 4.0 °; the flattest area is at the location on the profile that was under the swash zone at high water. The steepest slope was located immediately bayward of the location of the breakers at high water (Figure 5). At Site 2 the average slope is 4.5°, the steepest slope was at the toe of the seawall in the region of the swash zone at high water. At Site 3 the average slope of the transect was 6.0 °. The steepest slopes for all sites are 7.7 ° and 6.6 °, located 1.4 m and 3.0 m, bayward from the toe of the seawall at Site 3.

Table 8: Slope values at each sampling station for Cliffwood Beach.

Location	Elevation -MSL (m)	Slope (°)
Site 1	2.0	2.6
	1.5	5.6
	1.0	3.1
	0.5	4.6
Site 2	1.5	5.0
	1.0	4.2
	0.5	3.8
	0.25	5.0
Site 3	0.25	7.7
	0	6.6
	-0.25	3.7

4.1.8 Analysis of Data from Cliffwood Beach

4.1.8.1 Spatial Analysis: The results of the ANOVA (Table 9) indicate that there is not a significant difference in meiofaunal densities within the top portion of the core between sites at the 95 % confidence level, where the critical value is 7.71. There is a 87 % probability, however, that Sites 1 and 2 are significantly different at 1.5 m relative to MSL. The sampling station at Site 2 with an elevation of 1.5 m relative to MSL is located at the toe of the seawall.

For the bottom of the core, there is a significant difference, at the 99 % confidence level where the critical value is 16.0, at an elevation of 1.5 m between Sites 1 and 2. At the 90 % confidence level, there is a difference between Sites 1 and 2 at an elevation of 0.50 m relative to mean sea level.

Table 9: ANOVA results of meiofaunal density and beach elevation for Cliffwood Beach.

Elevation -MSL	Sites	0.0-0.03 m			0.03-10.0 m		
(m)		d.f.	F Ratio	F Prob	d.f.	F Ratio	F Prob
1.5	1, 2	1, 4	3.67	0.13	1, 4	19.71	0.01
1.0	1, 2	1, 4	0.05	0.83	1, 4	0.04	0.86
0.5	1, 2	1, 3	0.07	0.81	1, 4	6.72	0.06
0.25	1, 3	1, 4	0.61	0.48	1, 4	1.37	0.31

4.1.8.2 Correlation: The results of the correlation between meiofaunal densities for all samples and the physical attributes are shown in Table 10 and scatter plots for significant correlations are shown in Figure 9. For the top 0.03 m of the core, there exists a

significant positive correlation at the 95 % confidence interval (r = 0.40), between mean grain size and meiofaunal density but there is significant scatter (Figure 9). There also exists a positive correlation at the 90% confidence interval (r = 0.30), between sorting and meiofaunal density in the top portion of the core. Again, the scatter plots show significant scatter (Figure 9). In the bottom portion of the core, there is a negative correlation at the 95% confidence interval (r = -0.40), between moisture content and meiofaunal density. The correlation results indicate a significant relationship between some physical variables and meiofaunal density, however, the scatter plots demonstrate a lack of a strong linear association.

Table 10: Correlation results of meiofaunal density and physical attributes, Cliffwood Beach.

Depth (m)	Grain Size		Sorting		Moisture Content		Activation		Slope	
	r	p	r	p	r	p	r	p	r	p
0-0.03	0.40	0.02	0.30	0.10	0.11	0.56	0.07	0.69	-0.29	0.11
0.031-0.10	0.15	0.40	0.21	0.25	-0.40	0.02	-0.26	0.14	0.09	0.60

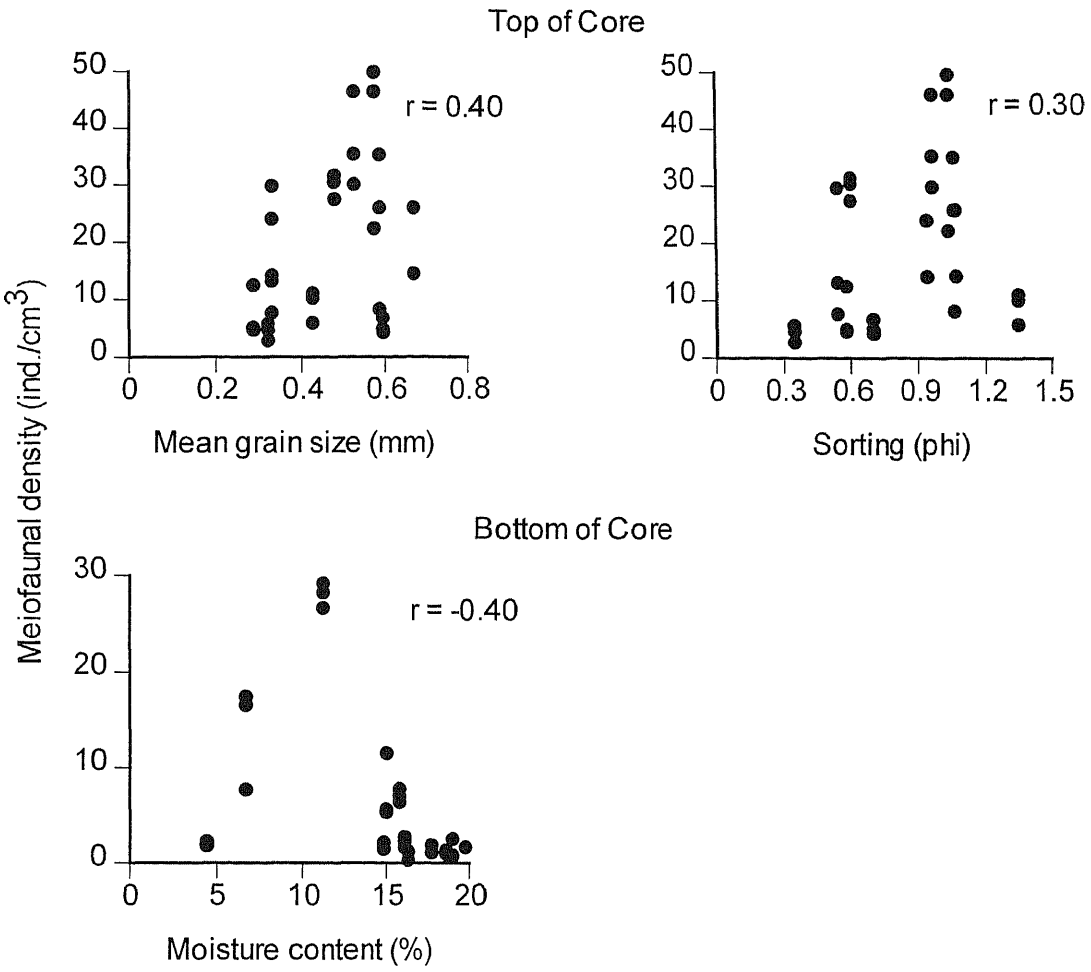

Figure 9: Scatter plots for significant correlations at Cliffwood Beach.

4.1.8.3 Surf-Scaling Parameter: The surf-scaling parameter is presented in Table 11. At Site 1, the surf-scaling parameter equals 1.2, suggesting strong reflection. Reflection increases longshore and at Sites 2 and 3, backed by the seawall, complete reflection occurred, where $\in$ equals 0.9 and 0.5, respectively.

Table 11: Surf-scaling parameter, $\in$, at Cliffwood Beach.

Site	Amplitude, a_b (m)	Wave period, T (s)	Slope, β (°)	$\in$
1	0.07	7.0	4.0	1.2
2	0.07	7.0	4.5	0.9
3	0.07	7.0	6.0	0.5

4.1.8.4 Sediment Mixing Depths: Sediment mixing depths are presented in Table 12. For all sites, the sediment mixing depth based on the significant wave breaking height (0.14 m) is 0.021 based on the results found for a meso-tidal estuary (Jackson and Nordstrom 1993) (Table 12). Average depth of sediment activation ranges from 0.011 m at Site 2 to a maximum of 0.015 m at Site 3, with the seawall located at a lower elevation on the profile.

