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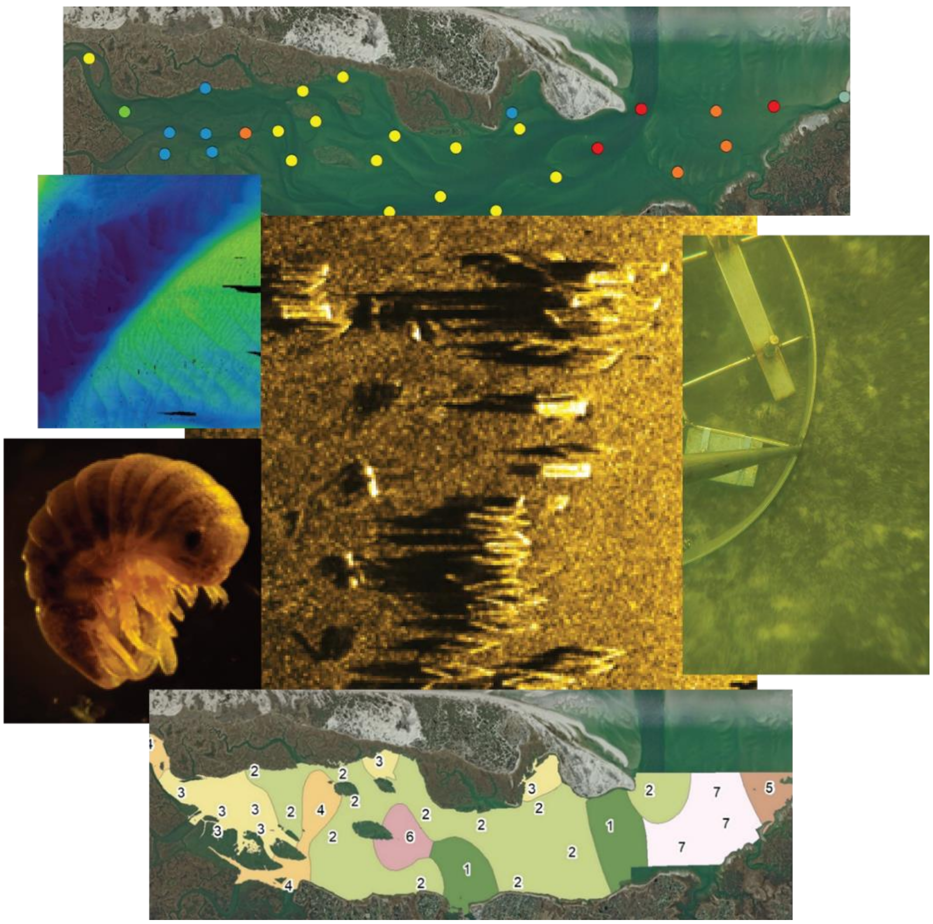
A Benthic Habitat Map for Barnstable Harbor



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Executive Summary

Coastal ecosystems are subject to environmental and human-induced stressors and managing these areas can be challenging. An effective first step in the management of coastal ecosystems is to establish a monitoring regime to document the state of the resource. The benthic habitat maps developed for this project create a reliable baseline to evaluate the effects of climate change, nutrient input, dredging activities, aquaculture as well as other processes and phenomena on coastal ecosystems. Benthic habitats are defined by their biological and physical components and recognizing their importance and relative contributions are essential to maintaining the ecosystem services provided by these areas and the biota that live there.

This study was undertaken to develop a benthic habitat map of Barnstable Harbor using a rigorous, repeatable, and scientifically defensible method that provides a set of baseline conditions in the Harbor to measure future change against. A benthic habitat map combines information about benthic invertebrates (animals lacking a vertebral column, e.g. molluscs, crustaceans, living on and in the seafloor) with acoustic data (bathymetry and sidescan sonar imagery), water column data (temperature, pH, dissolved oxygen, and salinity), sediment grain size data and other information, resulting in the delineation of biotopes (habitats associated with a particular ecological community). These data are then combined using the Coastal and Marine Ecological Classification Standard (CMECS), the national standard and federally mandated system for projects receiving any federal funding[1], to define the many components of the coastal ecosystem. CMECS, being a national standard, was chosen to aid future investigators in the replication of the methods used in this study. Often investigators do not follow standard mapping procedures, following the standards established by CMECS will allow more streamline comparisons, based in science, over time and between different embayments. Fieldwork, particularly involving boats, is time-consuming and costly, and the utilization of CMECS increases the utility of these maps to present and future managers of coastal systems.

Data were collected in two phases in 2018; phase 1 included vessel-based sonar surveys during the summer (May 30 – July 31) and phase 2 included grab samples for invertebrate and sediment analysis (October 1 – 4). Sampling stations were randomly stratified across 5 zones (subtidal creek, subtidal mouth, intertidal creek, intertidal, and aquaculture) as determined primarily by the acoustic data. Data analyses were conducted at the Center for Coastal Studies. Main findings include:

- Identification of 40,267 individuals belonging to 89 species were collected at 31 sample locations. The highest diversity in biotope 2 (65 species), where a combination of gravel and algae create a heterogeneous environment (varied bottom types) that provides cover and protection from predators for many smaller individuals. The most abundant stations can be

[1] This project received no federal funding

found in biotope 7 where a high number of Amethyst Gem clams (*Gemma gemma*) were found.

- Although Massachusetts does not release an official list of **invasive species**, a literature review showed that the common periwinkle (*Littorina littorea*) is an established invader in New England and can be found at 12% of stations in Barnstable Harbor. *Caprella penantis*, a species of skeleton shrimp (present at 9% of stations) is actively monitored within the Marine Invader Monitoring and Information Collaborative (MIMIC) at the Massachusetts Office of Coastal Zone Management. *Microdeutopus gryllotalpa*, a small amphipod crustacean, and present at 29% of stations, is classified as a cryptogenic species, meaning its geographic origin is unknown.

- Compared to studies conducted in the 1960s and 1970s, we detected an increase in southern species more adapted to warmer waters (Table 9). Two southern species were found in Barnstable Harbor in 1962 and 1970 respectively, 5 species in 1977 and 14 species in 2018. Since sampling methods employed 50 years ago were different from the ones employed in the study presented here, these results are not directly comparable but are illustrative and could indicate a potential **shift in species composition** that could be monitored regularly.

- Based on abiotic factors such as grain size metrics and organic matter content of the sediment, we could **explain 72.9% of species distribution in Barnstable Harbor**. This number is comparably high when compared to previously published studies conducted around New England, which achieved 21 – 84% explanation. A high explanatory rate means that, as long as grain size metrics remain stable, changes in species composition should be minimal. Water column factors such as dissolved oxygen, pH and salinity also play and important role in species distribution, however, these factors are subject to change by season, tides, anthropogenic inputs and weather events and have to be monitored across seasons and years before potential inclusion as an explanatory factor. A well-established dataset of water column factors could increase the explanatory power of CMECS in Barnstable Harbor.

- Since species distribution is highly dependent on sediment characteristics (72.9%), future monitoring could be limited to yearly sampling and analyses of grain size metrics from the stations established by this study. Any significant changes in grain size could warrant further investigation into potential changes in species diversity. Regular monitoring of water column parameters (dissolved oxygen, pH, salinity) would be the first step towards **establishing a baseline** for future inclusion as an explanatory factor in terms of species distribution. The main tidal channel in Barnstable Harbor is very stable and does not need annual dredging, were this to change the impacts would likely be felt systemwide.

- Vessel-based acoustic data show a very dynamic harbor near the main inlet channel with rapid drop off of energy levels with distance from the harbor entrance. The Harbor does have **marine debris** in many places, though there does not seem to be a single source or sink of marine debris. The items range in size from small rectangular objects, possibly aquaculture gear, to large unidentified items. None were shown to present a hazard to navigation at the time of mapping.

- The acoustic data was also useful in documenting the state of **sub-tidal resources**. Areas of salt marsh erosion were seen along the southern shore of Sandy Neck among other places. There were no signs of failure in the marina/inner harbor along the piers and pilings though this should not be used as an assessment for those areas, but rather a confirmation that failure was not imminent at the time of mapping.
- The data collected and maps created for this project will serve as a scientifically robust data set to establish baseline conditions within Barnstable Harbor but also to **measure future change** against. The entire project does not need to be repeated to do so, site-specific research can be done as needed, but similar methods to these should be employed at those locations.

Recommendations

The following recommendations are provided based on the findings of this project, the author's familiarity with this system and others like it on Cape Cod and beyond. They are not listed in order of importance.

1. Establish a monitoring program at a subset of stations throughout the study area and revisit those stations every 5-10 years or as needed. This could be done to look at a wide range of parameters including grain size, organic content, invertebrate diversity and abundance, invasive species, etc. These monitoring sites should include the sampling sites from the 1950s and 1970s to continue the long-term monitoring of those locations. Other sites should be added at critical locations to monitor them into the future.
2. Conduct a resource inventory of recreationally and commercially important fishes and their relationship to invertebrates and the biotopes mapped in this study.
3. Undertake a study to quantify salt marsh change throughout the Harbor. This could be done using publicly available remote sensing data, historical and recent aerial imagery and historical maps of the Harbor, which date back to the mid-1800s.
4. Develop a dataset of water column parameters to help past and future analysis of invertebrate species distribution and other ecosystem-wide characteristics.

1. Introduction

1.1. Study Area

Barnstable Harbor is a shallow, tidal coastal embayment, approximately 5.5 km long and 1.2 km wide, in the southern part of Cape Cod Bay. Its formation was a result of the deglaciation of the region approximately 18,000 years ago followed by the rise in sea level approximately 6,000 year ago that led to the Harbor taking on its current configuration (Uchupi et al., 1996). Sandy Neck, the barrier spit that partially encloses the bay, began to form 6,000 – 4000 years ago as tidal waters inundated the area and the net sediment transport started to move from west to east, as it does to this day (Borrelli et al., 2016). Sandy Neck continues to grow eastward but is prevented from shoaling the main tidal channel due to the dominance of the semi-diurnal (twice daily) tidal flow in and out of the harbor. Most other harbors on Cape Cod construct human-made structures to minimize shoaling or dredge periodically, some do both, to maintain a navigable channel. Natural evolution of a tidal inlet, such as the one in Chatham has been shown to alter tidal range (Borrelli et al., 2019b; Giese et al., 2020) and water quality (Howes et al., 2006a). The relatively stable, inlet at Barnstable Harbor provides consistent flushing and tidal range variability, which is not typical for natural inlets and has positive implications for resource management, recreational activities, and ecosystem benefits.

The salt marsh in Barnstable Harbor has been long studied by Redfield 1972 (Redfield and Rubin, 1962) and currently occupies more surface area in the Harbor than open water, as it has in the past (Ayers, 1959). Although much of the salt marsh was not mapped during the vessel-based survey, due to the objectives of this study, the approximate seaward edge of the salt marsh was mapped in many areas and therefore could be used to measure changes to salt marsh in the future. Tidal range was measured to be 3.0 m (Borrelli et al., 2021a) and it is estimated that the average residence time is less than half a day (Howes et al., 2017).

1.2. Benthic Habitat Maps

The purpose of this work was to integrate the physical and biological characteristics of benthic marine habitats from data obtained by CCS into a series of map products that describe the CMECS Geoform, Substrate, and Biotic Components. CMECS itself is “data agnostic” (FGDC, 2012), meaning that as a classification scheme, it does not prescribe a particular method, set of methods, or analysis techniques. Indeed, this is a strength of CMECS, and one that allows the user to separate this type of project into three distinct steps: data collection, analysis, and classification.

There are three recognized approaches for integrating benthic physical and biological data into habitat maps (Brown et al., 2011). The first approach, “abiotic surrogacy”, does not truly integrate physical and biological data but assumes that physical environmental patterns correspond to biological patterns. The abiotic surrogate approach is applied at broad scales and is used to define benthic landscapes from remotely sensed data, often with little or no ground-truthing. For example, Dunn and Halpin (2009) modeled seafloor rugosity from low-resolution (90m) bathymetry data as a proxy for high biodiversity.

The second and most common approach, known as "assemble first, predict later", can be used to develop single-species maps or assemblage maps based on observed physical and biological characteristics using a classification scheme as a guide (Brown et al., 2011). With this approach, physical and biological datasets are each analyzed separately, i.e., geologic characteristics are delineated from acoustic and grain size data, then biological characteristics are identified from analysis of grab samples or underwater photography. Maps are constructed by overlaying the occurrence of biological characteristics with the geologic characteristics and determining the correlation between datasets. The degree of correlation between geologic and biological characteristics is used as justification for assigning habitat units from the chosen classification scheme and extrapolating those habitat units across the study area into places where sampling data were not collected. However, benthic infauna often overlap sediment transitions or boundaries and equating substrate with benthic assemblage type will lead to inaccurate maps (Diaz et al., 2004; Shumchenia and King., 2010; Stevens and Connolly, 2004). This underscores the need for the third approach.

The "predict first, assemble later" approach, described by Brown et al., (2011) as more sophisticated and objective than the previous two, and noted that more recent studies are beginning to use this strategy. The concept underlying this approach is that the physical and biological data together are used to inform the development of map units – species or assemblages are modeled as functions of multiple physical variables. In the case of single species mapping, this approach is known as habitat suitability modeling (Howell et al., 2016). Applied to species assemblages or communities (e.g., Degraer et al. 2008), this approach identifies physical variables that explain the most variance in benthic community structure, then uses those variables to create predictive habitat maps.

Since this study sought to represent ecologically meaningful physical-biological linkages and develop full-coverage habitat maps in a rapid and reproducible manner, we chose to implement the third analysis strategy: "predict first, assemble later". Further, this analytical approach has been previously employed to identify and predict CMECS Biotopes in a shallow soft-sediment environment in Northeastern United States (Shumchenia and King., 2010), (McHenry et al., 2017) (Mittermayr et al., 2020a; Mittermayr et al., 2020b). Distance based linear models were run to identify the driving physical variables responsible for the variation in benthic community structure in Wellfleet. Additionally, the thresholds of each significant variable were calculated to determine different levels or gradients of variables influencing species community. This information was used to develop full-coverage maps showing benthic assemblages and their determining physical drivers The resulting maps, therefore, contain units that correspond to CMECS Biotopes, "a combination of abiotic habitat and associated species" (FGDC, 2012).

2. Methods

2.1. Vessel-based Acoustic Surveys

2.1.1. Data Collection

Two research vessels were used to collect acoustic data, the R/V Marindin and the R/V Portnoy. The R/V Marindin is a 1995 Eastern I/O that has been modified for all-weather, shallow-water operations. It has a retractable bow mount with power hoist to raise and lower the sonar for safe operation and ease of deployment/retrieval. The bow mount eliminates most of the noise from the vessel and engine thus improving the quality of the acoustic data. This vessel combines an adequate beam (2.54 m) that yields stability at low survey speeds, a shallow draft (0.61 m) for safe operation in nearshore waters, and a modified V-hull for optimal transit time. The R/V Portnoy is a custom-built, ultra-shallow draft pontoon boat designed specifically to survey in low energy embayments around 1 m deep (Borrelli et al., 2021b). A 2-kW Honda™ gas-powered generator is used to power all electronics for the hydrographic surveys onboard both vessels.

To conduct high-resolution, vessel-based acoustic surveys an Edgetech 6205, a dual-frequency, phase-measuring sidescan sonar, was used. Its operating frequencies are 550 and 1600 kHz for sidescan sonar imagery and 550 kHz for bathymetry. The sidescan sonar range resolution is 1 cm, at 550 kHz, and 0.6 cm at 1600 kHz. The bathymetric range and vertical resolution are both 1 cm. The effective bathymetric swath width is 6-8 times the height of the sonar over the bottom (Edgetech, 2019). In addition, a Teledyne TSS DMS-05 Motion Reference Unit mounted on the sonar was used to collects data on heave, pitch, and roll, measuring heave to 5 cm and roll and pitch to 0.05° (Teledyne TSS, 2006). A HemisphereGPS® V110 vector sensor was used to measure heading. Two differential GPS receivers spaced 2 m apart yielded heading accuracies of <0.10° RMS (HemisphereGPS, 2009).

Bathymetric data comprises the vertical and horizontal positions of each sounding: x and y being the horizontal coordinates (latitude and longitude) and z representing the raw depth from the sonar to the seafloor. The raw depth is then corrected to a vertical datum (a reference point, such as mean sea level), and tide corrections using Real-Time-Kinematic GPS (RTK-GPS). A Trimble® R10 GNSS receiver utilizing RTK-GPS was used for positioning and tide correction for vessel-based surveys.

To collect RTK-GPS data, CCS uses a proprietary Virtual Reference Station network (KeyNetGPS) that provides virtual base stations via cellphone. This negates the need to setup a terrestrial base station or post-process the GPS data, thus reducing costs, streamlining the field effort, and maximizing vessel-based survey time. CCS undertook a rigorous analysis of this system beginning in 2012 to quantify the accuracy of this network. Twenty-nine (29) National Geodetic Survey (NGS) and Massachusetts Department of Transportation (MassDOT) survey control points were measured and compared with published state plane coordinate values relating to the

Massachusetts Coordinate System, Mainland Zone (horizontal: NAD83; vertical NAVD88). The overall uncertainty analysis for these data yielded an average error of 0.008 m in the horizontal (H) and 0.006 m in the vertical (V). A Root Mean Squared Error (RMSE) of 0.0280 m (H) and 0.0247 m (V) and a National Standard for Spatial Data Accuracy (95%) of 0.0484 m (H) and 0.0483 m (V) (Borrelli et al., 2021b).

Edgetech's Discover Bathymetric® software was used to monitor all incoming data streams and control settings for onboard acoustic instruments to optimize data quality for at-sea conditions. Survey planning was performed using Hypack Survey® for line planning, coverage mapping and helmsman navigation. Both Discover Bathymetric® and Hypack's Hysweep® were used to collect data with the final raw output in JSF and HSX file formats respectively.

2.1.2. Data Processing

The JSF files were imported into SonarWiz® where a combination of automated and manual data processing was undertaken, including bottom tracking, slant range correction, offset entry and gain setting adjustments. After appropriate processing of each data file, mosaics were generated, which were then exported in a raster format (Geotiffs).

Post-processing of bathymetric data was performed using CARIS HIPS®. Raw data (HSX) files were converted to CARIS proprietary format using vessel configuration files developed from vessel offsets, and device information. RTK-GPS tide corrections were applied in the conversion process. Sound velocity corrections were applied using measurements collected in-situ by an internal sound velocimeter located in the sonar housing and water column profiles obtained from casts performed for each survey using a Castaway® CTD. Calibration tests were performed in the field in order to determine motion and timing offsets (roll, pitch, yaw, and latency). Those offsets were recorded in the vessel file and applied when the survey lines were merged. Total Propagated Uncertainty (TPU) was computed using device manufacturer specifications recorded in the vessel configuration file. Filters were applied to remove depth outliers and "noise" typically found in the outer regions of the swath. Where necessary, area editors were used to remove spurious soundings.

2.2. Benthic Sampling

To determine the biological and physical structure of the benthic habitats, field surveys were conducted for invertebrate and sediment characterization, water column structure, and video imagery during October 1-4, 2018. Benthic survey stations were determined using a stratified random design, in order to effectively characterize Barnstable Harbor. To provide balanced spatial coverage across the systems and statistical power of randomization we stratified the sampling by 5 zones (subtidal creek, subtidal mouth, intertidal creek, intertidal, and aquaculture) as determined primarily by sidescan sonar survey. The elevation used to delineate areas between intertidal vs subtidal was taken from the nearest tidal station, in Sesuit Harbor, where the US Geological Survey maintain a real-time tide gage (waterdata.usgs.gov) and the National Oceanic and Atmospheric Administration have modeled such information (tidesandcurrents.noaa.gov). The final locations of the benthic sampling stations (Figure 1) were then exported from ArcGIS and uploaded into a Garmin GPSMAP® 78 for use on the survey vessel.

2.2.1. Field Work

All samples were collected aboard the R/V Marindin using a Young modified Van-Veen (4 L) grab sampler (Figure 2). An EXO2® sonde was used for the collection of water column data, (pH, dissolved oxygen, temperature, and salinity), and a Garmin GPSMAP® 78 to obtain horizontal and vertical coordinates for each sample. A GoPro Hero 5™ was attached to the Van-Veen grab and high-resolution video was collected for each sample to aid in bottom characterization and documentation. The video was of sufficient resolution that screenshots could be obtained for imagery related needs (Appendix A). At each station, three biological replicates were taken. Each waypoint recorded was labeled by date, system name, station name and replicate number. All GPS data points were downloaded to a .csv file and imported into ArcGIS for subsequent mapping.