Table 12: Measured and calculated ($\overline{Z}$) at Cliffwood Beach.

Location	Averaged measured activation $\overline{Z}$ (m)	Averaged calculated activation $\overline{Z} = 0.15H_b$ (m)
Site 1	0.013	0.021
Site 2	0.011	0.021
Site 3	0.015	0.021

4.1.8.5 Permeability: Permeability values are presented in Table 13. At Cliffwood Beach permeability increases with distance from the upper limit of swash at high water at Site 1 for the top and bottom of the cores (Table 13). At Site 2, the beach profile is at a

lower elevation fronting the seawall causing a shift in permeability values on the lower foreshore. Permeability increases with distance from the seawall and then decreases on the lower foreshore for the top and the bottom locations. At Site 3 the shift is more pronounced, and permeability is lowest at the sampling site at the lowest elevation.

Table 13: Permeability (k) of sediments at Cliffwood Beach.

Location	Elevation -MSL (m)	k (m^2)	
		0-0.03 m	0.031-0.10m
Site 1	2.0	1.2×10^{-10}	1.5×10^{-10}
	1.5	3.8×10^{-10}	7.1×10^{-10}
	1.0	7.2×10^{-10}	7.1×10^{-10}
	0.5	1.0×10^{-9}	7.1×10^{-10}
Site 2	1.5	1.7×10^{-10}	1.9×10^{-10}
	1.0	9.5×10^{-10}	3.6×10^{-10}
	0.5	1.0×10^{-9}	4.3×10^{-10}
	0.25	6.5×10^{-10}	6.8×10^{-10}
Site 3	0.25	1.3×10^{-10}	2.0×10^{-10}
	0	8.1×10^{-10}	2.8×10^{-10}
	-0.25	2.8×10^{-10}	1.2×10^{-10}

4.2 Keyport Harbor

4.2.1 Average Meiofaunal Density and Type at Keyport Harbor

Figure 10 presents average meiofaunal densities cross-shore for each transect and longshore at similar elevations relative to mean sea level. Standard deviations are shown in parentheses for the top and the bottom of the core samples. The coefficient of variation ($\sigma/\bar{x}$), for the top of the core, ranges from 0.04, 6.0 m bayward of the bulkhead at Site 1, to 0.52, on the upper foreshore at Site 2, with an average of 0.24. The results for the bottom of the core, show a coefficient of variation from 0.08, on the upper foreshore at Site 2, to 1.10, at the base of the bulkhead at Site 1, with an average of 0.32.

Densities are greater in the top 0.03 m than the bottom 0.07 m of core samples. The average of all the densities for the top of the core is 11.9 ind. cm^{-3} with a standard deviation of 2.7 and the average of all densities for the bottom of the core is 8.6 ind. cm^{-3} with a standard deviation of 1.9. An average of 44.1 % of the total meiofauna are found in the top 0.03 m of the cores. At each site, the percent of meiofauna located in the top of the core, increases in the bayward direction, ranging from 21.3% landward of wave breaking at high water to 83.1% on the lower foreshore at Site 2.

Sites 1 and 3, both fronted by bulkheads, show a similar cross-shore pattern of meiofaunal distribution. There is a low average density at the base of the bulkhead and an increase in density in the bayward direction. At the lowest elevation on the profile, densities are relatively low. Site 2, the control site, shows a decrease in average density bayward from the upper limit of swash at high water. The largest densities are located at

the highest elevation at Site 2 in the location of the swash zone at high water, and the lowest are found at the lowest elevation at Site 1.

Nematodes account for 93.0 % and 74.0 % of the meiofauna for the top and bottom of the cores, respectively (Table 14). Copepods make up 2.5 % of the top of the cores and 12.0 % of the bottom of the cores. Other types of meiofauna account for 4.4% of the top of the cores and 5.4% for the bottom of the cores. There exists more variety in the type of meiofauna found at Keyport Harbor compared to Cliffwood Beach. Variety is higher at Site 2 where there is no beach armoring and at sampling stations that are at least 3.0 m bayward of the bulkheads at Sites 1 and 3, where sediment activation is lower due to less interaction between waves and the structure.

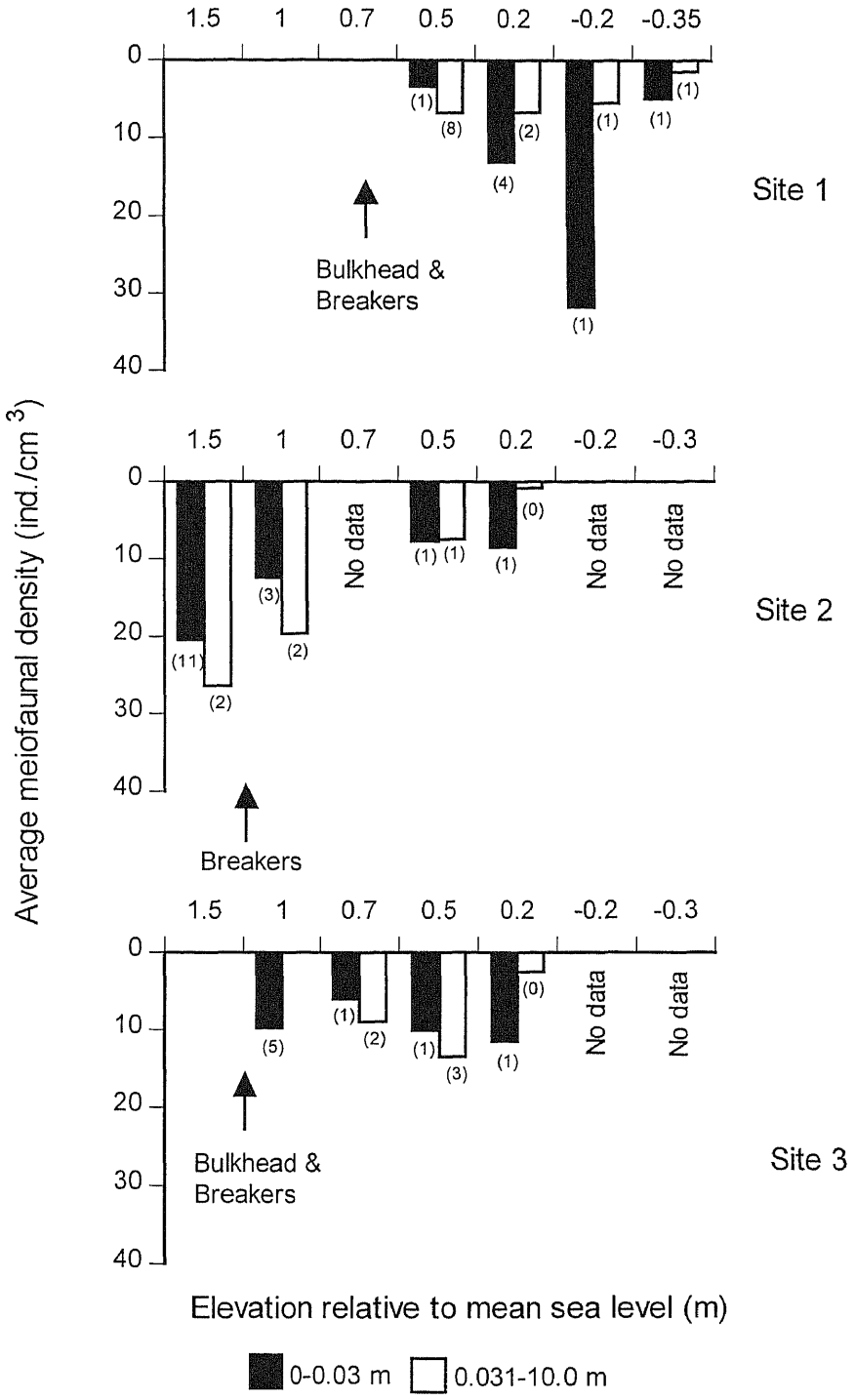

Figure 10: Average meiofaunal densities (ind. cm^{-3}) relative to mean sea level (m) at Keyport Harbor, September 21, 1997. Breakers represent location at high water. Standard deviations are in parentheses for top and bottom of the core.

Table 14: Classification of meiofauna by type at Keyport Harbor.

Location	Elevation -MSL (m)	Nematoda		Copepoda		Other	
		Top	Bottom	Top	Bottom	Top	Bottom
Site 1	0.5	63	460	1	42	3	4
	0.2	229	240	15	42	0	0
	-0.2	401	130	14	11	14	12
	-0.35	74	7	0	0	0	0
Site 2	1.5	126	672	0	0	0	288
	1.0	147	461	0	256	0	15
	0.5	101	142	18	100	16	21
	0.2	123	12	0	0	3	0
Site 3	1.0	75	n/a	0	n/a	2	n/a
	0.7	99	199	0	49	7	8
	0.5	129	312	43	99	9	17
	0.2	165	93	4	0	16	3

4.2.2 Site Characteristics at Keyport Harbor

Strong onshore winds from the northwest persisted over the tidal cycle. Table 15 presents hourly data on water and sand temperature, wave height and period, and swash width. Mid-day air temperature was 17.3 °C. Water temperature increased over the tidal cycle with a low of 15.3 °C in the morning at Site 3, increasing to a high of 19.8 °C. Sand temperature followed a similar pattern to water temperature changes with a low of 14.2 °C, at 8:09 and a high of 20.2 °C at 14:06. Water salinity from the samples taken, at mid-rising and mid-falling tide, was 23 ‰.

Table 15: Hourly visual site observations during the tidal cycle at Keyport Harbor on September 21, 1997.

Site	Time	Water temp. (°C)	Sand temp. (°C)	Significant Wave height (m)	Wave period (s)	Swash width (m)
1	08:03	15.3	14.5	0.24	1.6	4.5
	09:03	15.7	15.3	0.22	1.8	1.5
	10:03	waves	breaking	on	bulkhead	3.0
	11:03	waves	breaking	on	bulkhead	0.0
	12:03	waves	breaking	on	bulkhead	0.0
	13:03	waves	breaking	on	bulkhead	0.0
	14:03	waves	breaking	on	bulkhead	0.0
	15:33	19.6	18.8	0.18	1.6	0.0
	16:10	19.5	18.9	0.10	1.9	2.0
	17:01	19.3	19.1	0.08	1.7	2.5
2	08:09	15.3	14.2	0.24	1.7	6.0
	09:06	15.2	16.0	0.27	1.9	4.0
	09:50	16.1	15.2	0.22	2.1	5.0
	10:55	17.2	18.0	0.24	2.2	4.0
	12:03	18.6	19.0	0.18	1.7	4.0
	13:19	18.8	20.0	0.22	1.8	5.0
	14:02	19.1	19.1	0.16	1.8	3.0
	15:06	19.1	18.4	0.19	2.0	4.0
	16:05	19.5	19.4	0.13	1.6	5.0
	17:06	19.1	19.7	0.08	1.8	2.0
3	08:13	14.8	14.6	0.26	1.8	4.0
	09:09	15.1	15.6	0.22	1.8	4.0
	09:54	16.1	16.0	0.21	2.3	5.0
	10:53	18.0	n.d.	0.22	1.8	4.0
	11:55	waves	breaking	on	bulkhead	0.0
	12:55	waves	breaking	on	bulkhead	0.0
	14:06	19.3	20.2	0.16	1.9	2.5
	14:55	19.4	19.3	0.21	1.9	4.0
	15:57	19.8	19.7	0.11	1.7	2.0
	17:10	19.4	19.6	0.08	1.9	2.0

Visual breaking wave height was between 0.08 m and 0.27 m on the foreshore. The lowest and the highest waves were breaking at Site 3. Visual wave periods ranged from 1.6 s to 2.3 s, at Site 1 and Site 3, respectively. Swash widths were less than 6.0 m at all sites. Waves were breaking at the toe of the bulkhead at Site 1 and 3 during high water. Wave breaking occurred on the base of the bulkhead at Site 1 beginning 2.5 hrs after low water on rising tide and ending 2.5 hrs before low water on the falling tide.

Changes in water depth, wave height, and wave period on the low tide terrace over the tidal cycle from data gathered with the pressure transducer presented in Figure 11. Significant wave heights ranged from 0.08 m at high water to 0.27 m during rising tide. Wave periods recorded on the low tide terrace are similar to the visual estimates of 2.0 s (0.5 hz). Figure 12 presents the spectral estimate from data gathered near high water (12:15). The locally generated wave has a peak frequency of 0.47 hz (2.1 s).

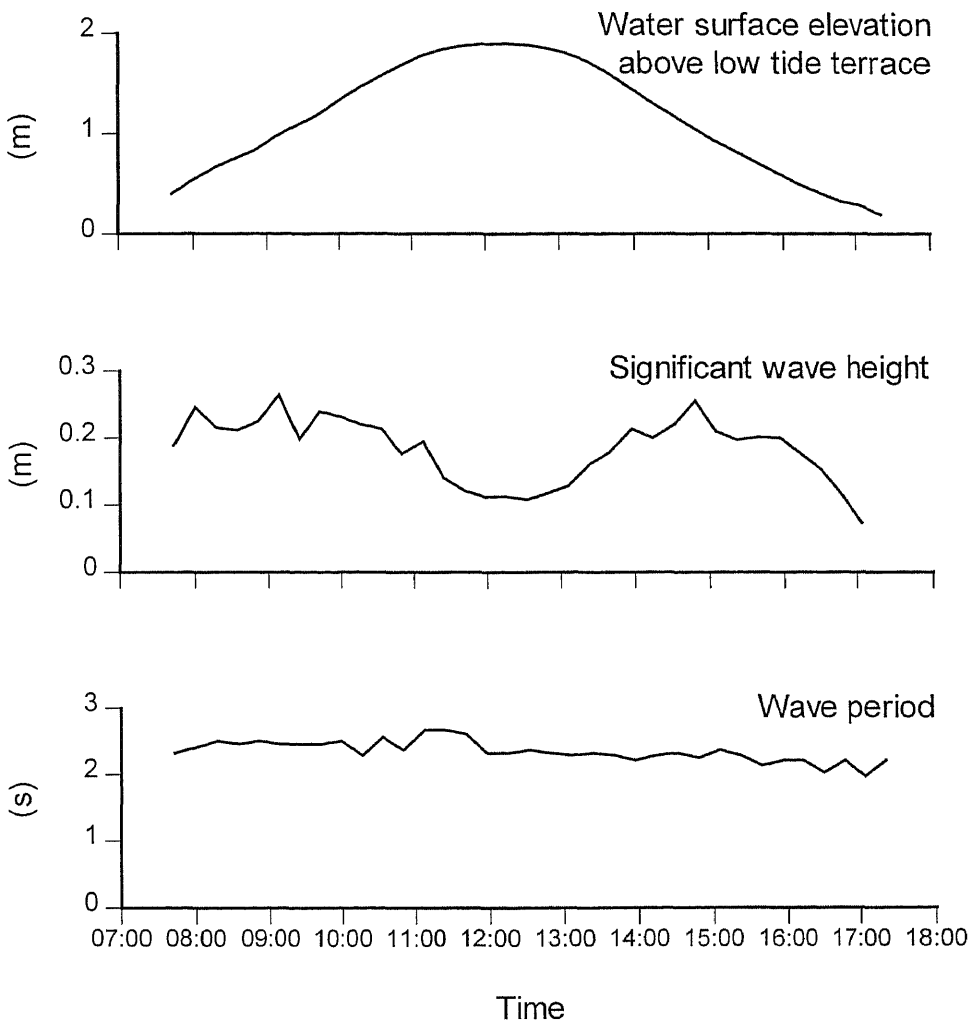

Figure 11: Changes in water depth, wave height, and wave period over a tidal cycle at Keyport Harbor, September 21, 1997.