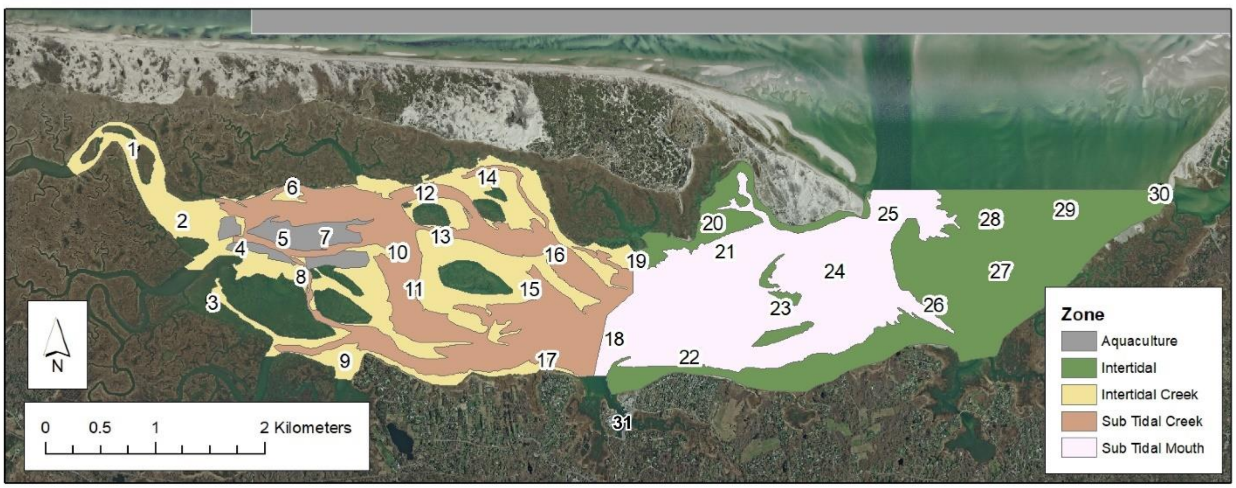

Figure 1. *Map of Barnstable Harbor showing stratified random sampling stations 1-31.*

Biological Samples

At each benthic survey station, four replicate grab samples were collected from the seafloor, three biological replicate grab samples and one sediment grab sample using a Young modified Van Veen grab sampler (Figure 2). The anchor line was let out approximately 1 meter between each grab sample replicate to ensure that no previously disturbed areas were resampled. The Van Veen grab samples a surface area of 0.04 m2 to a depth of 0.1 m below the seafloor for a total volume of 0.004 m3 (4 liters); It is well-suited for sand- to mud-sized samples (≤2 mm) but does not function as well in areas with coarser grain sizes. A successful sample was attained when the two scoops of the Van Veen grab were fully closed, at least 2 liters of material were sampled, and the surface of the sample was level-indicating the Van Veen grab did not sample the seafloor at an angle. The sampler has viewing plates allowing the user to view the top of the sample without disturbance for verification or further sub-sampling. When unsuccessful sampling was encountered due to rocks or shells interfering with the jaws closing, four attempts were made to sample with the Van Veen before the station was rejected. In this case, the nearest next randomly selected station replaced the original station. A GoPro Hero 5™ camera was mounted on the Van Veen grab frame, perpendicular to the seafloor collecting videos for each (accepted and rejected) grab attempt.

Figure 2. *Young-Modified Van Veen Grab Sampler onboard the R/V Marindin*

The contents of the Van Veen were then emptied into a bucket; a low energy wash of seawater was used to rinse any substrate adhering to the Van Veen into the bucket. Any large bivalves, crabs, or vertebrates (fish) were measured, counted and identified (or photographed for later identification) before being returned to the water. Larger, mobile organisms collected by this method are considered ancillary data, as benthic grab sample gear cannot provide quantifiable estimates of their abundance or density. In the laboratory, the contents of the bucket were prepared for invertebrate analysis. Water column data was collected using an EXO2 sonde. One cast was conducted at each station before collecting the grab samples to collect temperature, salinity, pH and dissolved oxygen data. Once the boat was anchored at the station, the cast was made. A GPS point was taken for each cast.

Sediment Samples

In addition to the three biological samples taken at each station, a fourth sample was used to document the grain size of the sediment. This sample was taken between the second and third biological replicate to ensure that the sediment sample was generally representative of the substrate sampled by the biological replicates. The surface sediment was transferred to a 100 ml Whirl-Pak®, and later dried at the lab for future analysis.

2.2.2. Sample Processing

Biological Samples

To determine the benthic invertebrates found in each biological grab sample, the contents of each grab sample were sieved through a 1 mm mesh to retain organisms, detritus, and substrate greater than 1mm in size. A low energy wash and gentle manual agitation was used to sieve the sample to reduce damage to biological specimens. The material retained on the sieve was transferred to triple-labeled glass jars and preserved with 95% ethanol with Rose Bengal to dye invertebrates. Date of field sampling, preservation, processing and identification were all recorded on sample tracking data sheets as well as any notes about samples.

To sort out or "pick" the invertebrates from the substrate, the preservative was drained from the sample and disposed of according to CCS hazardous waste management plan. The sample was gently spread out into a large white plastic trays and water was added. The sample was visually inspected using a 3-fold magnification on a magnifying LED lamp and all invertebrates were picked out of the sample and sorted into general categories as discerned by the unaided eye (i.e. worms, shellfish, amphipods etc.). All personnel and volunteers were trained by the project biologist on proper picking technique and on general visual cues to find invertebrates. Quality control for each sample was performed by the project biologist according to CCS Quality Assurance Project Plan (QAPP) for Invertebrate Sampling Projects. Specimens were then preserved in 70% ethanol in 20 ml glass scintillation vials.

Specimens were identified by the project biologist using a dissecting microscope. All initial and final identifications, counts, and any notes were recorded on the identification data sheet. Specimens were identified to species level when possible or to genus, families or orders depending on the difficulty of identification. All identified specimens were counted. Pictures were taken of representative specimen of each species using a digital microscope camera. Unidentified specimens were photographed using a digital microscope camera and preserved to be identified/verified at a later time.

Digital video footage was reviewed for habitat characteristics and heterogeneity and for biotic components. Digital still images were obtained from videos. The entire frame of the image was analyzed by trained reviewers. Benthic cover was characterized following grain size analysis substrate descriptors (Appendix A, Table A1). Relative abundance of macroalgae and macrofauna in each image was determined by identifying organisms to the lowest practical taxon. Percent presence (%) was determined 25 random points were overlaid on the image, and the constituents ("Bare", "Shell", "Macro-Algae", "Eelgrass" or "Woody debris") underneath each point was identified.

Sediment Samples

To characterize the sediment substrate of the benthic habitat for each sample location, sediment samples were processed for organic matter content and sediment grain size analysis.

Organic matter content by loss on ignition (LOI): To determine organic matter content of sediments for each sample, 20-30 grams of sediment were placed on pre-weighed aluminum trays, and the wet weight of the sample was recorded before being placed in a drying oven at 105°C for 24 hours (Heiri et al., 2001; Mittermayr et al., 2020b). Dried samples were removed from the oven and placed in a desiccator. Each sample was weighed, and the dry weight was recorded. After recording the initial dry weight, all samples were broken using either a clean spatula for sandy samples or a clean mortar and pestle to grind finer samples. After a sample was ground, it was re-dried and reweighed to account for any lost material. To determine the proportion of organic matter, the homogenized samples were placed in a muffle furnace at 550°C for four hours (Mittermayr et al., 2020b; Snyder et al., 2004). After ignition, the samples were re-weighed, and the percent organic matter as loss on ignition was determined by the following calculation.

$$LOI\ (\%) = (M_{dry} - M_{dish}) - (M_{ignite} - M_{dish}) / (M_{dry} - M_{dish}) * 100$$

Where M_{dry} is the weight of the dried sample (at 105° C) plus the aluminum dish, M_{ignite} is the weight of the ignited sample (at 550° C) plus the aluminum dish, and M_{dish} is the weight of the aluminum dish. LOI data were then corrected for salt content by using salinity data from CTD casts.

Grain Size analysis: Percentages of each of the size fractions for each sample were calculated from grain size data measured by the following methods.

Coarse grain size (> 64 µm): Sediment samples were split and organic material was burned off in a muffle furnace at 550°C for four hours. Samples were then sieved between 64 µm and 4 mm according to manufactures instructions before processing with a Horbia Camsizer at the Woodruff Lab, within the University of Massachusetts, Amherst, MA. Processed sediments were retained. All grain size results were saved to .csv files. All data were reported using Wentworth grain size thresholds and classes (Folk, 1974).

Fine grain size (< 1 mm): Sediment samples were split and organic material was burned off in a muffle furnace at 550°C for four hours. Sediment was then gently washed with tap water to remove salt and potential ash before processing with a Beckman-Coulter laser diffraction particle size analyzer at the University of Massachusetts, Amherst, MA. All grain size results were saved to .csv files. All data were reported using Wentworth grain size thresholds and classes (Folk, 1974).

2.3. Benthic habitat mapping framework

Each dataset used in the production of the final data products can be mapped and interpreted separately; this is an entirely valid exercise. However, we know that abiotic factors such as grain size, sediment organic content, and geomorphology explain some amount of the variance observed in benthic community composition. In many cases the reverse may also be true, where certain biotic assemblages may influence the physical composition and/or structure of the environment (e.g., shellfish beds, tube worm mats, eelgrass beds). These physical-biological relationships are critical to effective resource management, and therefore we attempted to characterize them and extract any information that could be useful for the mapping of benthic habitats.

We classified the CMECS Geoform Component and Substrate Component using the physical data. We then classified benthic community data using the CMECS Biotic Component. Finally, we used statistical approaches to identify physical variables that explained the highest proportion of the variance in the benthic community data and classified the benthic community data based on these variables. This latter type of classification is referred to as a "biotope" in CMECS, but with the added requirement that the physical-biological associations are predictable and repeated throughout the natural environment. Because the biotopes reported here are based on a single set of observations for each area, we refer to these results as "preliminary biotopes". Preliminary biotopes give us a sense for which physical variables are influencing or driving benthic community composition in each study area.

2.3.1. Physical Characteristics

CMECS Geoforms

The CMECS Geoform component describes the major geomorphic and structural characteristics of the coast and seafloor, but is not intended to be a geological classification per se (FGDC, 2012). Rather, the Geoform Component describes aspects of the physical environment that are relevant to and drivers of benthic community composition and distribution (FGDC, 2012). We delineated Geoforms by classifying several metrics derived from the bathymetry grid for each area using the Benthic Terrain Modeler (BTM) Toolbox in ArcGIS Desktop (Wright et al., 2012). Using the bathymetry grid as an input, we calculated slope, fine-scale bathymetric position index (BPI), and broad-scale BPI.

The slope for each cell was calculated as the maximum rate of change from the cell to its neighbor using the BTM Toolbox. The output was a continuous raster.

BPI is a focal mean calculation where a cell's elevation is compared to surrounding cells within a user-defined area. BPI is greater than zero where ridges or crests exist and less than zero where depressions or valleys exist. BPI is calculated using the following equation,

$$BPI < scalefactor > = int\left(\left(bathy - focalmean(bathy, annulus, irad, orad)\right) + 0.5\right)$$

Where *scalefactor* = outer radius in map units, *irad* = inner radius of annulus in cells, *orad* = outer radius of annulus in cells, and *bathy* = bathymetric grid.

Given that the input bathymetry grid had a resolution of 0.25 m^2, search radii were chosen that ensured that the algorithm would detect features <1km^2 in size (i.e., between the expected size of CMECS Level 1 and 2 Geoforms). Broad-scale BPI was calculated using an inner radius = 25 m and an outer radius = 250 m. Fine-scale BPI was calculated using an inner radius = 5 m and an outer radius = 25 m. These search radii, therefore, could detect features from 5 meters across to 250 meters across. Using the BTM Toolbox, the BPI grids were standardized by subtracting the mean, dividing by the standard deviation, and multiplying by 100.

To distinguish geomorphological features based on Broad- and Fine-scale BPI values, slope, and depth, the classification dictionary in the BTM Toolbox (Table 1) was developed for this study. To distinguish between "Flat" (0 - < 5°) and "Sloping/Steeply Sloping" (>5°) areas, the CMECS Slope Modifier was used. The CMECS "Shallow Infralittoral, 0-5 meters" Benthic Depth Zone modifier was found to be insufficient for describing relevant Level 1 and Level 2 Geoform types in the CCNS study areas. Therefore, habitats within flat areas were further distinguished by using contemporary tidal statistics calculated and used the intertidal thresholds of -1.71 m NAVD88 m as a modifier. Tidal statistics for Barnstable Harbor were collected during a concurrent study in the area and a summary of results and methods are provided in (Borrelli et al., 2021a). All elevations in this document and accompanying data are reported in either the local tidal datum, typically in Mean Lower Low water (MLLW) or in the North American Vertical Datum of 1988 (NAVD 88). The use of NAVD 88 allows for the comparison of different locations regardless of local tidal conditions. NAVD 88 is a geodetic datum and thus an elevation of, for example, 5.3 m (NAVD 88) would be the same elevation in Barnstable Harbor as it would be in Lewis Bay. However, 5.3 m (MLLW) would be different elevations in the two areas. The MLLW is used here as often times local managers and the public know a place based on the local tidal datums.

Anthropogenic structures are not easily quantified by the indexes used in the benthic terrain modeler. As such, sidescan imagery and local knowledge can be used to identify where the classification scheme is incorrect, e.g. oyster aquaculture cages in western Barnstable harbor. In order to account for these known features, the aquaculture cages were hand digitized in ArcGIS and merged with the BTM output creating a final Geoform Map.

Table 1. *Classification dictionary developed in the Benthic Terrain Modeler (BTM) toolbox for Cape Cod National Seashore. BPI values are standardized and multiplied by 100 (i.e., dimensionless). Depth in NAVD88 meters.*

Geoform	Broad BPI	Fine BPI	Slope (°)	Depth (NAVD88 m)
Basins and channels	< -100	N/A	N/A	N/A
Intertidal Flats < -1.71 m	-100 – 100	<100	0-5	< - 1.71
Subtidal Flats	-100 – 100	<100	0-5	> - 1.71
Bedforms and shallow slopes >5°	-100 – 100	<100	>5	< - 3.5
Margins and deeper slopes >5°	-100 – 100	<100	>5	> - 3.5
Platforms	-100 – 100	<100	N/A	N/A
Banks	> 100	N/A	N/A	N/A
Aquaculture	Hand digitized			

CMECS Substrate

The CMECS Substrate Component is a characterization of the composition and particle size of the surface layers of the substrate (FGDC, 2012). Substrates represent the non-living components that support, intersperse, or overlay the living components of the seafloor environment (FGDC, 2012). The CMECS Substrate Component uses Wentworth grain size thresholds and classes (Folk, 1974).

To classify Substrate Subgroups at each sampling point, percentages of gravel, sand, silt, and clay fractions of each sample were used. Classification was performed using SEDCLASS software (Poppe et al., 2003), and then the relevant Substrate Groups, Subclasses, and Classes for each sample were identified.

To develop a continuous map of substrate types for Barnstable Harbor, we interpolated the median grain size at each sampling point using the interpolation spline with barriers in ArcGIS 10.3. The resulting median grain size surfaces were then classified by CMECS Substrate Subgroups. While interpolation will introduce uncertainty into the final products, the tradeoff for full coverage (i.e. reproducible maps) is worthwhile. Importantly, the median grain size metric was expected to yield a different classification result than the classification derived from the station specific weight percentages of gravel, sand, silt, and clay. The resulting median grain size surfaces were then classified according to the Wentworth scale.

2.3.2. Biological characteristics

CMECS Biotic component

The CMECS Biotic Component deals with the classification of organisms in both the water column and on the seafloor; in this study we focus on organisms on the seafloor (i.e., CMECS Biotic Setting = Benthic Biota). We can further narrow our scope of classification to the Biotic Class “Faunal bed” since all of the observations provided by CCS were from sediment grab samples. Faunal beds are highly dependent on substrate type and include two Subclasses: “Attached fauna” and “Soft sediment fauna”. The next two hierarchical levels are Biotic Groups and Biotic Communities. We defined Biotic Communities based on dominance, then described the appropriate Biotic Group and Class for each Community.

Biotic Communities were defined by cluster analysis of the benthic infauna species data in PRIMER (Clarke and Gorley, 2015). First, the species-sites matrix was reduced to include only those species contributing to the top 95% of the total observed abundance. To verify that this new species-abundance matrix was representative of the benthic community in each area, the correlation coefficient between matrices based on the original and top 95% of total observed abundances were calculated. A Pearson correlation resulted in statistically significant similarity between 100% and 95% abundances. As a result, the 95% abundance matrices were found to be representative of the dataset. Using the top 95% dataset, the mean abundance was calculated for each species across all three replicate samples at each site. Then, the data were fourth root transformed to reduce the influence of highly-abundant species and a dissimilarity matrix was calculated using the Bray-Curtis index of dissimilarity. PRIMER’s SIMPORF and Cluster methods were employed, to determine the optimal number of clusters. If the same species was dominant in more than one cluster, they were classified as the same CMECS Biotic Community (FGDC, 2012).

A GoPro was attached to the Young-modified Van Veen grab collected video of the substrate at each station. The video was examined, which aided in identification of constituents on the substrate, and the frame capture function was used in Adobe Primer to export for further analysis. The still images collected from each station was imported into Coral Point Count with Excel Extensions (CPCe) to classify the substrate cover (Kohler and Gill, 2006). A total of 25 randomly placed point were overlaid on the image, and the constituents (“Bare”, “Shell”, “Macro-Algae” or “Eelgrass” or “Woody debris”) underneath each point was identified. The number of points was based off the variability of the photos (number of categories present) and published values to produce a statistically accurate representation of the substrate cover (Kohler and Gill, 2006; Pante and Dustan, 2012).

Preliminary Biotopes

To more fully examine the relationships between physical variables and benthic community composition, distance based lineal modelling (DistLM) was conducted using the PERMANOVA+ extension on PRIMER (PRIMER-E v7, Plymouth). The model analyses the relationship between a multivariate dataset (benthic community dataset), as described by a resemblance matrix (Bray Curtis dissimilarity) and a set of one or more predictor variables (sediment characteristics) using distance-based redundancy analysis (dbRDA) (Figure 3). The routine allows for sediment characteristics to be considered individually or grouped together in specific sets and obtains p-values testing the null hypothesis (no relationship) using the appropriate permutation methods (Clarke and Warwick, 2001). DistLM does a partition of variation according to a regression or multiple regression model and can be used to analyze models containing a mixture of categorical and continuous variables.

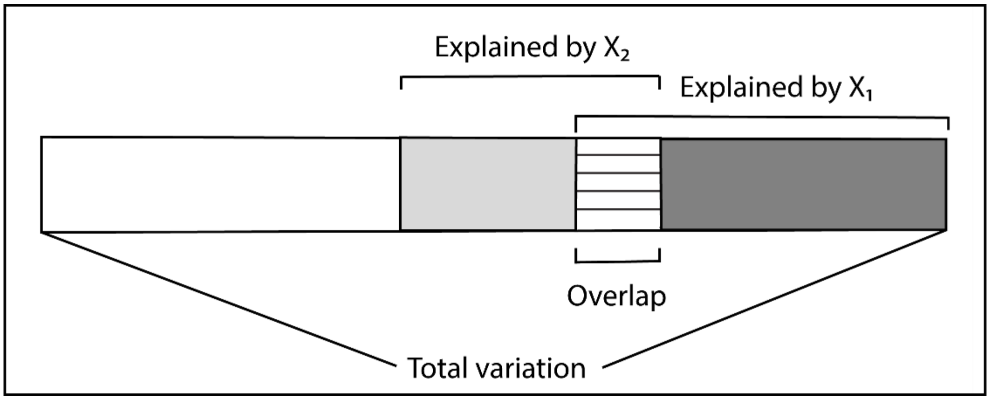

Figure 3. *Conceptual diagram of regression as a partitioning of the total variation into portions that are explained by the predictor variables (X_1 and X_2), a portion that can be explained by both variables (overlap) and a portion that is left unexplained. (Clarke and Warwick, 2001)*

Substrate metrics were chosen in particular, because they were consistently associated with benthic invertebrate sampling stations. Defining biotopes using only substrate variables and excluding ephemeral water column metrics, allowed for retention of the maximum number of stations examined with DistLM and thus classifying biotopes in the most robust way. Before running the DistLM, all substrate predictor variables were checked for correlations and excluded if $R^2 > 0.95$. This was the case for "median". The remaining predictor variables used for this analysis are listed in Table 2.