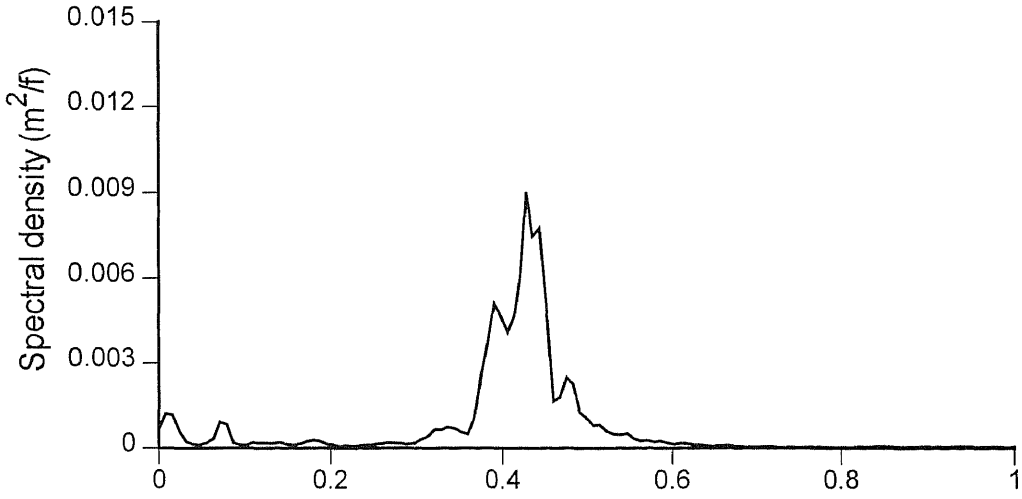

Figure 12: Spectral estimate of pressure transducer data gathered at high water (12:15).

4.2.3 Sediment Characteristics at Keyport Harbor

4.2.3.1 Top of Core: Mean grain size at the top 0.03 m of the sediment core samples is in the range of fine to coarse sand (Table 16). At Site 1, the finest sediments (0.36 mm) are found at -0.20 m relative to MSL and the coarsest (0.80 mm) are found at the lower foreshore. The sediments are more poorly sorted, from 0.57 ϕ to 1.79 ϕ in the bayward direction. At Site 2, mean grain size generally decreases, from coarse sand (0.58 - 0.65 mm) to fine sand (0.19 mm) at the lower foreshore. The sorting coefficient increases from 0.68 ϕ to 0.85 ϕ in the bayward direction. At Site 3, mean grain size increases from 0.40 to 0.67 mm and the sediments change from well sorted to poorly sorted, in the bayward direction.

Mean grain size for the sediments at the toe of the wall is finer at Site 3 at an elevation of 1.0 m MSL than at Site 2 at an elevation of 1.0 m MSL. Mean grain sizes are considerably finer on the lower foreshore at Site 2 (0.20 m MSL) compared to mean

grain size at the same elevation at Site 1, 3.0 m bayward of the bulkhead, and Site 3, 15.0 m from the bulkhead. That is, at an elevation of 0.20 m relative to mean sea level, mean grain size is 0.19 mm at Site 2, 0.67mm at Site 1, and 0.56 mm at Site 3. Sediment sorting increases in the bayward direction at all sites, however, at Site 2, the sorting coefficient ranges from moderately well sorted to moderately sorted, and for Sites 1 and 3, the range is from well sorted to poorly sorted.

Table 16: Sediment characteristics for the top of the core at Keyport Harbor.

Location	Elevation -MSL (m)	Mean Grain Size (mm)	Mean Grain Size (ϕ)	Sorting (ϕ)
Site 1	0.50	0.47	1.08	0.57
	0.20	0.67	0.58	1.32
	-0.20	0.36	1.48	1.21
	-0.35	0.80	0.33	1.79
Site 2	1.50	0.58	0.78	0.68
	1.00	0.65	0.62	0.75
	0.50	0.48	1.07	0.84
	0.20	0.19	2.42	0.85
Site 3	1.00	0.40	1.32	0.47
	0.70	0.41	1.28	0.59
	0.50	0.67	0.58	0.88
	0.20	0.56	0.83	1.11

4.2.3.2 Bottom of Core: Mean grain size of the bottom 0.07 m of the cores is in the range of fine to coarse sand (Table 17). Mean grain size at Site 1 decreases in the bayward direction from 0.89 mm to 0.57 mm. However, immediately in front of the bulkhead (0.50 m MSL), grain size is finer at 0.54 mm and moderately sorted (0.87 ϕ).

Sediments are moderately sorted at the upper and lower foreshore but poorly sorted at mid-foreshore, with a maximum of 1.60 ϕ. At Site 2, mean grain size increases from 0.61 to 0.85 mm and sorting increases from 0.59 ϕ to 0.95 ϕ, in the bayward direction. At the lowest elevation (0.20 m MSL), mean grain size is fine (0.23 mm) and the sediments are moderately well sorted. At Site 3, the sediment characteristics for the bottom of the core at the base of the seawall are unavailable because the stratum was too hard to penetrate due to the presence of rubble at the toe of the wall. Mean grain size at 5.0 and 15.0 m from the bulkhead are classified as medium and moderately well sorted and at 10.0 m bayward from the structure, the sand is coarse and moderately sorted.

The most poorly sorted sand is found at Site 1, 6.0 m bayward of the bulkhead. The most well sorted sand is located at Site 3, 5.0 m from the bulkhead. Mean grain sizes are considerably finer at the bottom of the profile at Site 2 compared to mean grain size at a similar elevation at Site 1, 3.0 m bayward of the bulkhead, and Site 3, 15.0 m from the bulkhead. That is, at 0.20 m relative to mean sea level, mean grain size is 0.23 mm at Site 2, 0.89 mm at Site 1, and 0.44 mm at Site 3.

Table 17: Sediment characteristics of the bottom of the core at Keyport Harbor.

Location	Elevation -MSL (m)	Mean Grain Size (mm)	Mean Grain Size (ϕ)	Sorting (ϕ)
Site 1	0.50	0.54	0.88	0.87
	0.20	0.89	0.17	1.30
	-0.20	0.87	0.20	1.60
	-0.35	0.57	0.80	0.98
Site 2	1.50	0.61	0.72	0.84
	1.00	0.61	0.72	0.89
	0.50	0.85	0.23	1.15
	0.20	0.23	2.15	1.17
Site 3	1.00	n.d.	n.d*	n.d.*
	0.70	0.44	1.17	0.55
	0.50	0.72	0.48	0.95
	0.20	0.44	1.17	0.75

* Stratum too hard to penetrate due to the presence of the wall

4.2.4 Depth of Sediment Activation at Keyport Harbor

Depth of sediment activation and net change were recorded for Keyport Harbor (Figure 13). Maximum sediment activation occurred at 0.50 m above mean sea level, immediately in front of the wooden bulkhead at Site 1, Keyport Harbor (0.23 m). At Site 2, maximum sediment disturbance occurred at a distance of 25.0 m bayward from the upper limit of swash and just bayward of the breakers at high water. At Site 3, maximum sediment activation was located 10.0 m from the base of the cement bulkhead.

Net change did not exceed 0.08 m at Site 1, and 0.02 m at Sites 2 and 3. At Site 1, net change indicates erosion of the upper foreshore and minimal change at the lower foreshore. At Site 2, sediment deposition occurred at the upper foreshore in the zone of

wave swash at high water and on the lower foreshore near the break in slope and erosion occurred at mid-foreshore. At Site 3, maximum net change occurred at mid-foreshore.

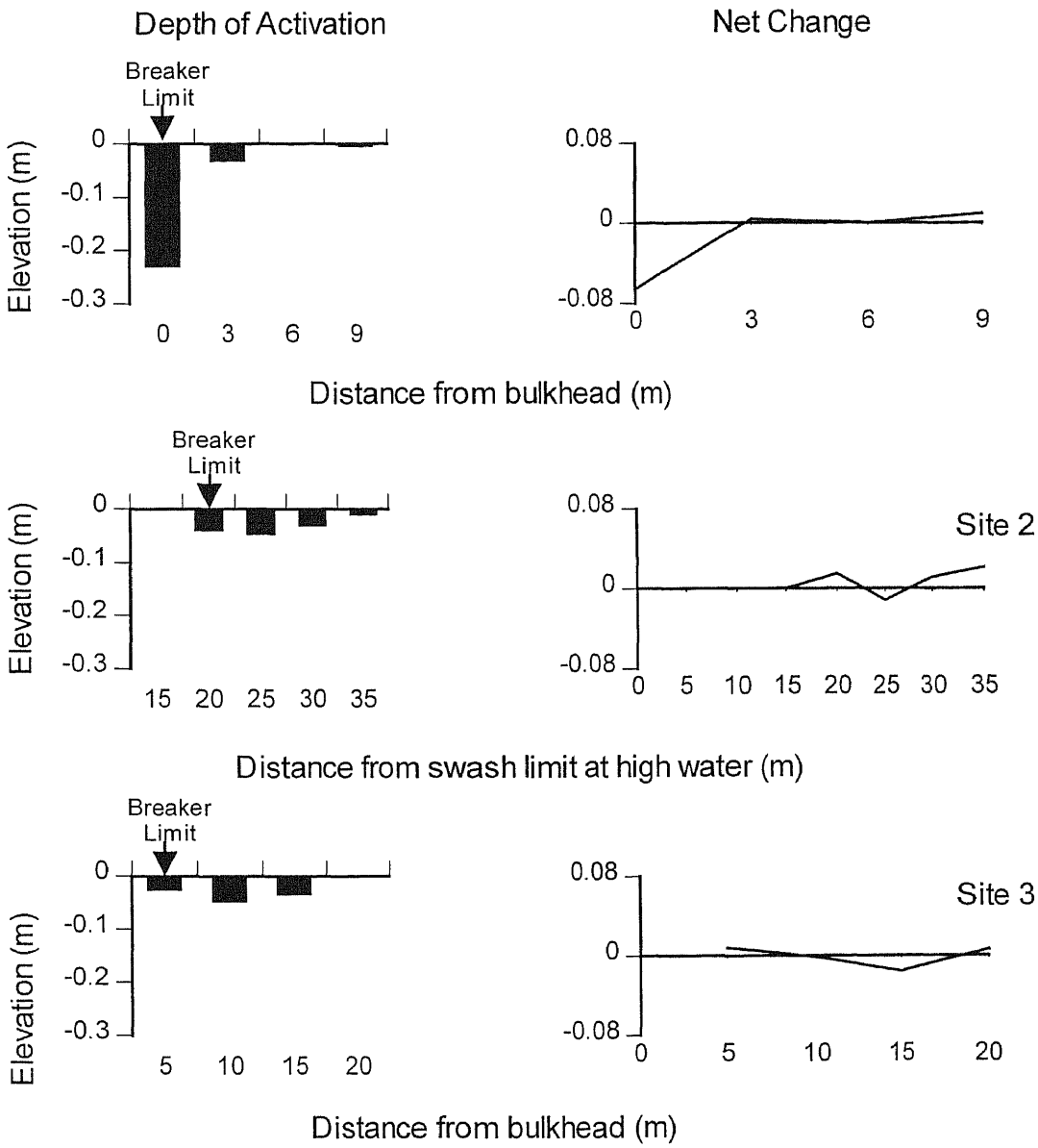

Figure 13: Depth of activation and net change at Keyport Harbor.

4.2.5 Moisture Content at Keyport Harbor

Moisture content is presented in Table 17. Results from the top core samples indicate that the lowest moisture content (1.74 %) occurred at 1.00 m above MSL where there was rubble at the toe of the wall at Site 3 and the highest value (31.80 %) was located at 0.20 m above MSL, at Site 2. For the bottom core samples, the lowest value (5.74 %) occurred at 0.70 m above MSL at Site 3 and the highest value (23.41 %) occurred at 0.20 m above MSL, at Site 2.

Moisture content in the top of the core at the bottom of the profile at Site 2 is much higher (31.80%) compared to moisture content at a similar elevation at Site 1 (16.97%) and Site 3 (16.05%). Moisture content in the bottom of the core at 0.20 m above mean sea level at Site 2 is higher compared to moisture content values at similar elevations at Sites 1 and 3.

Table 18: Moisture content for the top and bottom of the core, Keyport Harbor.

Location	Elevation -MSL (m)	Moisture Content (%)	
		0 - 0.03 m	0.03 - 0.10 m
Site 1	0.50	2.33	8.93
	0.20	16.97	16.92
	-0.20	15.15	21.21
	-0.35	12.93	15.38
Site 2	1.50	3.83	7.07
	1.00	9.16	12.74
	0.50	18.72	17.58
	0.20	31.80	23.41
Site 3	1.00	1.74	n/a
	0.70	4.89	5.74
	0.50	7.66	10.56
	0.20	16.05	19.27

4.2.6 Time of Inundation at Keyport Harbor

The period of inundation due to waves and tide was estimated for each sampling station and is presented in Table 19. Inundation times are similar between sites at the same elevation. At an elevation of 1.0 m (MSL), inundation times are 210 min. (Site 2) and 150 min. (Site 3). At an elevation of 0.5 m (MSL), inundation times are 380 min. (Site 1), 350 min. (Site 2), and 370 min. (Site 3). At an elevation of 0.20 m, inundation times are 480 min. (Site 1), 540 min. (Site 2) and 510 min. (Site 3).

Table 19: Period of inundation for the intertidal zone over a spring tidal cycle.

Location	Elevation -MSL (m)	Inundation time (min.)
Site 1	0.50	380
	0.20	480
	-0.20	550
	-0.35	670
Site 2	1.50	5
	1.00	210
	0.50	350
	0.20	540
Site 3	1.00	150
	0.70	290
	0.50	370
	0.20	510

4.2.7 Beach Slope at Keyport Harbor

Beach slopes measured at each sampling station are presented in Table 20. At Site 1, the average slope was 6.0° and local slope values range from 6.3° near the bulkhead to 4.8°

on the lower foreshore. At Site 2, the average beach slope was 6.2° with slopes ranging from 5.8° to 6.7°. At Site 3, the average slope (4.0°), is lower than the other sites and ranged from 2.9° to 4.7°.

Table 20: Slope values at each sampling station for Keyport Harbor.

Location	Elevation -MSL (m)	Slope (°)
Site 1	0.50	6.4
	0.20	6.3
	-0.20	6.7
	-0.35	4.8
Site 2	1.50	6.2
	1.00	5.8
	0.50	6.7
	0.20	6.2
Site 3	1.00	n/a
	0.70	2.9
	0.50	4.7
	0.20	4.4

4.2.8 Analysis of Data from Keyport Harbor

4.2.8.1 Spatial Analysis: The results of the ANOVA (Table 21) indicate that there is a significant difference between sites at an elevation of 0.5 m (MSL) for the top of the cores. A Tukey HSD test between sites indicates significant differences in meiofaunal densities at the 95% confidence level between all sites. No differences in meiofaunal densities were found between sites at elevations 1.1 m and 0.2 m relative to mean sea

level in the top 0.03 m of the cores. No differences were found between sites in the bottom 0.07 m of the core at all elevations.

Table 21: ANOVA results of meiofaunal density and beach elevation for Keyport Harbor.

Elevation -MSL (m)	d.f.	Sites	0.0-0.03 m		0.031-10.0 m	
			F Ratio	F Prob	F Ratio	F Prob
1.0	1, 4	2, 3	0.57	0.49	n/a	n/a
0.5	2, 6	1, 2, 3	37.05	0.00	1.94	0.22
0.2	2, 6	1, 2, 3	3.32	0.11	2.46	0.17

4.2.8.2 Correlation: The results of the correlation between meiofaunal densities and the physical attributes are shown in Table 22 and scatter plots for significant correlations are shown in Figure 10. For the top 0.03 m of the core, there exists a negative correlation at the 95 % confidence level (r = -0.43), between depth of sediment activation and meiofaunal density with significant scatter in the plot of these two variables (Figure 10). There is also significant scatter but a positive correlation at the 95 % confidence level (r = 0.36), between beach slope and meiofaunal density. In the bottom portion of the core, there is a negative correlation at the 99 % confidence level (r = -0.59), between moisture content and meiofaunal density. There also exists a negative correlation at the 90 % confidence level (r = -0.31) between sorting and meiofaunal density. Both correlations demonstrating significant scatter. The correlation results indicate a significant relationship between the variables, however, the scatter plots demonstrate a lack of a strong linear association.