Table 2. *Sediment and grain size characteristics used to run distance based linear models.*

Grain size metric	Grain size metric
Location	% organic matter
Mean	Geoform
Mode	Video_ % Shell
Sorting	Video_ % Algae
Skewness	Video_ % Woody debris
Kurtosis	Video_ % Sand
% Gravel	Video_ % Mud
% Sand	Video_ % Gravel
% Mud	

Indicator species were determined for the most influential characteristics when possible by using LINKTREE. LINKTREE identifies thresholds in each of the variables (e.g. geoforms or grain size metrics) that correspond to occurrences of different benthic assemblages. The benthic assemblages corresponding to these thresholds were used to determine indicator species for the underlying variables.

An indicator species is defined as frequently associated with certain environmental conditions or characteristics (e.g. Geoform: basins and channels) while being not often associated with any other environmental condition or characteristic (e.g. any other Geoform). Indicator species were calculated according to (Dufrene and Legendre, 1997):

$$IndVal_{ij} = A_{ij} * B_{ij}$$

Where Aij is the proportion of the individuals of species i that are present in biotope j and Bij is the proportion of stations in biotope j that contain species i.

The indicator species values range from 0 (poor indicator) to 1 (perfect indicator). PRIMER's RELATE function, based on a Pearson Correlation, was used to determine the significance level of the indicator species. Only indicator species with a significance level < 5% were reported.

To develop a continuous map of biotope types for Barnstable Harbor, we interpolated the categorical biotope classifications as presence or absence at each stations, per biotope. Biotopes were interpolated between each station using interpolation with barriers. The biotope interpolations were then merged creating a continuous map. Although the interpolations introduce uncertainty between stations, the continuous map allows for future comparisons.

3. Results

3.1. Vessel-based Acoustic Surveys

Barnstable Harbor was mapped between May 22nd and July 31st, 2018, across 18 vessel-based acoustic surveys. A total of 544 km (338 miles) of survey lines were conducted creating a total of 1,912 ha of coverage (Figure 4). Within that area a total of 969 ha of bathymetric data were collected, yielding a mean depth of 2.09 m (Figure 5). Differences in sidescan and bathymetric coverage of processed data occur because of how the data are collected. Sidescan coverage is a function of range from the port and starboard transducers, which is set by the operator. In order to acquire a 50 m swath of sidescan, the operator sets the port and starboard ranges to 25 m. Conversely, bathymetric data coverage is a function of water depth, the deeper the water, the wider the swath and vice versa. Efforts were made to map ~2 hours before and after high tide in shallow areas whenever possible to optimize the efficiency of data collection.

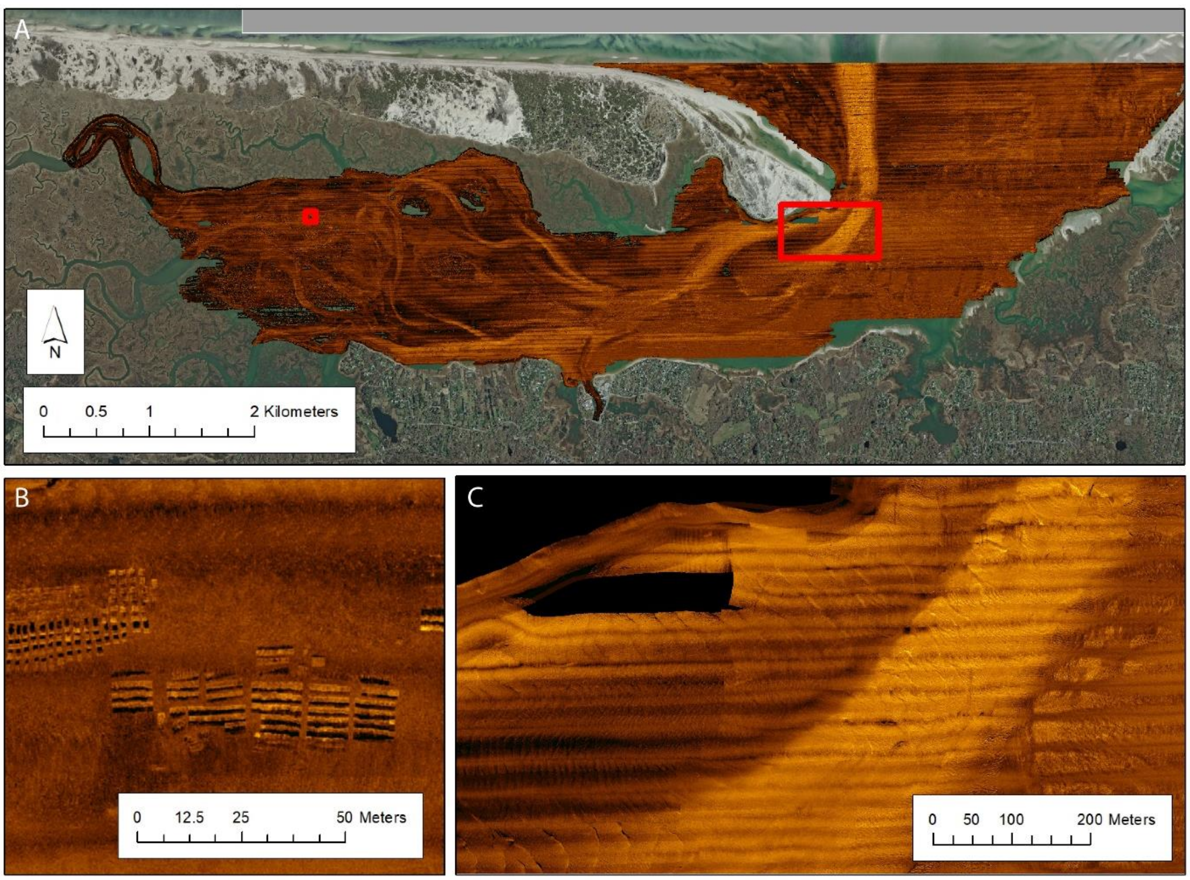

Figure 4. *Sidescan sonar imagery in Barnstable Harbor. (A): mosaic of sidescan sonar data. Grid resolution = 0.25 m^2. Red rectangles represent areas of interest below. (B): aquaculture site in the Harbor. (C): main channel in the Harbor*

The sidescan imagery for the project were collected at a range of 40 m (16%), 50 m (64%) and 73 m (20%) depending on daily conditions and location. This method of mapping results in better detection and characterization of bottom features. A bathymetric coverage ratio of 6:1 to 8:1 (swath width to water depth) was typical for this survey, for example in 2 meters of water the bathymetric swath widths were 12 to 18 meters wide, much narrower that the sidescan imagery, which explains the differences in coverage discussed above.

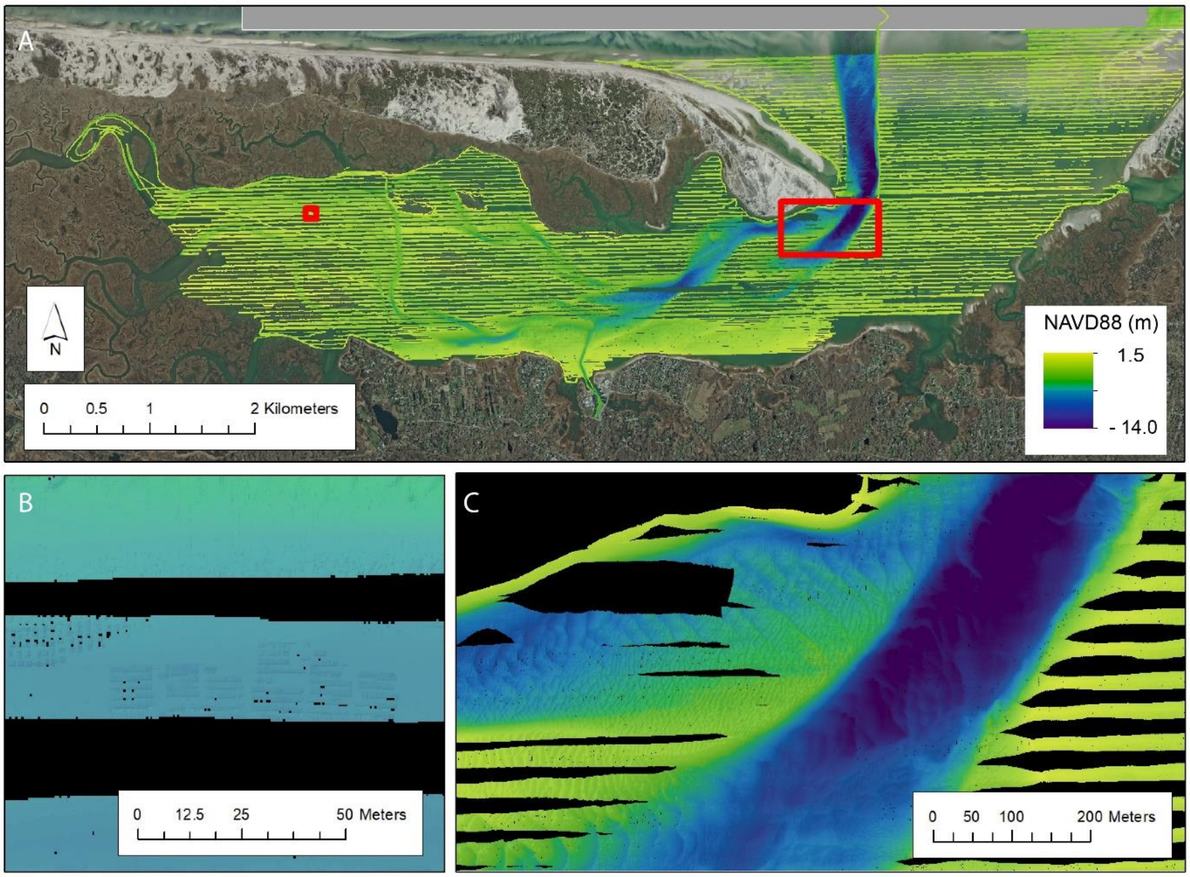

Figure 5. *Bathymetric data in Barnstable Harbor. (A): Digital Elevation Model, Grid resolution = 0.25 m^2. Red rectangles represent areas of interest below. (B): aquaculture site in the Harbor. (C): main channel in the Harbor.*

Salt marsh provides vital ecosystem services and sidescan sonar, though not designed to map salt marsh, can provide data on this resource as one of several ancillary data products that arise out of mapping the seafloor in shallow waters. The vessel-based surveys were not designed to capture the edge of the salt marsh and it is not a comprehensive map of the salt marsh edge in Barnstable Harbor, but as Figure 6 shows, where mapped, it can provide information to other investigators and managers about the status of the salt marsh. Further, it can yield data difficult to attain otherwise. Sidescan sonar imagery is essentially a 2-dimensional map with real-world coordinates attached to each pixel so in this instance the user can measure salt marsh position, determine which marsh shorelines are eroding and how much is being lost. The material on the seafloor would be difficult to see via aerial photographs and many of the salt marshes in Barnstable Harbor are inaccessible and/or difficult to get to get to for visual verification. Also, if divers or others were to visually locate pieces of sloughed off salt marsh it would be difficult to ascertain their position to with the accuracy and repeatability of the sonar data. The sidescan data could be used to ascertain locations, stakeout known areas of salt marsh erosion for repeat, land-based inspections. Borrelli et al, 2020 also developed a new method to map historical changes in salt marsh using aerial photographs and that method could be used in Barnstable Harbor to document historical changes in salt marsh.

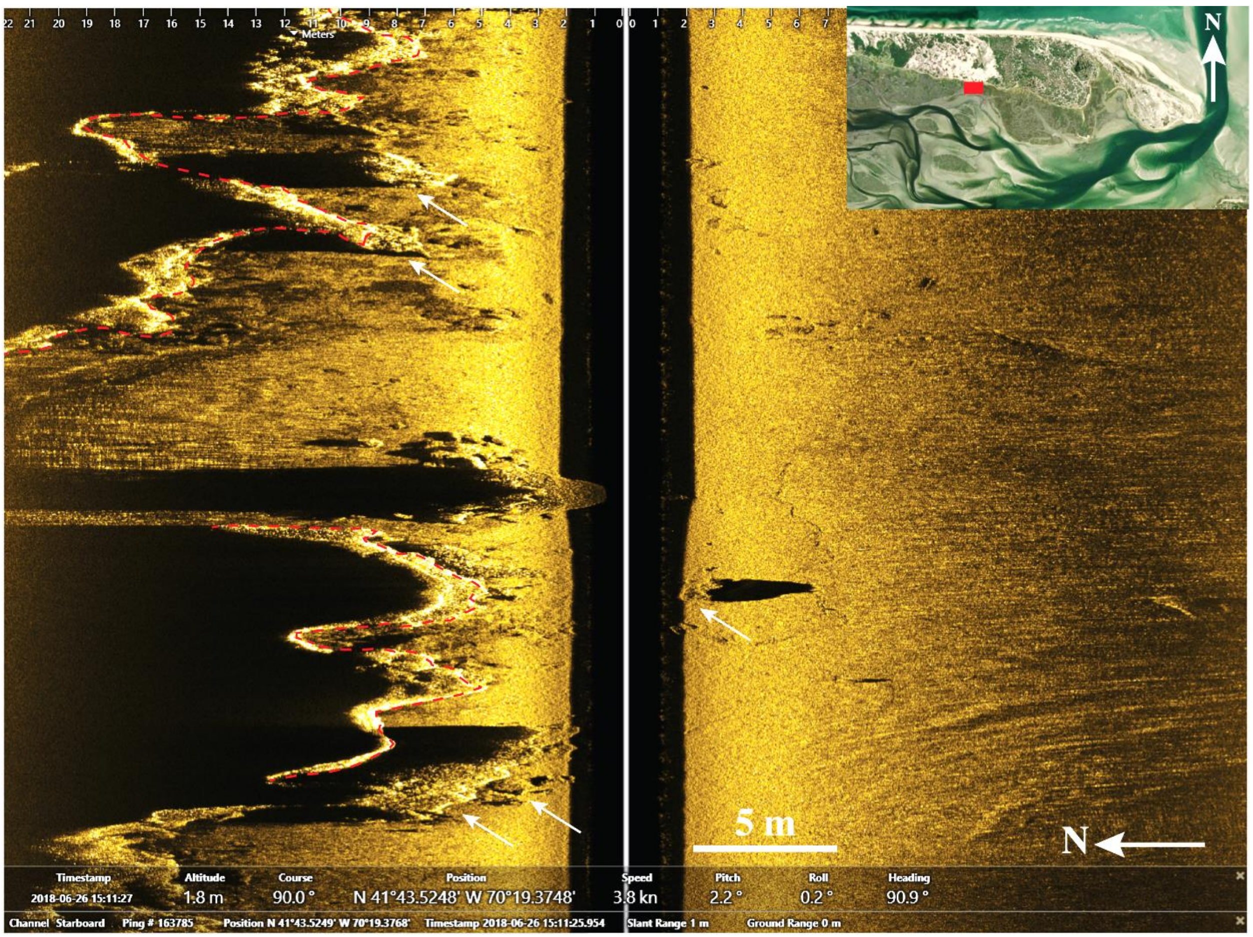

Figure 6. *Salt marsh and sidescan sonar. The red dotted lines denote the approximate location of the salt marsh edge. The white arrows indicate large pieces of salt marsh that have been eroded from the salt marsh edge. This is a 'raw' sonar image.*

3.2. Benthic Sampling

On October 1st, 2nd, and 4th 2018, 31 stations within Barnstable Harbor were sampled in triplicate, resulting in a total of 93 sieved and preserved biological samples. In addition, sediment samples, water quality parameter data, and video data were collected at each station. Sampling was stratified across 31 stations from including aquaculture (n = 3), intertidal (n = 7), intertidal creek (n = 7), subtidal creek (n = 7), subtidal (n = 7) as identified by sidescan imagery (Figure 1). Video data was collected at all 31 sites. Screen captures were taken (Appendix A) to classify each area. Stations were primarily sand habitat with several including mud (station 31) and woody debris (station 6); no stations contained eelgrass (Appendix A, Table A1).

3.2.1. Biological Characteristics

CMECS Biotic Component

Out of 89 taxa and 40,267 individuals (Appendix C) in Barnstable Harbor, 14 invertebrate species comprised 95% of all individuals. Since no invertebrates were detected at station 31, it had to be excluded from the biotic component and biotope analysis. PRIMER's SIMPROF and Cluster analysis indicated that the optimal number of clusters is 7 (Figure 7, Table 3). In a case such as this one, where one species (Amethyst Gem Clam, *Gemma gemma*) is the dominant species in multiple clusters (Table 3), CMECS recommends the use of the second most abundant species as a co-occurring element. Classifying each significant cluster into CMECS Biotic Communities based on dominance yielded 7 Biotic Communities, two of which (clusters 4 and 6) have the same dominate species and co-occurring element (Figure 8, Table 3). For a full list of biotic components by station see Table 6A.