Table 22: Correlation results of meiofaunal density and physical attributes, Keyport Harbor.

Depth (m)	Grain Size		Sorting		Moisture Content		Activation		Slope	
	r	p	r	p	r	p	r	p	r	p
0-0.03	-0.11	0.52	0.16	0.35	0.06	0.74	-0.43	0.02	0.36	0.04
0.031-0.10	0.15	0.40	-0.31	0.08	-0.59	0.00	-0.18	0.34	0.05	0.79

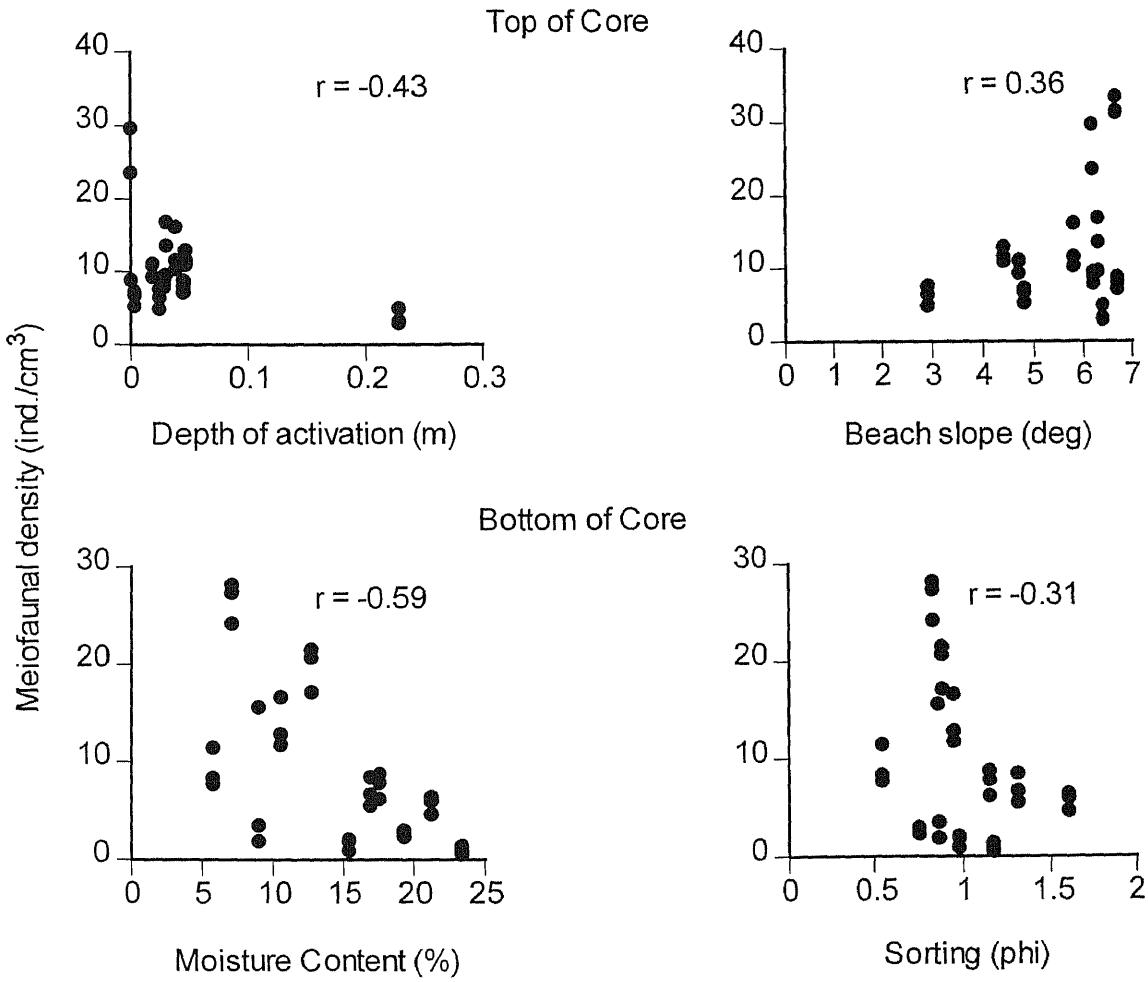

Figure 14: Scatter plots for significant correlations at Keyport Harbor.

4.2.8.3 Surf-Scaling Parameter: The surf-scaling parameter is presented in Table 23.

At Sites 1 and 2, the surf-scaling parameter is 6.6 and 7.3, and is classified as an

intermediate beach state. At Site 3, the surf-scaling parameter is significantly higher than the other sites, and equals 16.8, an intermediate beach state but more dissipative compared to the other sites.

Table 23: Surf-scaling parameter, $\in$, at Keyport Habor.

Site	Amplitude, a_b (m)	Wave Period, T (s)	Slope, β (°)	$\in$
1	0.08	2.1	6.0	6.6
2	0.095	2.1	6.2	7.3
3	0.09	2.1	4.0	16.8

4.2.8.4 Sediment Mixing Depths: Sediment mixing depths are presented in Table 24. At Site 1, based on an average significant wave breaking height of 0.16 m, estimated $\bar{Z}$ value for a meso-tidal estuary is 0.024 (Jackson and Nordstrom 1993). The average depth of sediment activation was found to be significantly higher at 0. 088 m. At Site 2, significant wave height was 0.19 m and average depth of sediment activation, 0.024 m was found to be close to calculated. At Site 3, average depth of sediment activation was 0.025 m.

Table 24: Measured and calculated $\bar{Z}$ at Keyport Harbor.

Location	Averaged measured activation $\bar{Z}$ (m)	Averaged calculated activation $\bar{Z} = 0.15H_b$ (m)
Site 1	0.088	0.024
Site 2	0.024	0.029
Site 3	0.025	0.027

4.2.8.5 Permeability: The permeability values are presented in Table 25. At Keyport Harbor, at 0.50 m relative to mean sea level, permeability values are lowest at Site 3 (1.0 x 10^{-9} m^2) and highest at Site 2 (5.2 x 10^{-10} m^2), the control site. A comparison of the sampling stations at 0.20 m relative to mean sea level, permeability values are equal (1.0 x 10^{-9} m^2) at Site 1, 3.0 m bayward of the bulkhead and at Site 3, 15.0 m bayward of the toe of the seawall. These values are greater than at Site 2, the control site, where k = 8.2 x 10^{-11} m^2 (Table 25).

Table 25: Permeability (k) of sediments at Keyport Harbor.

Location	Elevation -MSL (m)	k (m^2)	
		0-0.03 m	0.031-0.10m
Site 1	0.50	3.5 x 10^{-10}	6.8 x 10^{-10}
	0.20	1.0 x 10^{-9}	3.0 x 10^{-9}
	-0.20	4.7 x 10^{-10}	4.0 x 10^{-9}
	-0.35	5.0 x 10^{-9}	8.8 x 10^{-10}
Site 2	1.50	6.1 x 10^{-10}	8.4 x 10^{-10}
	1.00	8.5 x 10^{-10}	3.3 x 10^{-10}
	0.50	5.2 x 10^{-10}	2.0 x 10^{-9}
	0.20	8.2 x 10^{-11}	1.8 x 10^{-10}
Site 3	1.00	2.2 x 10^{-10}	n/a
	0.70	2.7 x 10^{-10}	3.0 x 10^{-10}
	0.50	1.0 x 10^{-9}	1.0 x 10^{-9}
	0.20	1.0 x 10^{-9}	3.9 x 10^{-10}

4.3 Summary of Results

Data gathered suggests the following relationships between meiofaunal, wave, and beach characteristics at sites where shore-parallel armoring is present and at sites where no shore-parallel armoring is present:

1. Sediments are finer and well sorted immediately fronting a structure.
2. Moisture content is lower fronting a structure compared to the control site at a similar elevation.
3. Beach slopes are steeper at sites fronting shore-parallel armoring.
4. Beach elevation fronting structures is lower than at the control sites at similar horizontal distance from the break in slope.
5. Depth of sediment activation increases in front of structures under high wave energies.
6. Meiofaunal densities increase with distance from structures.