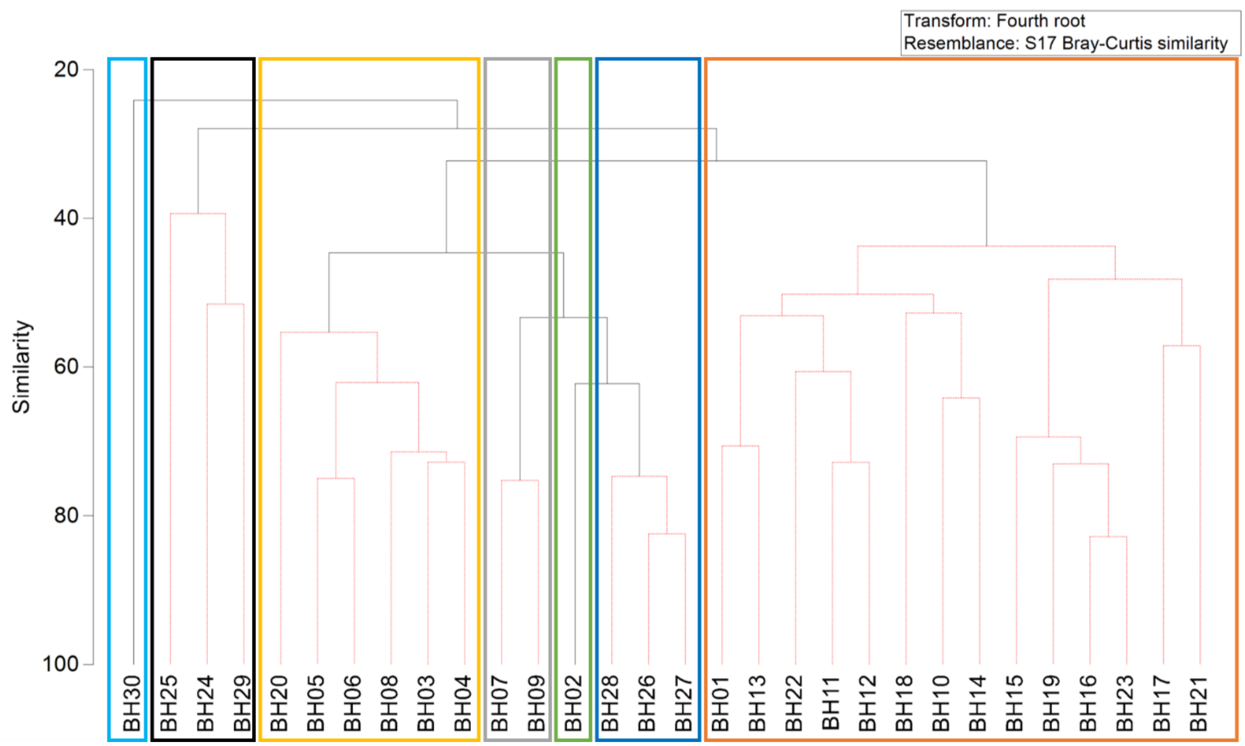

Figure 7. *PRIMER's cluster analysis based on species composition at each station. Colored boxes indicate clusters.*

Table 3. *Calculated clusters for Barnstable Harbor with most abundant species and component classification according to CMECS. Asterisk (*) indicates species not yet included in the official CMECS catalog.*

Cluster	**Dominant species**	**Second most abundant species**	**CMECS Biotic community**	**CMECS Biotic group**
Cluster 1	*Gemma gemma*	*Sphaeroma quadridentatum*	*Gemma gemma* bed with mobile isopod crustacean	Clam bed
Cluster 2	Hydrobia*	Haustoriidae sp	Hydrobia snail bed	Mobile mollusk on soft sediment
Cluster 3	Capitella sp.	*Streblospio benedictii*	Capitellid worm bed	Small surface-burrowing fauna
Cluster 4	*Gemma gemma*	Oligochaets	*Gemma gemma* bed with Oligochaet worms	Clam bed
Cluster 5	*Gemma gemma*	Capitella sp.	*Gemma gemma* bed with Capitellid worms	Clam bed
Cluster 6	*Gemma gemma*	Oligochaets	*Gemma gemma* bed with Oligochaet worms	Clam bed
Cluster 7	*Gemma gemma*	Haustoriidae sp	*Gemma gemma* bed with Haustoridae amphipods	Clam bed

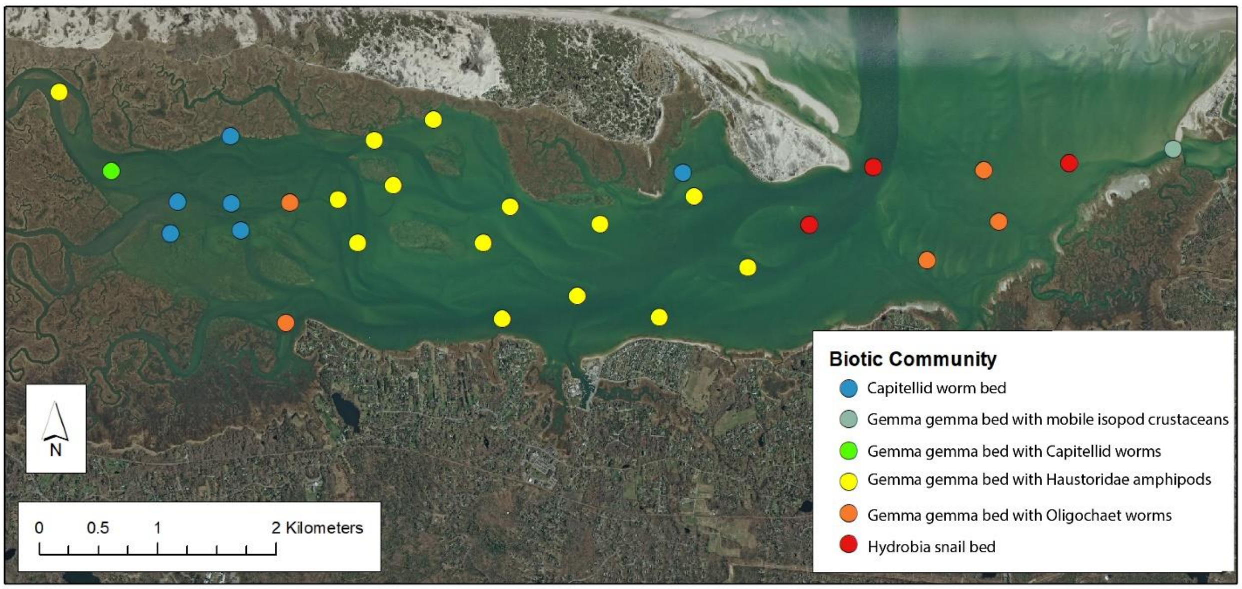

Figure 8. *CMECS Biotic Communities calculated based on dominant and second most abundant species.*

3.2.2. Physical characteristics

CMECS Geoforms

CMECS Geoforms were analyzed using the Benthic Terrain Modeler extension in ArcGIS v.10.6 from the bathymetric data collected during the acoustic survey. Slope, broad and fine scale BPI as well as the bathymetric data were utilized to classify the structures throughout Barnstable Harbor. Intertidal and subtidal flats, were the majority of Geoforms found throughout the system (Figure 9). Geoforms were produced from both the bathymetric data set from the acoustic surveys, and the bathymetric LIDAR that was flown over the area in the same season by the US Army Corps of Engineers (OCM Partners, 2022). Sidescan sonar and bathymetry were used to digitize the aquaculture cages in western Barnstable Harbor and were merged in the map creating the 8th geoform in the study area (Figure 10). The LIDAR Geoforms (Figure 11) were only used to confirm Geoforms for statistical analysis when the acoustic survey data did not overlap with an adjacent benthic invertebrate station.

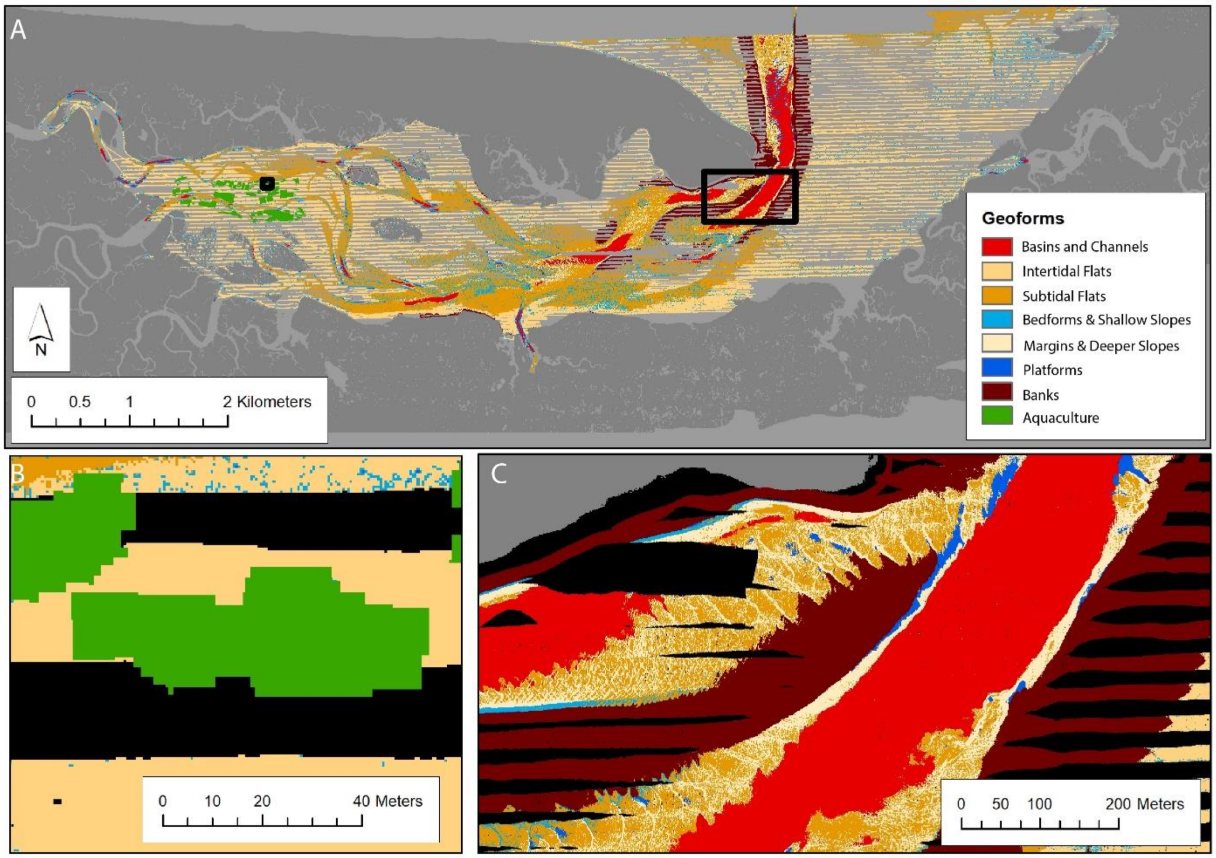

Figure 9. *Geoforms produced from acoustic bathymetric datasets. (A) An overview of the system's geoforms; (B) the hand digitized aquaculture geoforms from bathymetry and sidescan data; (C) Dynamic geoforms at, within, and around the main channel exiting the harbor.*

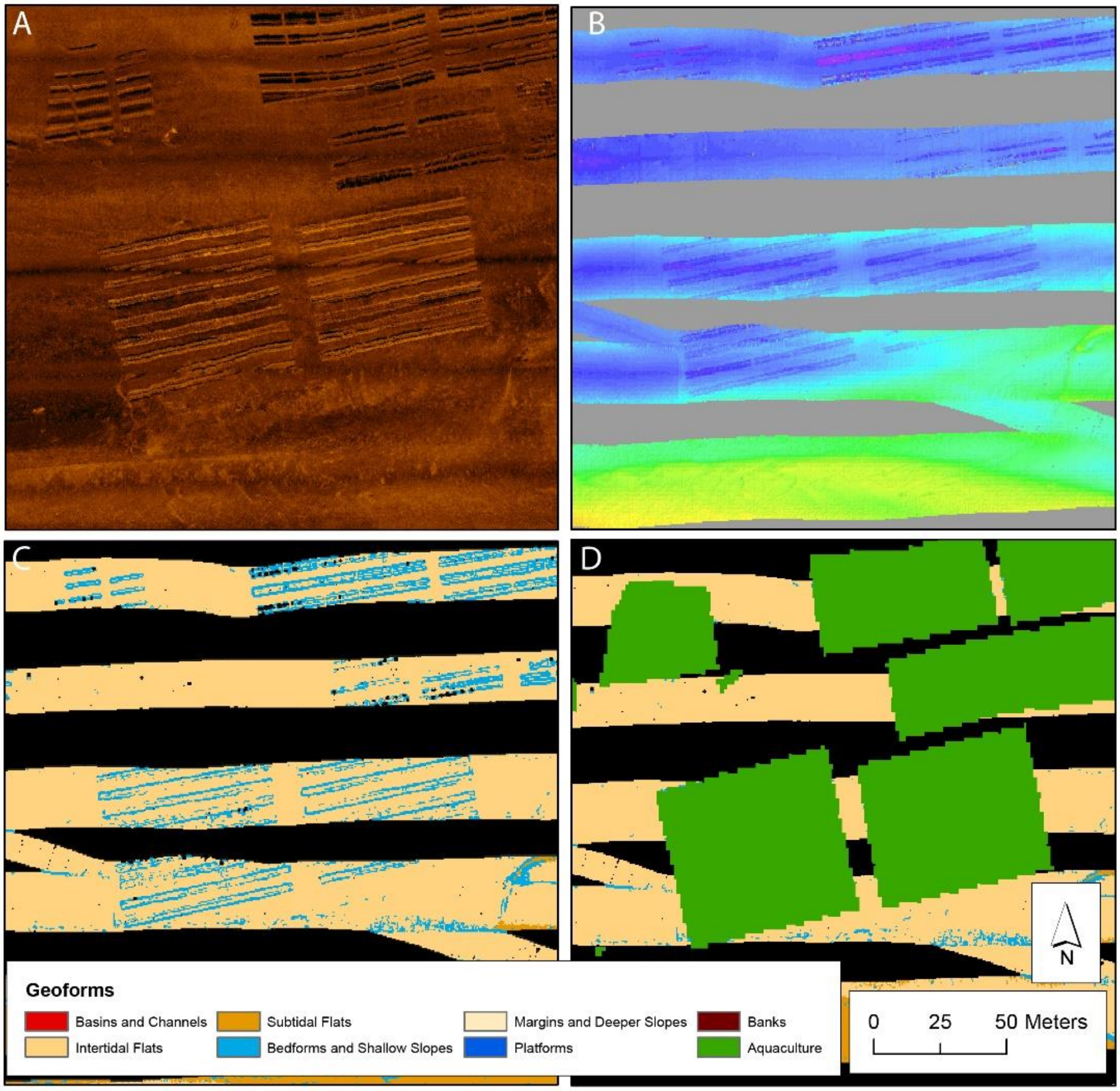

Figure 10. *Imagery of oyster aquaculture cages in sidescan sonar (A) and bathymetry (B) output of Benthic Terrain Molder (C) with oyster aquaculture cages identified as "Bedforms and Shallow Slopes". Modified Geoform map (D) with hand-digitization of areas identified from both the bathymetry and sidescan imagery as aquaculture gear.*

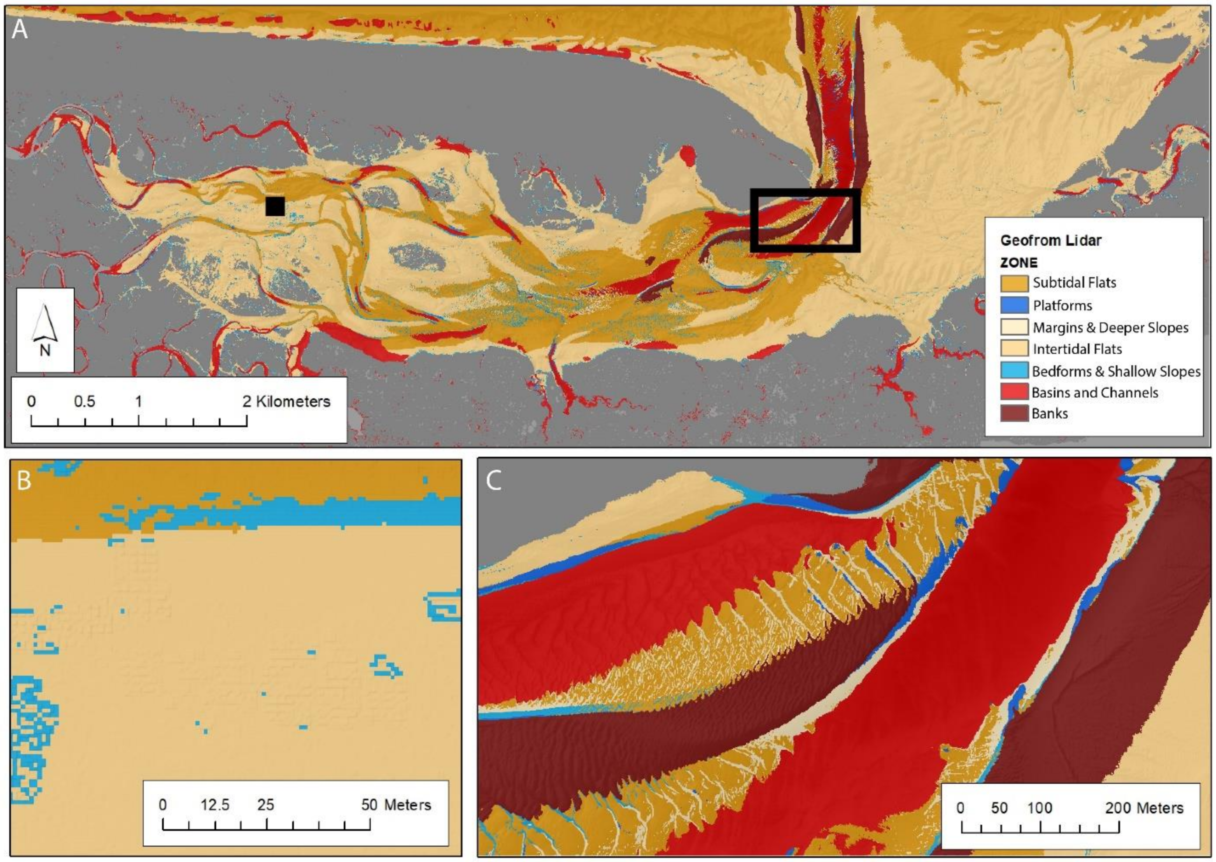

Figure 11. *(A) Geoforms produced from bathymetric LIDAR; (B) area containing aquaculture gear not readily visible in the coarse (1 m^2) data; (C) Geoforms of the main channel with less detail than that of the finer resolution (0.25 m^2) acoustic data.*

CMECS Substrate

For the CMECS Substrate Group and Subgroup classification, percent gravel, sand, silt and clay and median grain size (D_{50}) was interpolated between stations using the spline with barriers tool in ArcGIS v.10.6. Interpolated maps show the majority of sediment throughout the system to be slightly gravelly or sand while 6 stations were found to be muddy sand and mud (Figure 12, Table 4, Table 7A).

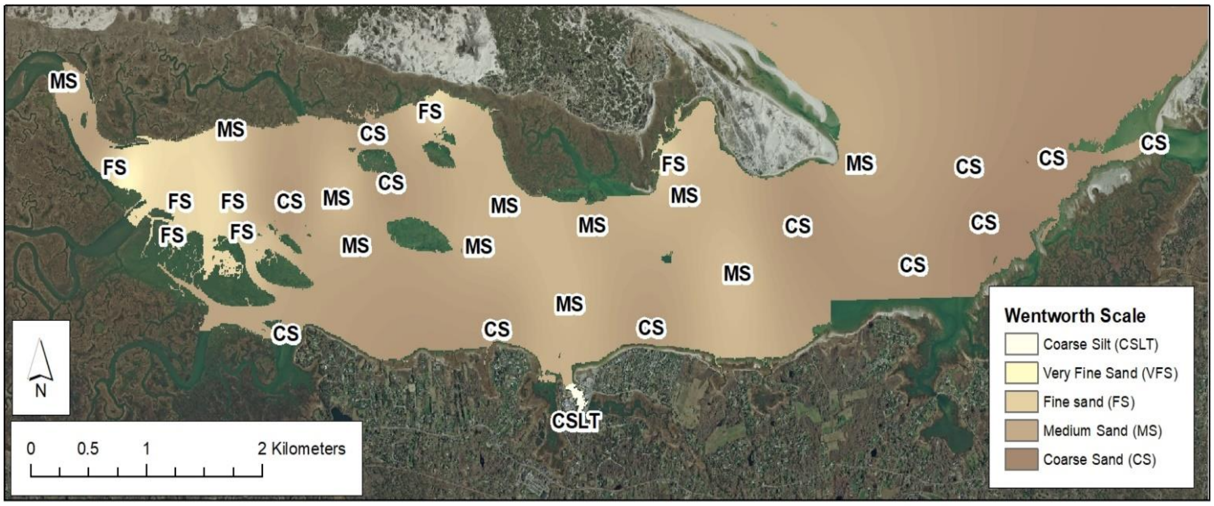

Figure 12. *Interpolated grain size across Barnstable Harbor using the Wentworth scale.*

Table 4. *CMECS Substrate and CMECS Geoform categories at stations 1-31 in Barnstable Harbor*

Station	CMECS Substrate	CMECS Geoform		Station	CMECS Substrate	CMECS Geoform
01	Sand	Intertidal Flat		**17**	Slightly Gravelly	Subtidal Flat
02	Muddy Sand	Intertidal Flat		**18**	Slightly Gravelly	Margins/Deeper Slope
03	Muddy Sand	Intertidal Flat		**19**	Slightly Gravelly	Shallow Slope
04	Muddy Sand	Intertidal Flat		**20**	Sand	Intertidal Flat
05	Muddy Sand	Intertidal Flat		**21**	Slightly Gravelly	Subtidal Flat
06	Muddy Sand	Basin/Channel		**22**	Slightly Gravelly	Shallow Slope
07	Slightly Gravelly	Subtidal Flat		**23**	Sand	Shallow Slope
08	Sand	Intertidal Flat		**24**	Slightly Gravelly	Margins/Deeper Slope
09	Slightly Gravelly	Intertidal Flat		**25**	Slightly Gravelly	Basin/Channel
10	Sand	Intertidal Flat		**26**	Slightly Gravelly	Intertidal Flat
11	Sand	Subtidal Flat		**27**	Slightly Gravelly	Intertidal Flat
12	Sand	Basin/Channel		**28**	Slightly Gravelly	Intertidal Flat
13	Sand	Shallow Slope		**29**	Slightly Gravelly	Intertidal Flat
14	Slightly Gravelly	Intertidal Flat		**30**	Slightly Gravelly	Shallow Slope
15	Slightly Gravelly	Intertidal Flat		**31**	Mud	Harbor
16	Slightly Gravelly	Subtidal Flat				

3.2.3. Preliminary Biotopes

Biotope categories were interpolated between stations using the *spline with barriers* tool in ArcGIS v.10.6. Interpolated maps display a reproducible representation of biotopes throughout Barnstable Harbor (Figure 13).

The results of PRIMER's DistLM show that a total of 72% of species distribution in Barnstable Harbor can be explained by sediment and grain size characteristics (

Figure 14, Table 2), with skewness (19.69%), % mud (9.0%), mode (7.33%) and Geoform (1.11%) explaining the majority. Skewness describes the degree of asymmetry. Positively skewed sediment grain size samples include a higher proportion of coarse-grained particles while negatively skewed samples include a higher proportion of fine-grained particles.

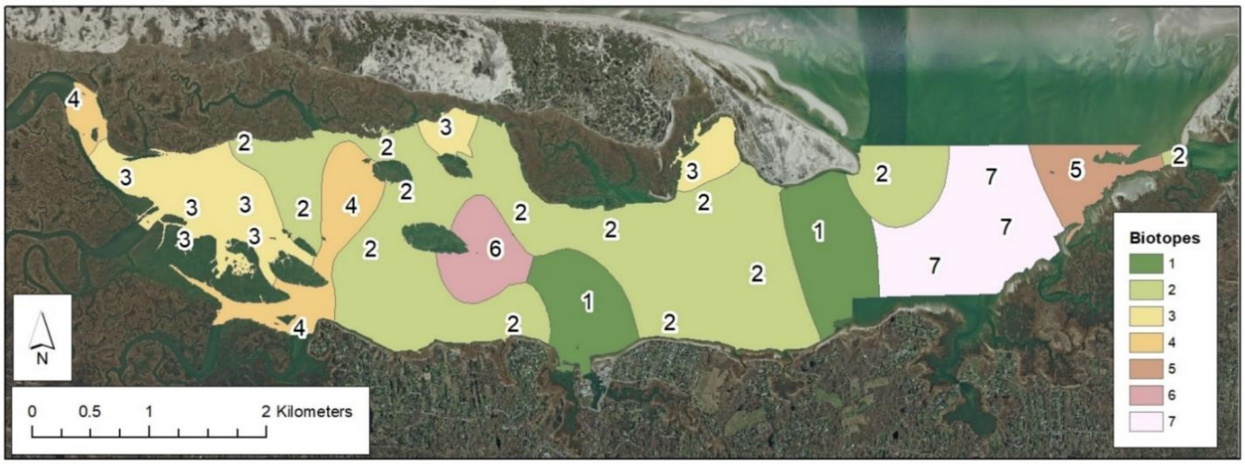

Figure 13. *Preliminary biotopes across stations in Barnstable Harbor. See Table 5 for physical, visual and biological descriptions of biotopes.*

LINKTREE showed two splits for Geoforms, separation stations into "margins and deeper slopes", "intertidal flats" and "other geoforms", one split for % mud, separating intertidal flats into "no mud" and "> 0% mud". One split of skewness and two splits for mode further separated the remaining 15 stations into 5 more biotopes (Table 5, Figure 15).

While indicator species were calculated for each biotope, the shear abundance of Amethyst Clams (*Gemma gemma*, n = 26,596) obscured any ecologically significant correlation between biotopes and individual species and resulted in *G. gemma* being calculated as indicator species for all biotopes.

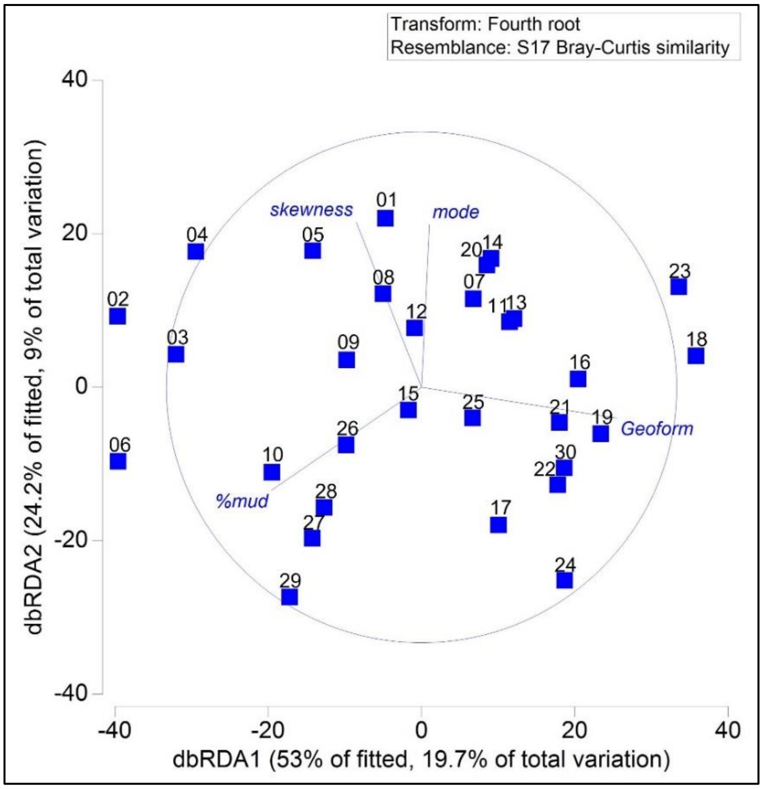

Figure 14. *Results of the DistLM analysis using Biotic Communities, sediment and grain size metric in a Non-metric multidimensional scaling plot. Axes are dimensionless, distance of symbols represents their relationship.*

***Table** 5. Physical, visual and biological descriptions on calculated biotopes.*

Biotope	Stations	Physical Description	Visual Description	Biological Description
1	18, 24	Margins and deeper slopes	97 % sand, 3% algae	Oligochaet Bed with mobile crustaceans
2	6, 7, 11, 12, 13, 16, 17, 19, 21, 22, 23, 25, 30	Other geoforms	83% sand, 6% gravel, 3% woody debris	*Gemma gemma* bed with mobile crustaceans
3	2, 3, 4, 5, 8, 14, 20	Intertidal Flat, some mud and granules	96% sand , 4% algae	*Gemma gemma* bed with small surface-burrowing fauna
4	1, 9, 10	Intertidal Flat, some mud and very coarse sand	99% sand, 1% shells	*Gemma gemma* bed with larger deep-burrowing fauna
5	29	Intertidal Flat, no mud and near symmetrically skewed	99% sand, 1% gravel	Oligochaet Bed with clam bed
6	15	Intertidal Flat, no mud, positively skewed and very coarse sand	100% sand	*Gemma gemma* bed with mobile crustaceans
7	26, 27, 28	Intertidal Flat, no mud, positively skewed and fine/very fine sand	94% sand, 4% algae, 1% shell and gravel	*Gemma gemma* bed with mobile molluscs

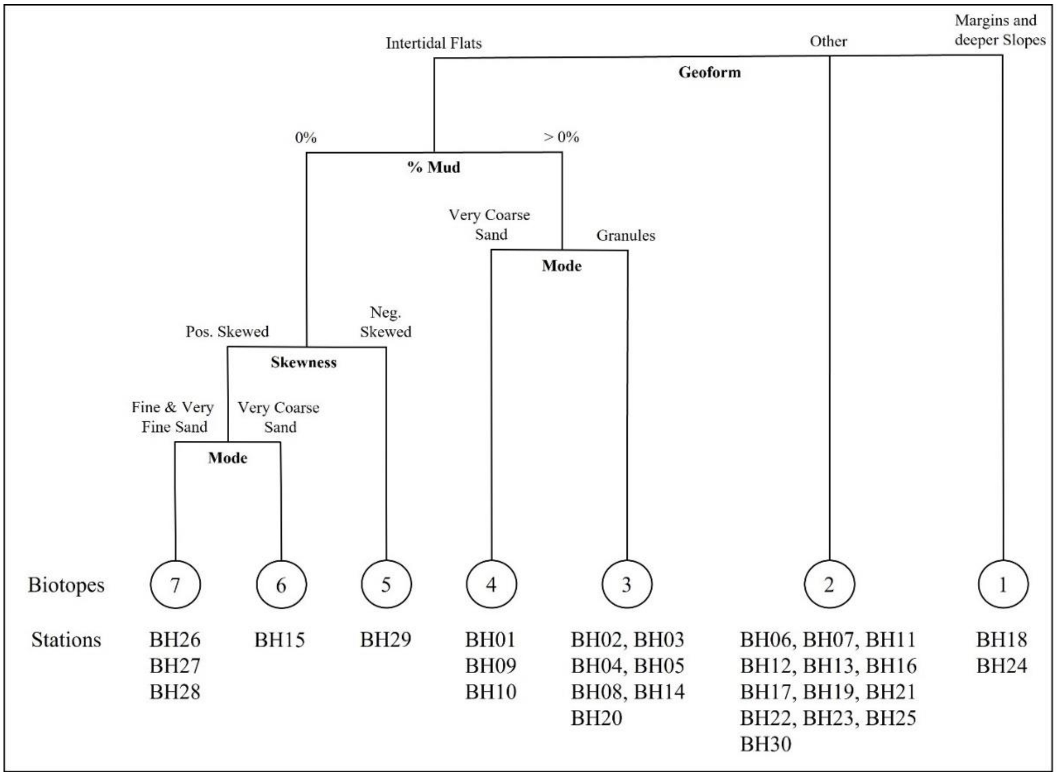

Figure 15. *Cluster diagram showing 7 optimal clusters (biotopes) based on sediment and grain size characteristics and the abundance of species that accounted for 95% of the total abundance in Barnstable Harbor.*

An ANOSIM conducted to determine the similarity between biotopes resulted in R=0.323 (p-value = 0.001) indicating different but overlapping biotopes. Since indicator species calculations were unreliable, a SIMPER (SIMilarity PERcentage) analysis was conducted to determine the species that contribute most to within biotope similarity, or how similar stations within one biotope are to each other and which species drives that similarity (Table 6). The analysis is only possible for biotopes including more than one station, biotopes 5 and 6 were therefore excluded.

Table 6. *Results of PRIMER's SIMPER analysis showing which species are responsible for inter-biotope similarity.*

Biotopes	Average Similarity (%)	Species	Contribution (%)
1	20.52	Haustoriidae sp	100
2	41.56	*Gemma gemma*	32.78
		Tellina agilis	26.85
		Haustoriidae sp	14
3	54.78	Capitella sp	26.11
		Gemma gemma	21.27
		Eteone longa	18.25
4	34.91	*Gemma gemma*	43.32
		Eteone longa	27.29
7	77.26	*Gemma gemma*	32.01
		Oligochaets	11.42
		Nereis succinea	10.87

4. Discussion

Barnstable Harbor presented many difficulties when mapping. The harbor has many shallow water and intertidal areas which present the surveyors with navigation hazards and time of survey restrictions. The shallow water portions of the harbor were typically only accessible approximately two hours before and after high tides, this somewhat restrictive survey window is not uncommon in many similar embayments on Cape Cod, but this couple with the size of the harbor and the shallowness of these areas made it particularly challenging. Further, the western portion of the harbor has an extensive aquaculture fishery which posed additional challenges (Figure 16). Much of the aquaculture gear is several inches off the bottom and therefore is more of a potential hazard to towed sonar gear. No such interactions occurred during the surveys of the Harbor despite these areas being well mapped.

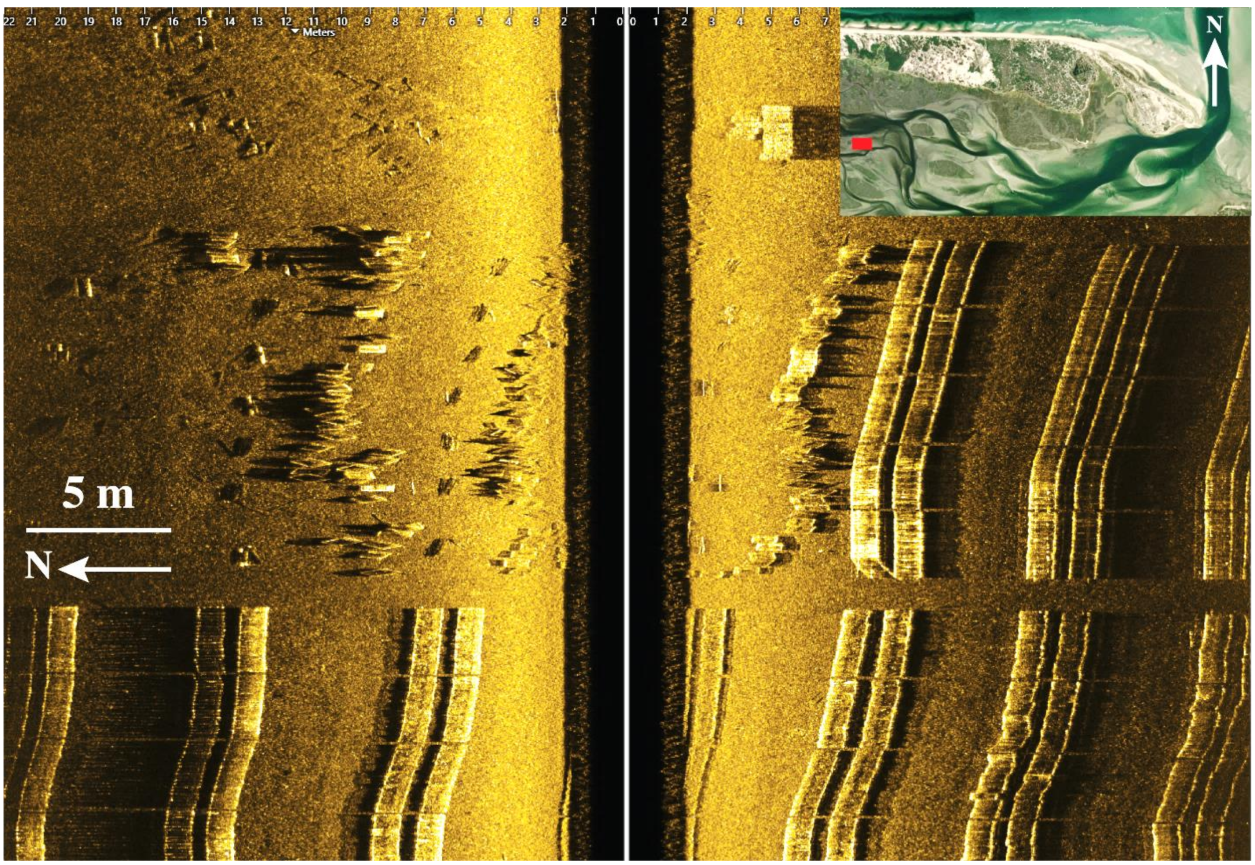

Figure 16. *Intertidal aquaculture. A sidescan sonar image of an aquaculture area from the harbor survey. This is a 'raw' sonar image.*

Sidescan sonar data has proven to be useful to look at changes to the bottom in terms of grain size, bed roughness, submerged aquatic vegetation and general habitat information. Areas with aquaculture gear on the seafloor can have impacts in this regard and sidescan sonar data can provide quantitative data on the changes to these areas through time. The data collected here provide a baseline data set for these areas that future change can be measured against.

Aquaculture fisheries can be monitored with acoustic (sonar) as well as other data collection techniques. Sidescan sonar data can provide a spatially extensive base layer upon which checks can be scheduled to look at impacts from the gear in specific areas. The sidescan mosaic is easily imported into a GIS database and can be used to examine other data with relation to bottom changes. For examples, water quality sampling stations could be overlain onto the sidescan data or in fact the benthic habitat maps and changes seen since the mapping took place in 2018 can be analyzed and drivers for the change better identified.

Marine debris is a large problem for coastal ecosystems and managers. The recovery of derelict, lost, abandoned, or discarded fishing gear or other debris in marine and freshwater environments has become an important tool worldwide for reducing debris in waterways and thus mitigating impacts to habitat and living resources. Recovery projects which use sonar to locate targets and assess their habitat impacts require users to interpret acoustic data for effective and efficient removal efforts. The advancements in survey technologies have allowed for the interpretation of gear as it relates to habitat and conditions of surrounding areas. Center staff have this expertise and have shown that marine debris is present in places throughout Barnstable Harbor (Figure 17).

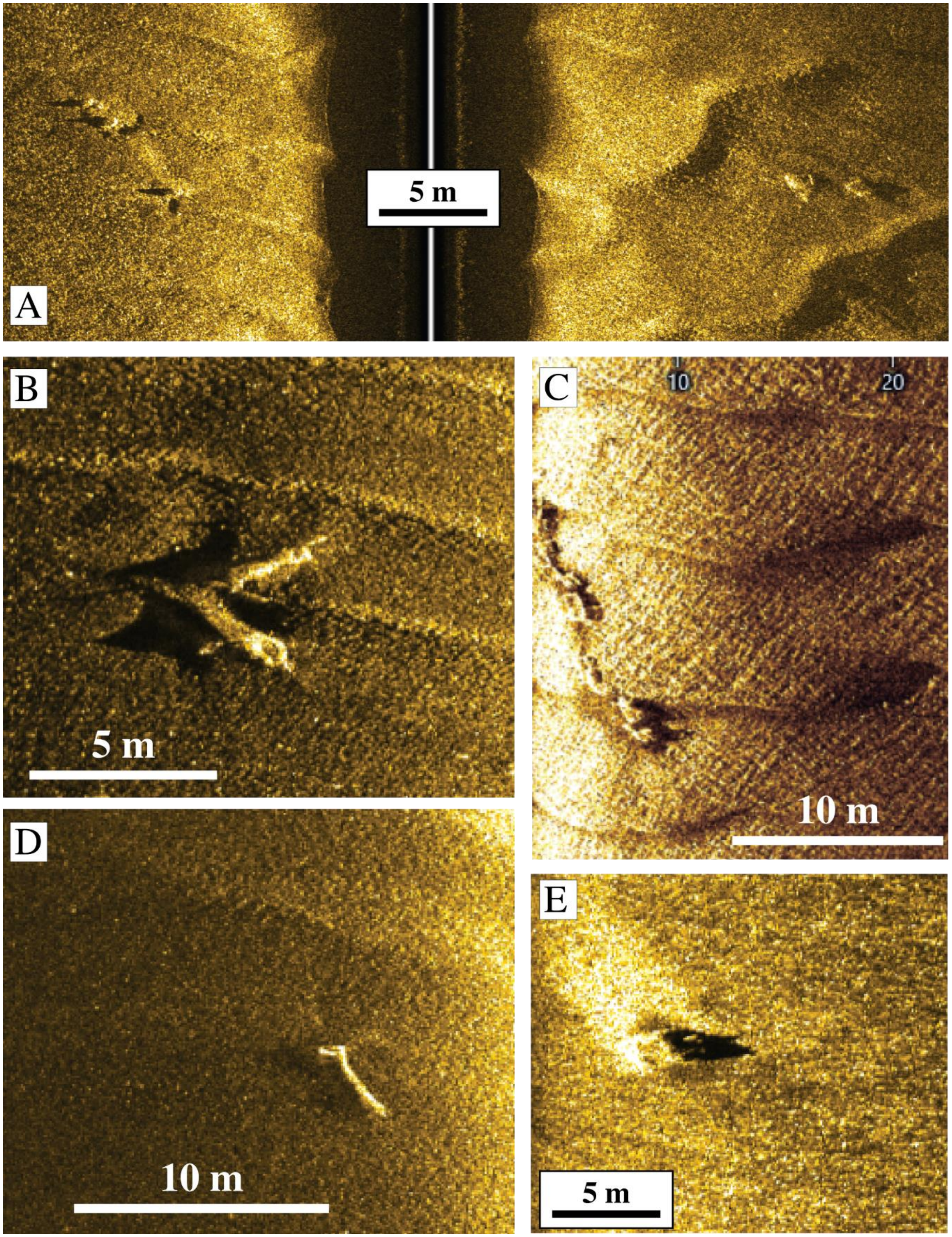

Figure 17. *Examples of Marine Debris in Barnstable Harbor. A: Raw sidescan sonar image. Left side shows unidentified marine debris, note - tall shadows indicating height off the seafloor. Right side two rectangular shaped objects. B: Large unidentified marine debris. C: Possibly a lobster trawl with line or other debris tangled into gear. D: large unidentified marine debris. E: Square-shaped marine debris note the different bottom type to the upper right. This could be an example of marine debris altering the bottom type.*

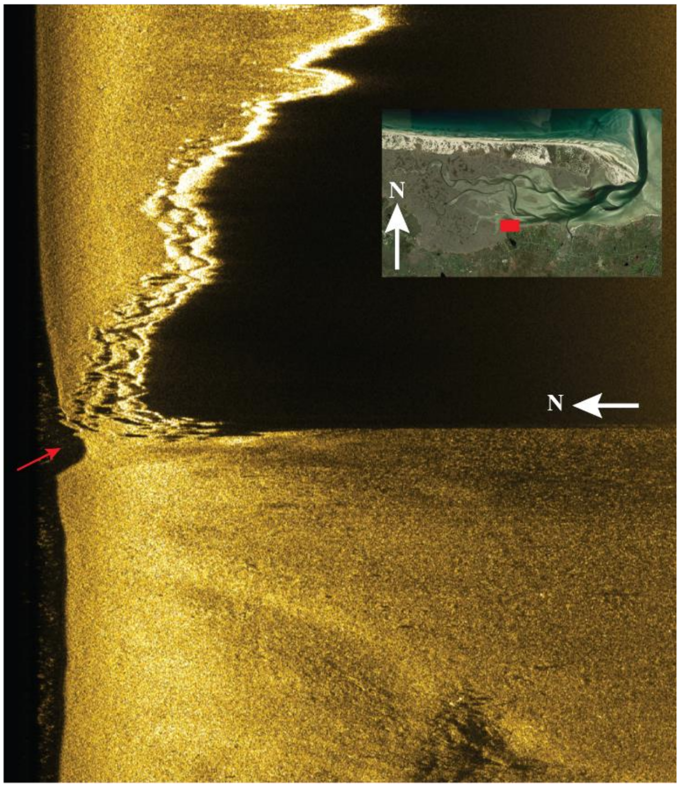

Figure 18. *An eroding marsh edge with sections of marsh falling into the nearby channel.*

Another useful data set that can be extracted from vessel-based acoustic data is the sub-tidal or intertidal information on coastal structures. Figure 18 shows an eroding marsh edge along the roughly northward facing shoreline. The red arrow shows an area with a channel at the edge of the marsh. This could, over time, work to undermine the stability of the marsh if accretion does not keep pace with erosion. Further examination indicates that this patch of marsh, lost about 500 m^2, approximately 1.5% per year. Using these data with repeat surveys, acoustic or otherwise, over time to monitor the areas may show that the channel is infilling, and threat of undermining is decreasing or that the channel is deepening, and the hazard may be rapidly increasing. Repeat surveys would also show the rate of change in these critical areas and could guide management options. Data on docks, piers, pilings, and other structures could also be assessed as could nearby natural resources.