CHAPTER 5

DISCUSSION

5.1 Meiofaunal Density, Zonation, and Type

Meiofaunal density varies depending on habitat attributes and location. A review by McIntyre (1969) reports limits in meiofaunal density between 30 and 30,000 ind. 10 cm^{-2}. Higgins and Thiel (1988) provide an updated summary of meiofauna density (ind. 10 cm^{-2}) for marine intertidal sand habitat. Total meiofaunal densities range from a minimum of 125 to 896 (ind. 10 cm^{-2}) in Delaware, USA (Hummon et al. 1976) to a maximum of 2270 to 6116 (ind. 10 cm^{-2}) in India (Ansari and Ingole 1983). At Cliffwood Beach densities range from 1 to 309 (ind. 10 cm^{-2}) at Site 1, and at Keyport Harbor, densities range from 2 to 207 (ind. 10 cm^{-2}) at Site 2. Meiofaunal densities from the two estuarine sites are less than previous studies perhaps due to a relatively small intertidal profile and the pollution associated with an urban estuary. Comparison of results is complicated by differences in sampling design where there is no vertical control on sampling location. The results of my study indicate that cross-shore differences of 7.5 m on the foreshore can result in differences of 170 ind. 10 cm^{-2} at sites without shore-parallel armoring.

The majority of fauna is found in the upper 0.02 m of sediment (Higgins and Thiel 1988) but in some sandy beaches organisms can live at depths greater than 0.10 m (Haefner 1996). Vertical zonation is usually controlled by the boundary between aerobic and anaerobic sediments and the primary factor is oxygen availability (Higgins and Thiel 1988). The greatest oxygen availability is found in the top layers of the sand surface, where the beach matrix is less saturated, and oxygen availability decreases bayward and

at depth with increasing saturation of the beach matrix. The result is a greater concentration of meiofauna within the top few centimeters.

At Site 1, Cliffwood Beach, just landward of wave breaking at high water, 31.2 % of the meiofauna were found within 0.03 m of the sand surface. The percentage increases to 82.7 % on the lower foreshore. At sites 2 and 3, meiofaunal densities at the top of core are higher and account for 69.3 % to 88.7 % of the entire core. At Site 1, Keyport Harbor, just landward of wave breaking at high water, 21.3 % of the meiofauna were found within 0.03 m of the sand surface. The percentage increases to 83.1 % on the lower foreshore. At Sites 2 and 3, meiofaunal densities found within the top 0.03 m follow a similar pattern compared to Site 1. Results of my investigation reveal that the majority of fauna in the top 0.03 m of sediment is spatially dependent.

Fegley (1987) found density of Nematodes within the top 0.01m of sediment to decrease with increasing current speeds after erosion of 5.0 mm of sediments. Pre- and post sampling was not part of this study but comparison of abundance in front of the bulkhead at Site 1 in Keyport and at similar elevation at Site 2 (with no structure) reveals greater abundances at Site 2. Grain size is similar and sorting is better at Site 1, therefore suggesting that higher current speeds caused by reflection at the bulkhead influences densities.

Nematoda regularly dominate the meiofauna in sand matrices, comprising from more than 50% of the total (Higgins and Thiel 1988) to 90-95 % of all individuals (Giere 1993). Copepoda are usually second in abundance but in terms of biomass they are often the most important and may dominate in some coarse grained sediments (Higgins and Thiel 1988). At Cliffwood Beach, nematodes account for 84.7 % of the meiofauna in the

top and bottom of the core for all sites and sampling stations. At Keyport Harbor, nematodes account for 93.0 % and 74.0 % of the meiofauna for the top and bottom of the cores, respectively. Communities of Nematodes and their diversity seem largely determined by sediment structure (Giere 1993). Every type of sediment is colonized by nematodes, from almost dry sand dune to heavy surf beach sand, coarse shell sublittoral grounds, and cold arctic waters to hot springs (Higgins and Thiel 1988). In this investigation, nematodes were found at every sampling station and exclusively colonized the upper foreshore, where moisture is low, and the areas at the toe of the seawall or bulkhead, that are prone to increased sediment activation. These results are similar to Soetaert et al. (1995) who found domination of Nematoda in the intertidal region of five European estuaries.

5.2 Spatial Pattern of Meiofaunal Density

McLachlan (1980) suggests the following stratification of the intertidal zone and meiofauna distribution focusing primarily on water content. The upper "dry sand stratum" is characterized by low water saturations and high fluctuations in temperature and salinity. Nematodes are dominant and copepods are scarce. A partly underlying "moist sand stratum" offers a more suitable water supply and has less fluctuations in temperature and salinity. Meiofauna density and diversity increases, with a particular increase in copepods due to the well-oxygenated conditions of this zone. In the "water table stratum" around the permanent groundwater layer, sand is always saturated, but moderate oxygen tensions and often brackish salinities result in a reduction of meiofaunal density and diversity. In the "low oxygen stratum", oxygen deficiency can extend to

considerable depth, and in beaches with a high content in organic matter, can become a zone of reduced conditions. McLachlan (1980) also emphasizes that this pattern could be modified by a change in beach factors, such as, wave action, sediment size, beach slope, tidal amplitude and temperature as it affects desiccation.

The pattern of meiofaunal cross-shore distribution outlined by McLachlan (1980) was found for this investigation at Sites 1 and 2 at Cliffwood Beach, and at Site 2 for Keyport Harbor. These sites are either characterized by being the control site (Site 1, Cliffwood Beach and Site 2, Keyport Harbor) or a site where shoreline armoring is located high on the intertidal profile and interaction between waves and the seawall is minimal under low wave energies (Site 2, Cliffwood Beach). At the remainder of the sites, a reversal in the trend occurs and meiofaunal density increases bayward of the structure. At Site 3 at Cliffwood Beach, the seawall could be influencing mean grain size and sorting, resulting in a lower meiofaunal density due to finer, well sorted sediments. At Sites 1 and 3 at Keyport Harbor, depth of sediment activation increases in the vicinity of the bulkheads due to high wave energies, resulting in a decrease in the number of meiofauna at the top of the core. It is expected that under higher wave energies at Cliffwood Beach, Site 2 would also experience greater sediment activation at the toe of the seawall and a decrease in the number of meiofauna.

The cross-shore pattern of meiofaunal abundance for Sites 1 and 2 at Cliffwood Beach, indicate a decrease in the density of fauna in the location of the swash zone at high water. The interstitial fauna are most vulnerable to wave action and currents in this area of the intertidal profile. A dramatic increase in the number of meiofauna just bayward of the breakers at high water implies that the habitat is more suitable due to less

energetic conditions with the fall of the tide (Nordstrom and Jackson 1992).

Hockin (1982) conducted a study to illustrate the effects of sediment particle diameter upon the meiobenthic Copepod community of an intertidal beach. Results indicated that there is no simple correlation between the sediment particle diameter and any of the simple descriptors of the community structure (density, diversity). Grain size and shape in a sandy habitat often stand out as the dominant influence upon meiofaunal abundance. It is not solely grain size that limits the distribution of the fauna, but the fraction of the pore system that is filled with water (Jansson 1967). The aeration of the interstitial habitat is greatly controlled by the permeability which, in turn, is effected by the size and shape of the sediments (Jansson 1967). At Cliffwood Beach for the top portion of the core, mean grain size and sorting are both positively correlated with meiofaunal density. Mean grain size and sorting, together, are a more conclusive descriptor of the interstitial pore space. Results that support a positive correlation between both physical parameters and density indicate that the fauna are influenced by the size of the pores in the beach matrix.