4.1. Benthic Habitat Mapping

4.1.1. Data Analysis and Classification Approach

The approaches used for data analysis and classification for this study were chosen based on previous work in similar environments (Borrelli et al., 2019a; Mittermayr et al., 2020a; Mittermayr et al., 2020b) with the broad goal to delineate ecologically meaningful map units rapidly and reproducibly and create maps using CMECS as a common language. The choice of analysis and classification approach was adapted to what the desired map products were. The raw data collected, analyzed and classified in this project can be used to address multiple question and provides a baseline for future ecological monitoring.

Mapping the CMECS Geoform Component

CMECS Geoform component analysis, reliant on acoustic surveys, identified 8 Geoform types in Barnstable Harbor (Figure 9, Figure 11, Table 4, Appendix D): Basins/Channels, Bedform and Shallow Slopes, Harbor, Intertidal Flats, Margins and Deeper Slopes, and Subtidal Flats. However, the non-bathymetric physical variables withing CMECS Geoforms (percent mud, percent sand, percent gravel, organic content) show us that Geoforms are not compositionally distinct, instead they often overlap. For example, intertidal and subtidal flats could not be separated by grain size metrics as they overlapped. Indeed, CMECS does not differentiate between intertidal and subtidal flats and instead uses the term "tidal flats" to describe this type of geofom (Appendix D). From a biological standpoint, these areas are vastly different as many marine species cannot survive outside the water, resulting in different species assemblages. CMECS was created to be adaptable to such situations and by differentiating subtidal and intertidal flats we were able to create habitat maps that more accurately describe Barnstable Harbor. While we did attempt to calculate indicator species for each of the five Geoforms (the sixth Geoform "Harbor" was omitted for this exercise as no invertebrate species were found there), the overwhelming abundance of the Amethyst Gem Clam (*Gemma gemma;* Figure 19, Table 3) obscured any ecological significance. *G. gemma* was calculated to be indicative of subtidal flats, intertidal flats and shallow slopes. Oligochaete and Capitellid worms were indicative of deeper slopes and basins/channels respectively, albeit statistically insignificant. In order to model and understand system changes, particularly if future studies are conducted by researchers with differing skill sets, utilizing an unsupervised classification scheme (e.g. benthic terrain modeler - BTM) is ideal as it has high agreement with the physical features identified in this analysis, and has been used extensively across the region. However, certain areas, e.g. man-made structures such as oyster culture gear, can be difficult to incorporate (Figure 16). Here we utilized both the sidescan imagery and bathymetric datasets to hand digitize the aquaculture cages to augment what the BTM cannot accomplish.

Figure 19. *Invertebrate species commonly found in Barnstable Harbor. Top left: Haustoriidae amphipod, top right: Amethyst Gem clam (G. gemma), lower left: Hydrobia snails, lower right: Sphaeroma quadridentata.*

Mapping the CMECS Substrate Component

The CMECS substrate classification based on weight percentages of gravel, sand, silt and clay was sometimes different than the classified interpolation of median grain size. Neither classification is wrong, but the differences in these two approaches demonstrate the complexity in decision-making required for benthic habitat mapping. The full coverage median grain size map (Figure 12, Table 2) is built on the assumption that sediments conform to gradients in the study areas (i.e., there are no stark boundaries in sediment type). The gradient model could be more often true than a discrete-boundary model, but there are certainly observed examples of the latter. However, sources of error in the interpolation process, and sampling spacing that does not match the scale of environmental heterogeneity should both be considered to influence the accuracy of the resulting substrate maps. In spite of these drawbacks, we opted to interpolate sediment characteristics instead of hand-drawing boundaries from aerial photography, bathymetry, and/or sidescan backscatter. Although those methods have been traditionally used by experienced coastal geologists, we assumed that the results would not be repeatable, nor would the knowledge and experience required to interpret such data be easily transferred to new staff, students, or other analysts.

Mapping the CMECS Biotic Component

For this study, dominance was used as the metric to define Biotic Communities, and Indicator Species Value (IndVal: a measure of the specificity and fidelity of a species) as the metric to define Biotopes. Using dominance is recommended in the CMECS Technical Guidance Document (FGDC, 2012), but can cause classification confusion when a single species may be dominant in several statistically distinct assemblages, as was the case in Barnstable Harbor for *Gemma gemma* at clusters 1, 4, 5, 6, and 7. *Gemma gemma*, or the Amethyst Gem Clam (Figure 19) is a very small (5 mm and smaller) clam that is abundant along Cape Cod coastlines and along the Atlantic coast of the US. In such cases, CMECS recommends the use of a co-occurring element by determining the second most abundant species for each cluster. This resulted in six distinct descriptions for seven clusters (Figure 7). Clusters 4 and 6 showed the same dominant (*G. gemma*) and second most abundant (Oligochaet worms) species. Determining an additional co-occurring element was attempted and resulted in Capitellidae worms (cluster 4) and Hydrobia snails (cluster 6) (Figure 15, Table 5) as second co-occurring element. Another option is to use a different metric to describe Biotic Component units altogether however, this is not recommended in the CMECS Technical Guidance document. This significant overlap in biotic communities between clusters underscores the importance of multiple components which, combined, can elucidate significant descriptors for Barnstable Harbor in particular and other coastal environments in general.

This study used the Indicator Species Value for species in each calculated biotope because it is a rapid and reproducible way to add biological information to a map based on sediment variables. The Indicator Species Value determines which species are both abundant in a certain biotope *and* rarely found in other biotopes (i.e., have high biotope fidelity). A permutation of the data provides a measure of significance. The association between a biotope and an indicator species can be used to predict species presence, given the presence of the biotope, or vice versa. In this way, indicator species can be valuable in repetitive mapping or habitat monitoring. Crucially, indicator species may not be dominants, but if they are identified in subsequent surveys, their presence may be used to infer a particular biotope type. However, due to the high abundance of *G. gemma* (more than 50% of individuals found were *G. gemma*), calculations resulted in this clam as indicator species for multiple biotopes as well as geoforms and other sediment characteristics used in the calculation of biotopes. This, as described above, negates the use of indicator species, and while an important tool, this exercise was not valuable in the case of Barnstable Harbor.

Preliminary Biotopes

To determine biotopes in Barnstable Harbor, sediment and grain size variables and infaunal abundance were examined as part of the biotope analysis. A total of 72% of species distribution could be explained by PRIMER’s distance based linear model (DistLM). The four most important drivers in terms of species distribution, explaining a total of 37.1%, were skewness, % mud, mode and geoform (

Figure 14) with the remaining thirteen sediment characteristics explaining the other 35.8%. LINKTREE (Figure 15) analysis showed a classification tree with six splits, resulting in 7 biotopes. An analysis of similarity (ANOSIM) showed that the calculated biotopes were “different but overlapping” (R= 0.32, p-value: 0.001). R-values smaller than 0.25 indicate high similarity, values between 0.25 and 0.5 indicate different but overlapping groups and values of more than 0.5 indicate high variation. An in-depth look at the analysis revealed that certain biotopes (4 and 6) exhibit higher dissimilarity within biotopes than between biotopes. While the within-biotope differences were not significant, they explained the low overall R-value. The similarity percentage (SIMPER) analysis explains which species are responsible for similarities between stations within biotopes. The analysis is only possible for biotopes with more than one station. While the Amethyst Gem clam (*Gemma gemma*) features as a contributing factor for inter-biotope similarity several times it is important to remember that not just prescence/absence of species determine biotopes, but also abundance of species. For example, biotope 7 (intertidal flats, no mud, positively skewed, fine/very fine sand with *G. gemma* bed with mobile molluscs) has a high within-biotope similarity (77.26 %) because every station within this biotope features incredibly high abundances of *G. gemma* (n > 1000), while biotope 2 (other geoforms with *G. gemma* bed with mobile crustaceans) features low abundances of *G. gemma* and high abundances of Haustoriidae Amphipods (average similarity: 41.56%).

Water column parameters (salinity, pH, dissolved oxygen and temperature) were excluded because they are influenced by many factors such as tides, weather, climate and nutrient loading, among others, which have not been investigated in the course of this project, and are likely changing at a faster pace than species in Barnstable Harbor can move. It is known that water quality greatly influences benthic habitat quality (Howes et al., 2006b) and factors such as dissolved oxygen likely play a role in driving the composition of benthic communities. More research, across multiple seasons and years, needs to be conducted in order to establish and integrate a sound water column component baseline.

Previous work using CMECS and similar statistical analyses, could explain 21-84% of the variance in benthic assemblage structure (Borrelli et al., 2019c; McHenry et al., 2017; Shumchenia and King., 2010). These studies place the results of this work in context, and indicate that the results reported here are well within the range of expectations for the methods used.

Stations 4, 5, and 7 were initially classified as aquaculture, however there was no significant difference to other stations based on species diversity and abundance. Indeed, stations 4 and 5 are part of biotope 3 and station 7 belongs to biotope 2, indicating that in this case mode, % mud, and skewness are more important in determining biotopes than artificial structures.

Among the various publications on studies conducted in Barnstable Harbor, three stood out because of their focus on invertebrate species: (Green and Hobson, 1970; Sanders et al., 1962; Whitlatch, 1977). The sampling methods and location described in these studies are not reproducible: “The precise sampling area at each station was determined by the site of impact of an object thrown by a rapidly rotating investigator." (Sanders et al., 1962). Nevertheless, valuable information could be gained on sediment grain size and species diversity in the Southwestern part of Barnstable Harbor, near Huckins Island. Sorting of sediments shifted from very well and moderately well sorted in the 1960s and 1970s to poorly sorted in 2018 and % mud decreased over time (Table 7).

Table 7. *Sediment grain size data from Sanders et al 1962, Green and Hobson 1970, Whitlatch 1977 and this study (2018) with MLW indicating mean low water.*

Year	Station	% Mud	Median grain size	Sorting
1962	A	0.62	fine sand	very well sorted
1962	B	20.46	very fine sand	very well sorted
1962	C	3.04	fine sand	very well sorted
1962	D	4.97	fine sand	very well sorted
1962	E	5.54	fine sand	very well sorted
1970	60 (cm above MLW)	1.1	fine sand	very well sorted
1970	90 (cm above MLW)	0.9	fine sand	moderately well sorted
1977	1	11.90	fine sand	very well sorted
1977	2	20.90	fine sand	very well sorted
1977	4	1.30	coarse sand	well sorted
1977	5	48.60	very fine sand	very well sorted
1977	10	4.10	medium sand	well sorted
1977	11	2.50	medium sand	well sorted
2018	08	0.06	fine sand	poorly sorted
2018	09	0.04	coarse sand	poorly sorted
2018	11	0.03	medium sand	poorly sorted

Faunal samples in the literature (Green and Hobson, 1970; Sanders et al., 1962; Whitlatch, 1977) were collected by coring and sieved through a 0.5 mm sieve, while this study used a Young-modified Van Veen grab and a 1 mm sieve. 11 species (7 Annelida, 2 Crustacea and 2 Mollusca) were found during all four sampling years while 21 species (9 Annelida, 5 Crustacea and 7 Mollusca) were found both in the 1960s/1970 and 2018. 45 species were only found in the earlier studies while 56 were only found in 2018 (Table 8).

Table 8. *Numbers of invertebrate species split up by groups (Annelida, Crustacea, Mollusca) collected for Green and Hobson 1970, Sanders et al 1962, Whitlatch 1977 and this study (2018)*

Year	Station	Species	Annelida	Crustacea	Mollusca
1962	A	14	6	0	4
1962	B	26	11	6	6
1962	C	37	15	5	10
1962	D	51	22	9	10
1962	E	37	15	10	8
1970	60 (cm above MLW)	13	19	4	10
1970	90 (cm above MLW)	9	17	4	9
1977	1	19	17	2	6
1977	2	12	12	1	1
1977	4	12	12	0	1
1977	5	15	13	2	1
1977	10	8	8	1	1
1977	11	4	4	0	1
2018	BH08	24	12	5	7
2018	BH09	21	7	5	8
2018	BH11	10	3	2	4

When it was available, information on range distribution of species was collected for all four studies. This was the case for 116 species. Ranges were divided into Virginian (V) – south of Cape Cod, Acadian (A) – north of Cape Cod and cosmopolitan (C) – present both south and north of Cape Cod (Table 9).

Table 9. *Range of species collected for Green and Hobson 1970, Sanders et al 1962, Whitlatch 1977 and this study (2018). V indicates Virginian, A indicates Acadian and C indicates cosmopolitan distribution.*

Year	Annelida			Mollusca			Crustacea		
	V	A	C	V	A	C	V	A	C
1962	1	0	22	0	0	16	1	1	13
1970	2	1	13	0	0	10	0	0	3
1977	5	2	22	0	0	6	0	1	8
2018	6	4	11	2	0	21	6	4	9

While the overall diversity did not significantly change (R: 0.264, p-value: 0.028) over the years, and increase in Virginian species could be observed. Particularly the presence of Mollusca and Crustacean species with a southern range increased (from 0 to 2 in the case of Mollusca and from 1 to 6 in the case of Crustacea). These numbers have to be considered ancillary as neither of the four studies was designed to look at range distribution of species and its changes over time. Nevertheless, Cape Cod is the biogeographical boundary between the Acadian (Nova Scotia to

Cape Cod) and Virginian (Cape Cod to Cape Hatteras) provinces (Hutchins, 1947) and an increase in cosmopolitan and Virginian species might be indicative of a shift to warmer water species.

The use of video analyses has become an important component of habitat assessment as they allow researchers to verify the micro-habitat (e.g. habitats on the meter scale) conditions that can influence the community structure, thus reducing the uncertainty in the analysis. Although in this study the benthic habitat surveyed was primarily sand (with minimal amounts of vegetation, debris and/or hard structures), the video analysis allowed us a better understanding of the conditions in which the samples were collected.

Sources of Uncertainty

There are many sources of uncertainty to consider in "snapshot" surveys of the environment. First, the uncertainty in the representativeness of the observations themselves – do the measured parameters deviate over time, and on a regular basis? It is extremely likely that there is temporal variation, but that type of variability cannot be assessed with the data collected for this study. The data collected for this study provide a baseline from which future variability could be measured and assessed.

Second, there are sources of uncertainty in the selected analysis methods, including mapping. In order to map the data, assumptions were made that the mean infaunal abundances at each station or the median grain size were appropriate representatives of the datasets. A potentially large source of uncertainty in the maps produced for this study is the interpolation procedure. The tradeoff of certainty for full coverage and reproducibility was considered to be worthwhile. The alternatives to this approach would be either point-based maps (not full coverage), or manually-drawn boundaries inferred from aerial photography, bathymetry, and/or backscatter imagery with assigned classifications based on a summary statistic (not reproducible).

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6. Appendix A – GoPro® screen grabs