At Cliffwood Beach, permeability increases with distance from the upper limit of swash at high water and meiofaunal densities decrease bayward from wave breaking at high water at Site 1 for the top and bottom of the cores. At Site 2, the beach profile is at a lower elevation due to the presence of the seawall causing a decrease in permeability values on the lower foreshore. Meiofaunal densities are lowest on the lower foreshore. At Site 3 the shift is more pronounced, and permeability is lowest where meiofaunal densities are highest at an elevation of -0.25 m relative to mean sea level.

At Keyport Harbor, at an elevation of 0.50 m (MSL), permeability values are lowest at Site 2 (5.2×10^{-10} m^2), where there is no shore-parallel armoring and highest at Site 3 (1.0×10^{-9} m^2), 10 m bayward of the bulkhead. At this elevation, meiofaunal densities are higher at Site 3. A comparison of the sampling stations at 0.20 m relative to mean sea level, permeability values are equal (1.0×10^{-9} m^2) at Site 1, 3.0 m bayward of the bulkhead and at Site 3, 15.0 m bayward of the toe of the seawall. These values are greater than at Site 2, the control site, where $k = 8.2 \times 10^{-11}$ m^2. Meiofaunal densities are similar at this elevation for all sites.

Water infiltration is the primary factor controlling the suitability of the interstitial environment for meiofauna because it influences food inputs, oxygen levels, and flow rates (Riedl and Machan 1972; McLachlan 1983). McLachlan and Hesp (1984), investigated water infiltration on beaches with alongshore variations in grain size and slope. Results indicate that bay beaches with a steeper slope and coarser sand, resulted in better drainage. Beaches in bays and estuaries with coarse grain sizes and steeper slopes should provide better habitat than beaches with finer and flatter slopes. In steeper slope environments, the main factor causing a decrease in meiofaunal numbers, is the presence of a mini-rip backwash (McLachlan and Hesp 1984). The scouring effects of this rip current, and the pulsations in interstitial water flow cause the meiofauna to be stripped from the sand grains. Sediment activation is greatest at Site 3 at Cliffwood Beach and at Site 1 at Keyport. At these sites, meiofaunal density is lowest which could be due to the increased water flow dislodging the fauna from the sand grains.

Swash is only able to infiltrate the sand surface when it flows over an unsaturated region above the effluent line. The effluent line separates saturated and unsaturated sand

and moves up and down the foreshore with the rise and fall of the tide (McArdle and McLachlan 1991). The interstitial fauna are directly affected by swash processes because they rely on water infiltration for oxygen and nutrients. Plant and Griggs (1992) observed the beach groundwater effluent line in the presence of seawalls. At high tide, the effluent line deflects seaward in front of the wall, that may be due to the impermeability of the rock revetment that underlies the beach surface near the wall. The revetment reduces the porosity and permeability of the beach matrix, causing a rapid response to water level changes. They concluded that in front of the seawall, the water table rose more rapidly and to a higher elevation than at levels downcoast from the seawall (Plant and Griggs 1992). Water held within the seawall above beach level does not infiltrate and therefore feeds the backwash flow (Plant and Griggs 1992).

At Site 1, Cliffwood Beach, and Sites 1 and 3, Keyport Harbor, infiltration is reduced and water is therefore retained longer in the vicinity of a shore-parallel structure. Meiofauna require that water flow through the beach matrix and the structures may be preventing an adequate supply of oxygen and nutrients.

Estuarine shorelines are characterized as having reflective beaches. Reflective beaches have short, frequent swashes, a narrow intertidal, a high frequency of swashes crossing the effluent line and a high percentage of uprushes above the effluent line. As a result of this, reflective beaches have maximum infiltration. This is a direct result of the associated swash climate and beach slope (McArdle and McLAchlan 1991) and has major implications for fauna. Reflective beaches have dynamic interstitial conditions with strong flushing, high oxygen and physical rather than chemical gradients (McArdle and

McLAchlan 1991). Fauna abundance and diversity increases as beaches move from reflective to dissipative.

The surf-scaling parameter, $\in$, was calculated for all sites to determine whether the beach is reflective or dissipative and to determine the impact of slope on meiofaunal density. At Site 1 at Cliffwood Beach, the value of $\in$ is 1.2 suggesting strong reflection. Reflection increases longshore and at Sites 2 and 3, backed by the seawall, complete reflection occurs, where $\in$ equals 0.9 and 0.5, respectively. Meiofaunal densities are greater at Sites 1 and 2 than at Site 3 due to the steeper slope and the increased reflective nature of the beach at Site 3.

At Keyport Harbor, Sites 1 and 2 have intermediate beach states ($\in$= 6.6, 7.3). Site 3, the surf-scaling parameter has a value of 16.8, due to a lower slope value (4.0°) making the beach more dissipative (Wright and Short 1983). Dissipative beaches are more conducive to slow burrowers and small, less robust species (McArdle and McLAchlan 1991). The presence of a greater number of copepods, which are burrowers, at Keyport Harbor compared to Cliffwood Beach, may be attributed to the more dissipative nature of the study sites at Keyport Harbor.

Sherman and Coull (1980) conducted a study to determine the resilience of ecosystems, that is, "the degree, manner and pace of restoration of initial structure and function in an ecosystem after disturbance" (Westman 1978). The investigators demonstrated that the meiofauna were capable of recolonizing the disturbed area (9 m^2) within one tidal cycle. At the major taxon level all taxa recovered to control and/or predisturbance densities within 12h of the disturbance. Moreover, there was no evidence

that recolonization was directional or related to stage of the tide. It is hypothesized that meiofauna recolonize disturbed areas horizontally via passive transport with the tide because it is unlikely that such small animals could crawl such a large distance within one tidal cycle (Sherman and Coull 1980). It is also believed that the disturbed site represented uninhabited space or an open resource to which the meiofauna migrated towards (Sherman and Coull 1980).

Activation depths are greater on reflective beaches due to the breaking process of plunging waves. The average depth of activation ($\bar{Z}$) is estimated to be 15 % of the breaking wave height for beaches in a meso-tidal estuary (Jackson and Nordstrom 1993). Average measured activation was 0.011 m and 0.015 m at Cliffwood suggesting that at low wave energies, the seawall is not having a large effect on the beach under low wave energies.

At Keyport, average measured activation at Site 1 is greater than predicted (Jackson and Nordstrom 1993). The area immediately bayward of the bulkhead is subject to the most activation and subsequently the meiofauna living in the vicinity of the bulkhead are subject to the most disturbance and result in lower meiofaunal densities.

Shore-parallel structures have minimal effect on cross-shore sediment processes and only have potential to damage neighboring beaches if longshore processes are interrupted (Kraus 1988). Morphological and hydrodynamic response to seawalls and bulkheads depends largely on the location of the structure on the beach profile (Kraus 1988). The greatest differences in beach morphology and meiofaunal density in this investigation occurred at Site 3 (Cliffwood Beach), where the seawall intersects the intertidal foreshore and waves break on the structure.

5.3 Conclusions

Shore-parallel structures have the potential to alter the interstitial foreshore and meiofaunal density depending on wave energies and the position of the structure on the intertidal foreshore. The following conclusions can be taken from this field investigation:

1. Meiofaunal densities from the two study areas are less than previous studies perhaps due to a relatively small intertidal profile and the pollution associated with an urban estuary.
2. The majority of the meiofauna is found in the top 0.03 m of sediment and is spatially dependent.
3. Shore-parallel structures alter the pattern of meiofaunal cross-shore distribution. Meiofaunal density increases bayward of the structure.
4. Meiofauna are vulnerable to wave action and currents in the swash zone where densities decrease.
5. Mean grain size and sorting, together, are a more conclusive descriptor of the interstitial pore space. An increase in grain size and sorting result in a higher meiofaunal density.
6. The seawall is not having a large effect on the beach under low wave energies. The area immediately bayward of the structure is subject to the most activation and subsequently the meiofauna living in the vicinity of the structure are subject to the most disturbance and result in lower meiofaunal densities.

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