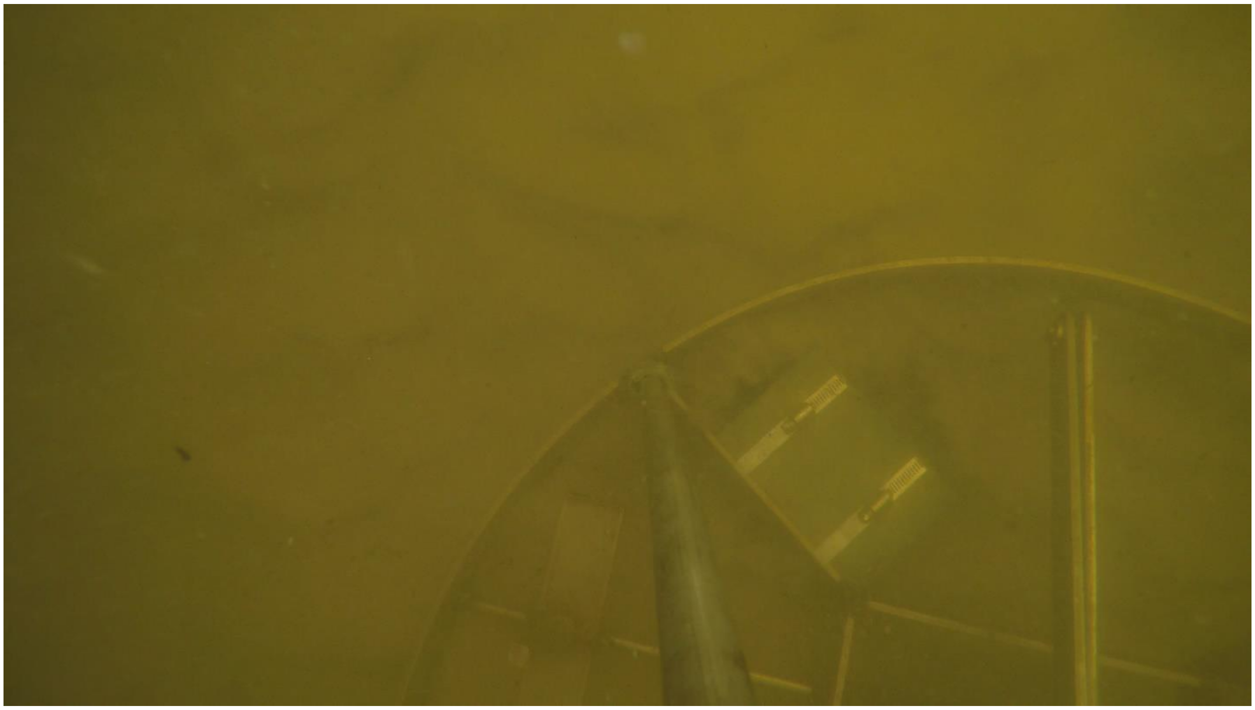

Figure A1. *GoPro Screen capture from station BH_01*

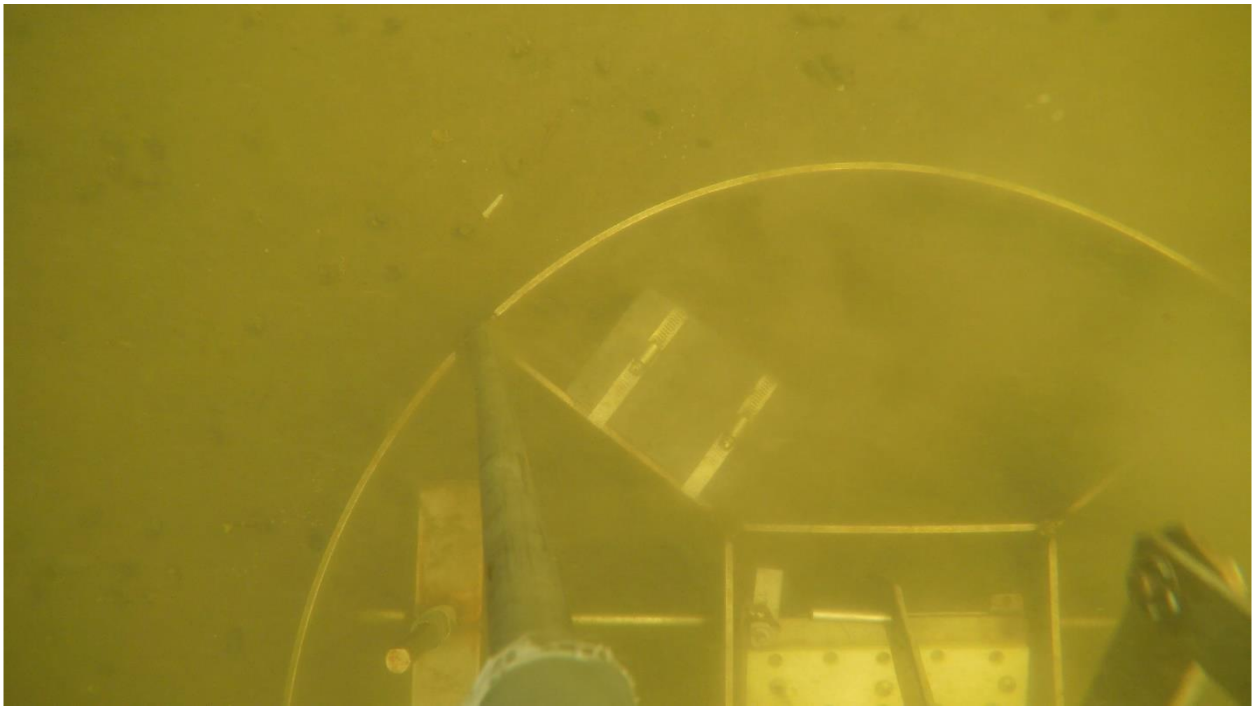

Figure A2. *GoPro Screen capture from station BH_02*

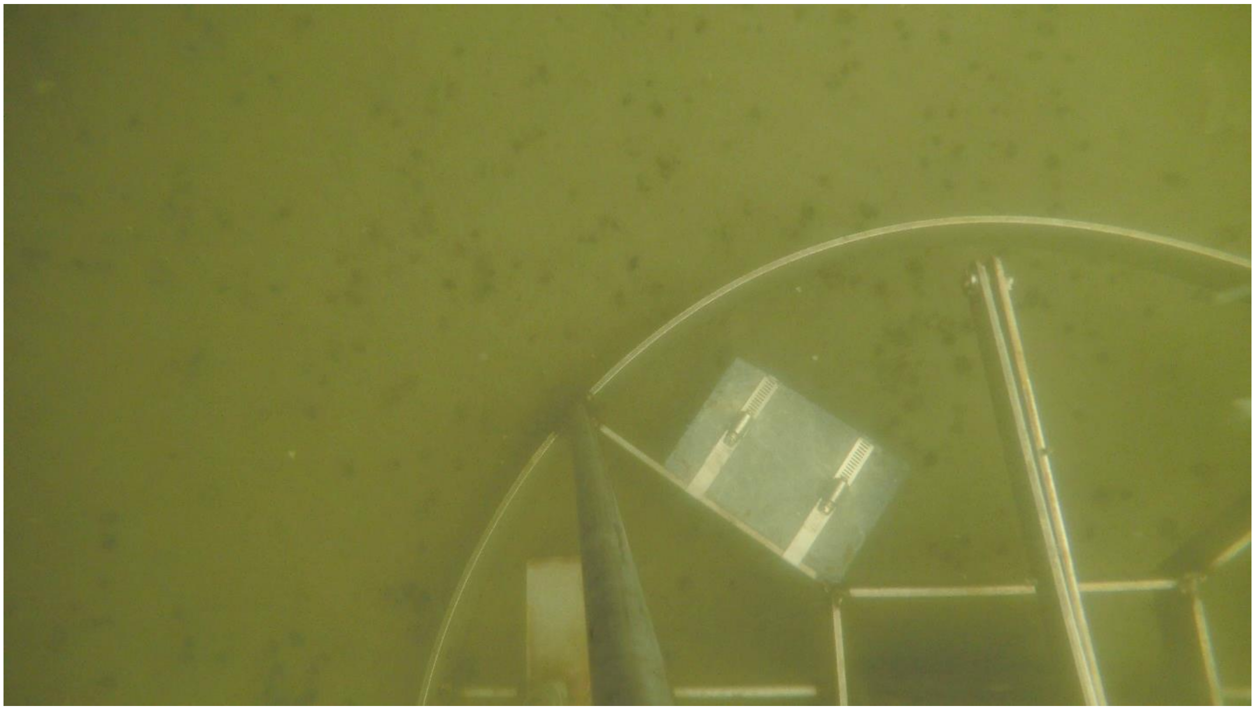

Figure A3. *GoPro Screen capture from station BH_03*

Figure A4. *GoPro Screen capture from station BH_04*

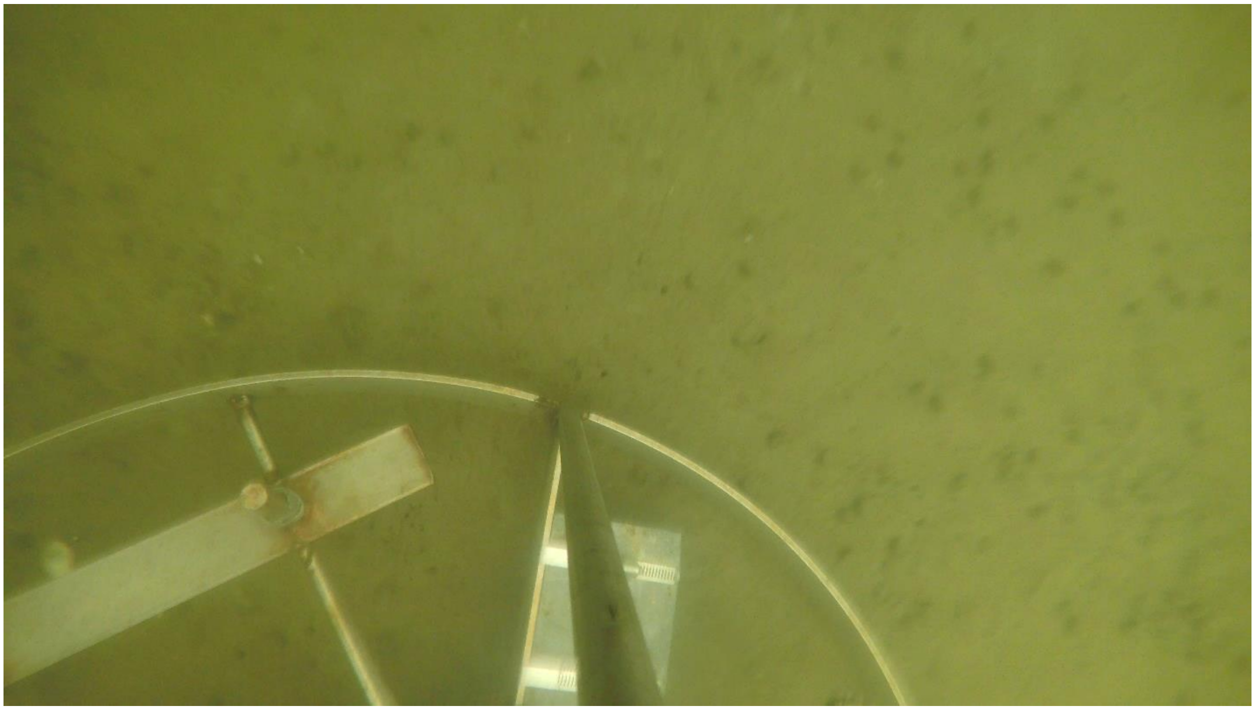

Figure A5. *GoPro Screen capture from station BH_05*

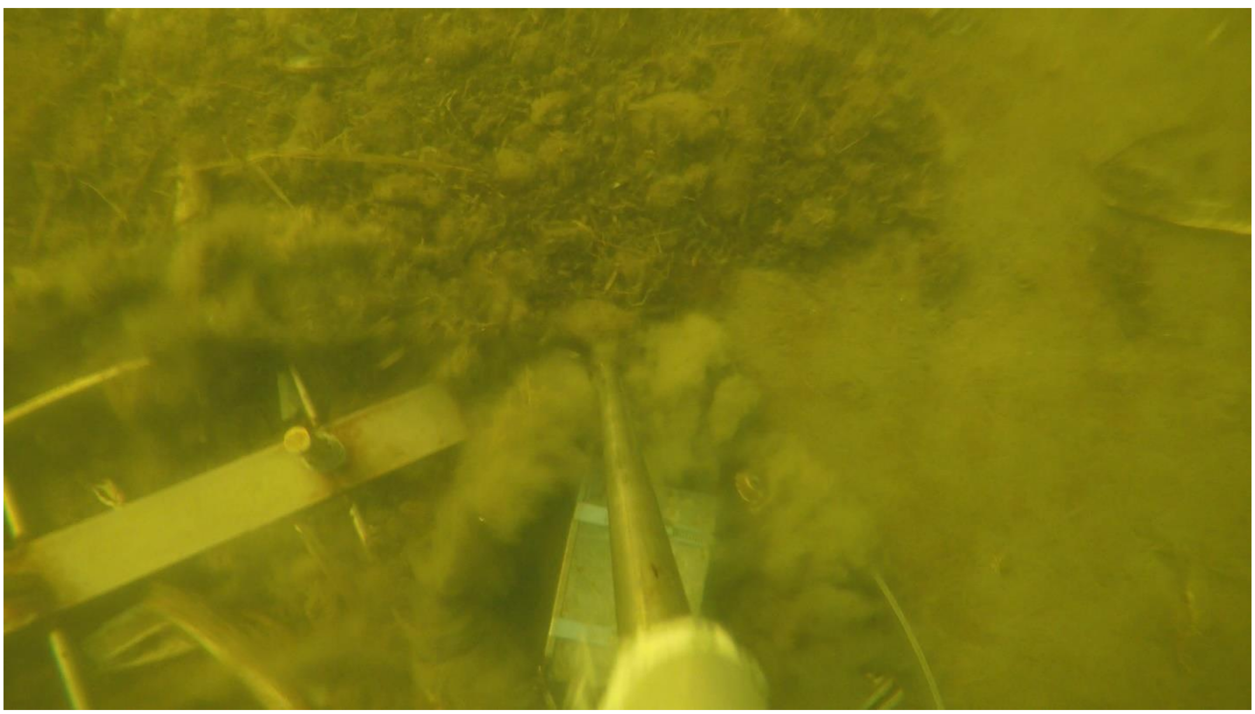

Figure A6. *GoPro Screen capture from station BH_06*

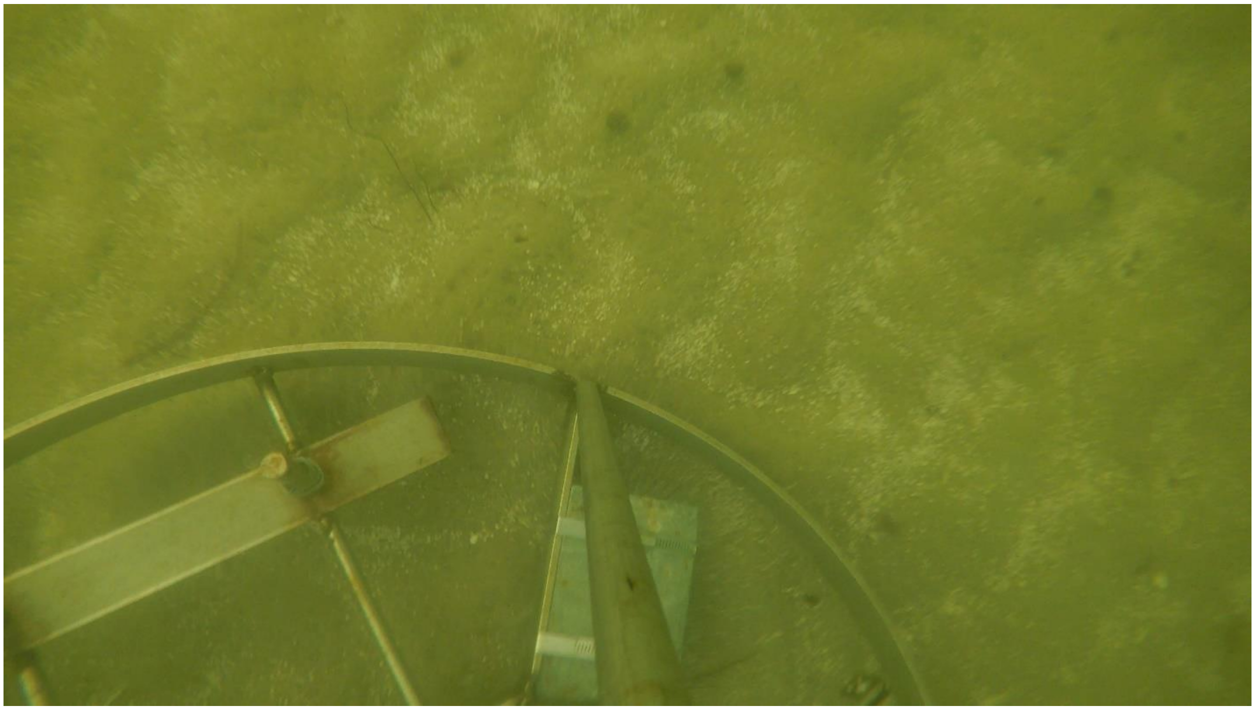
Figure A7. *GoPro Screen capture from station BH_07*

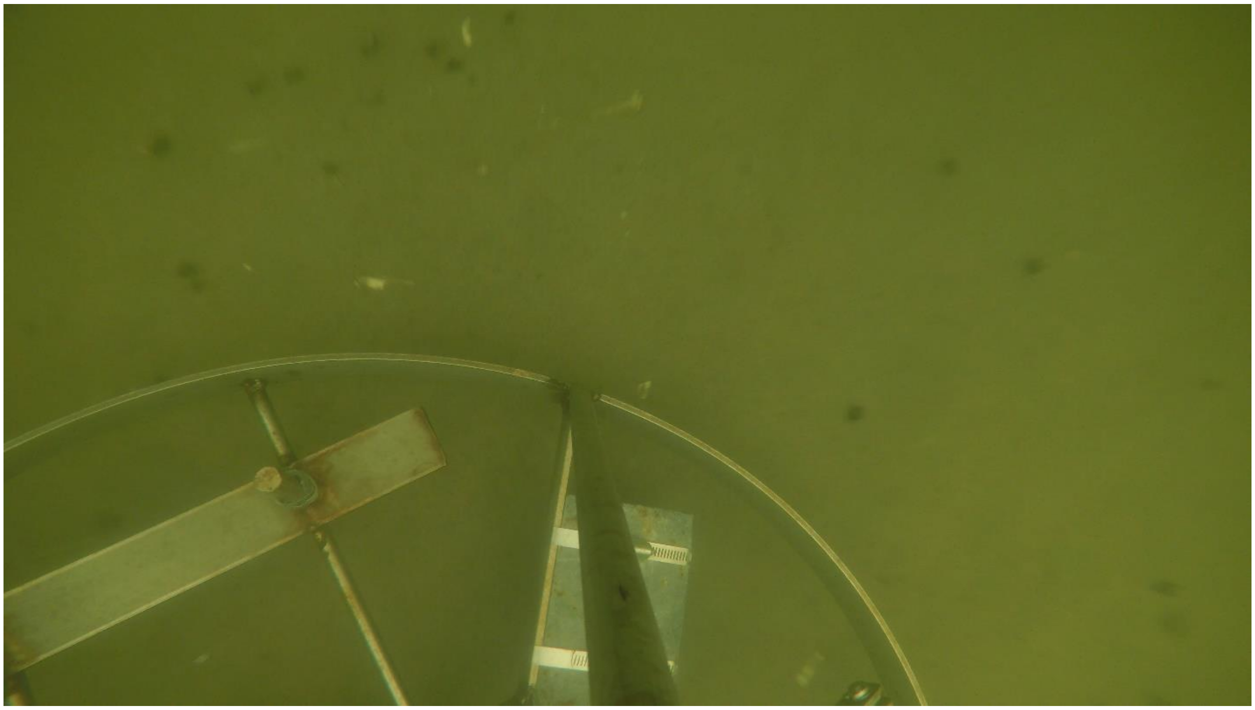
Figure A8. *GoPro Screen capture from station BH_08*

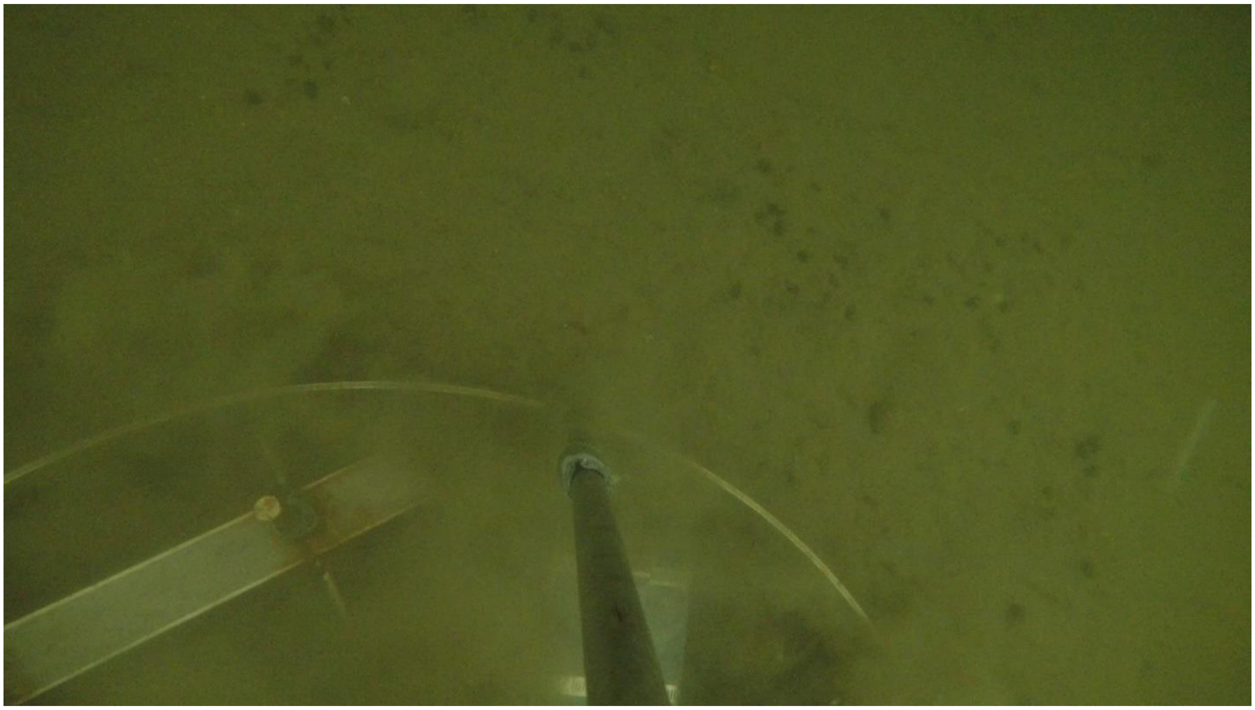

Figure A9. *GoPro Screen capture from station BH_09*

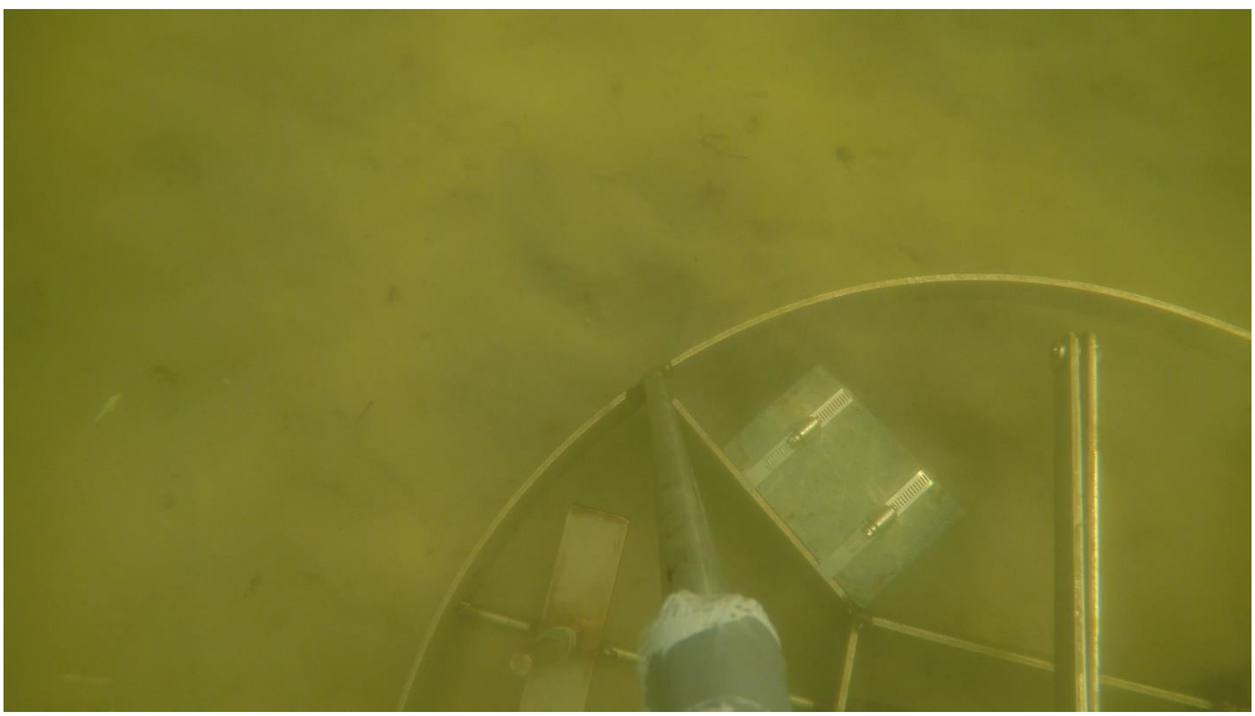

Figure A10. *GoPro Screen capture from station BH_10*

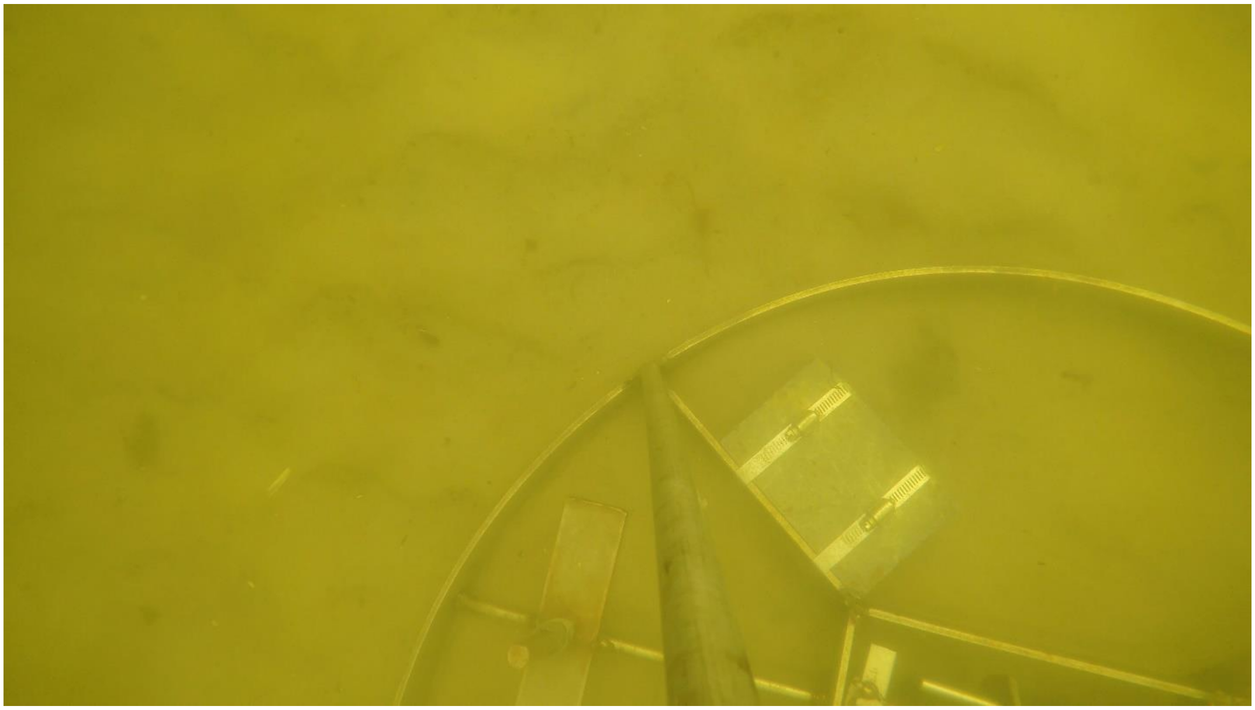

Figure A11. *GoPro Screen capture from station BH_11*

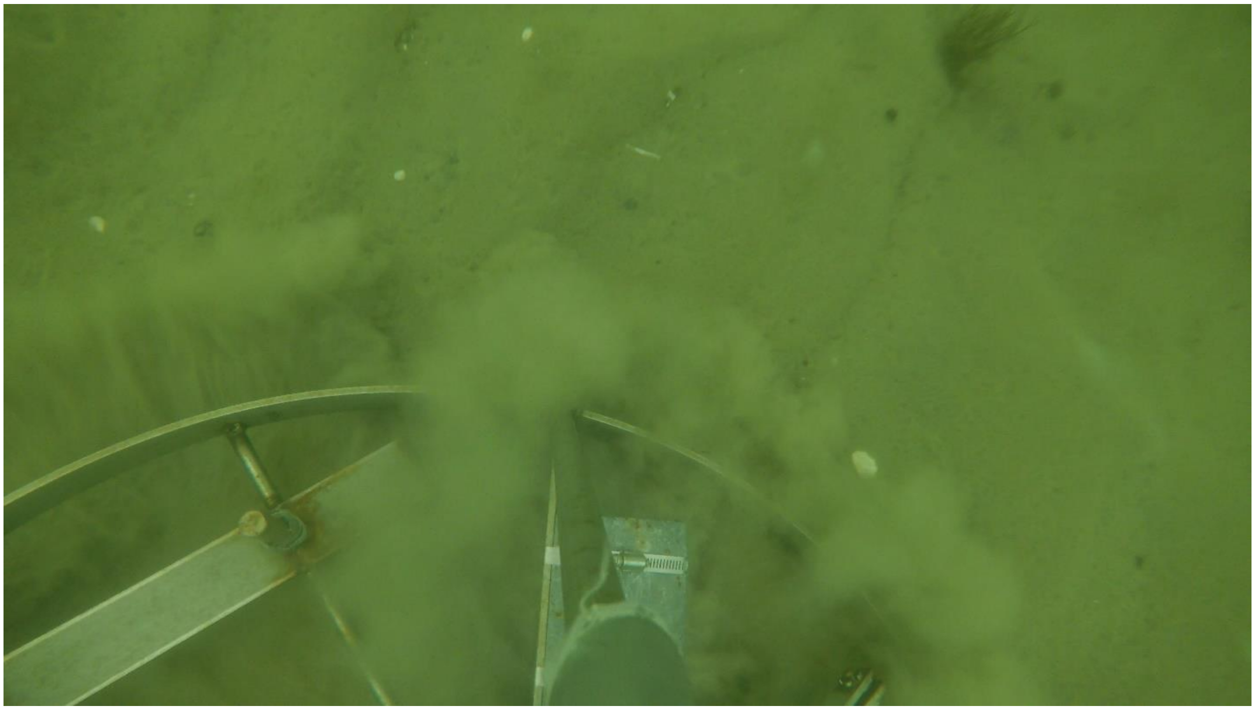

Figure A12. *GoPro Screen capture from station BH_12*

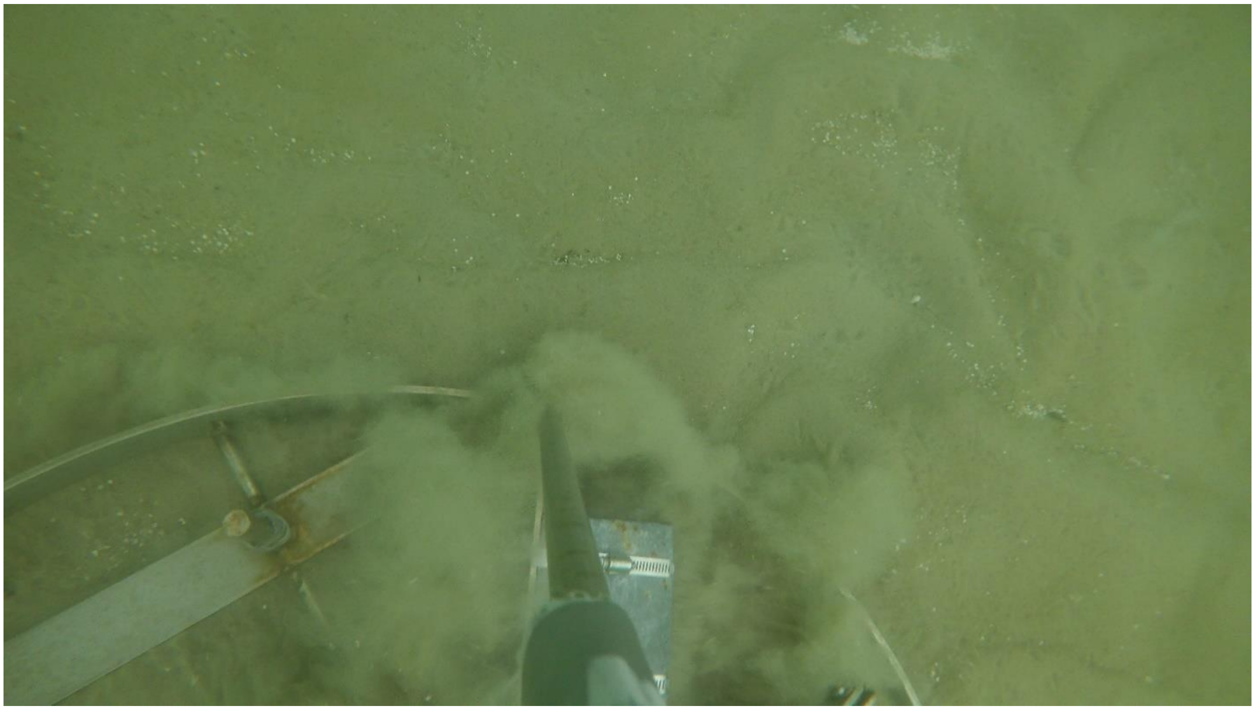

Figure A13. *GoPro Screen capture from station BH_13*

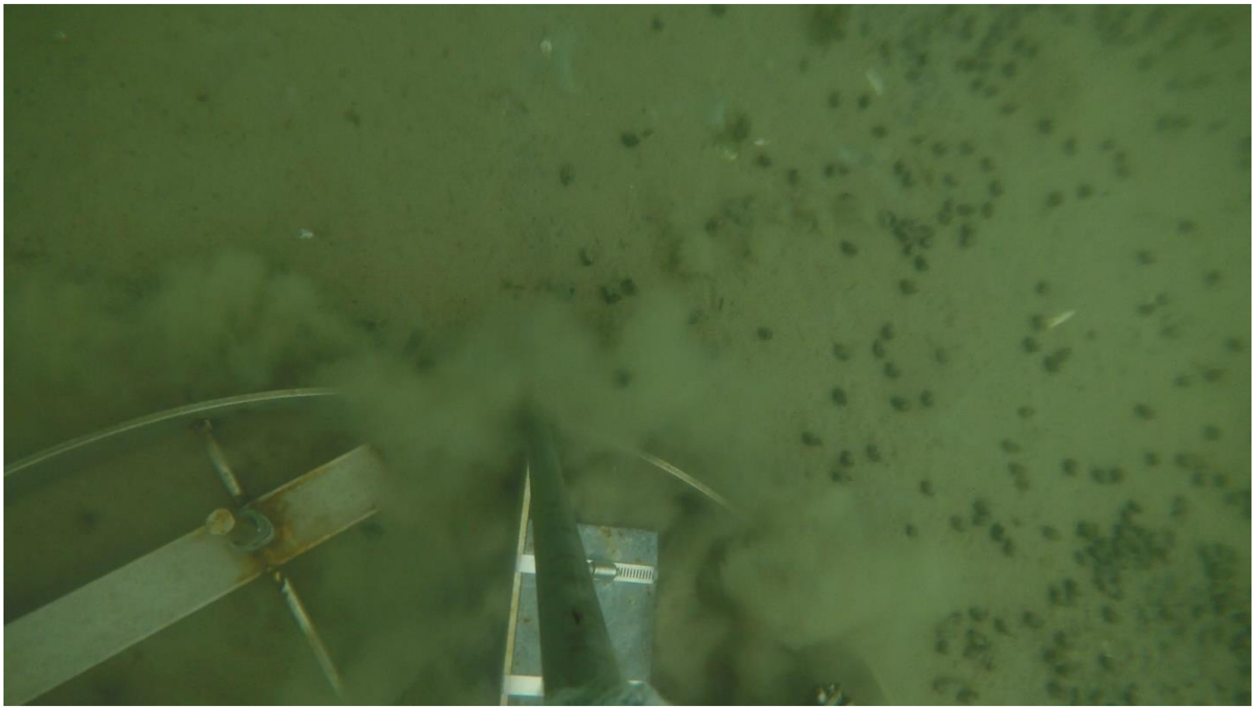

Figure A14. *GoPro Screen capture from station BH_14*

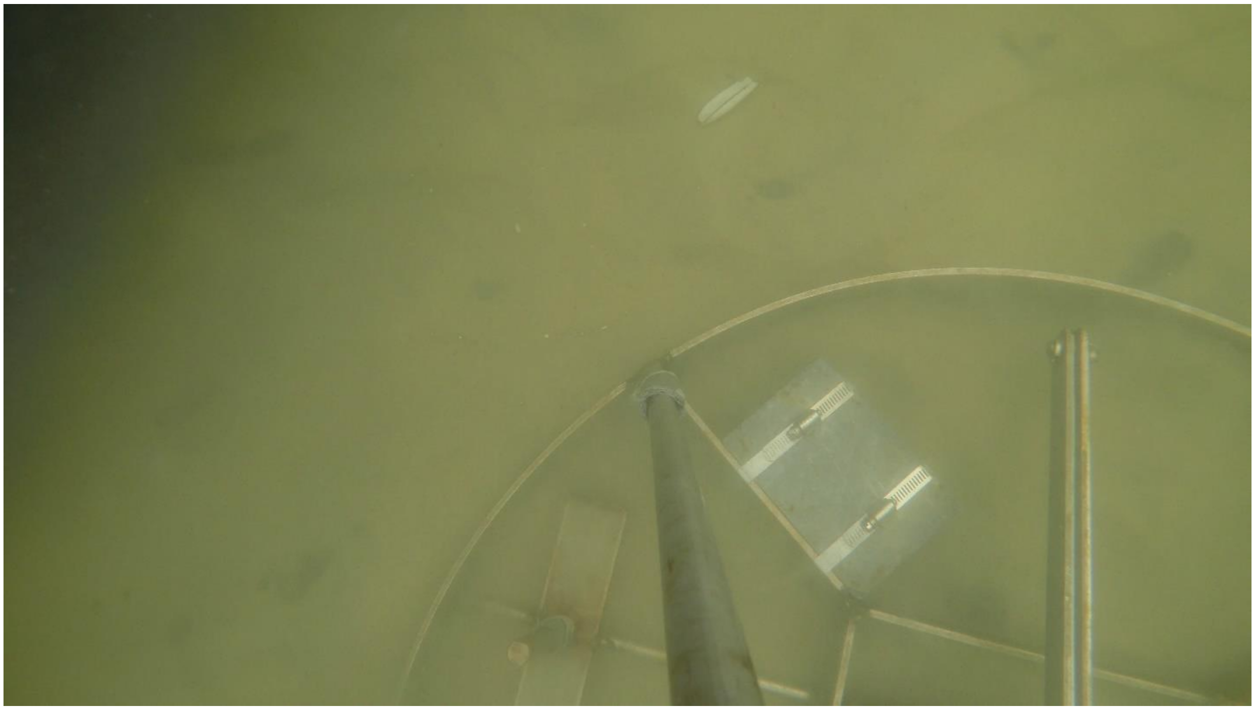

Figure A15. *GoPro Screen capture from station BH_15*

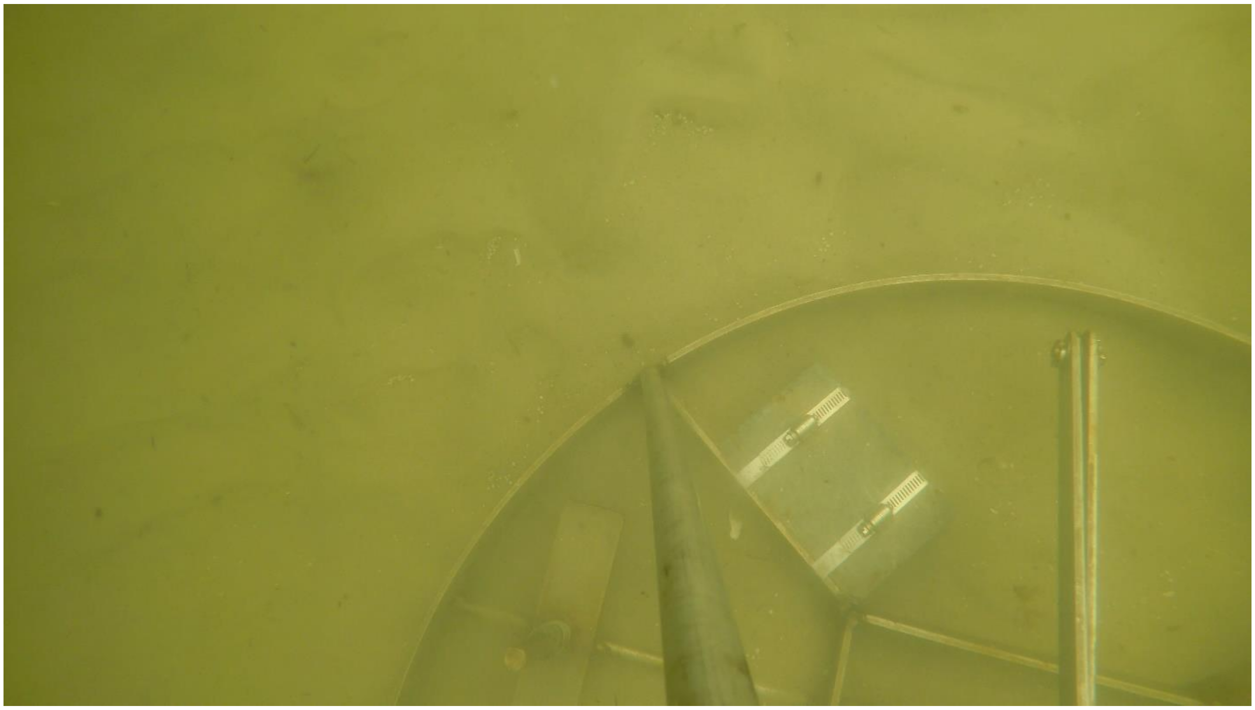

Figure A16. *GoPro Screen capture from station BH_16*

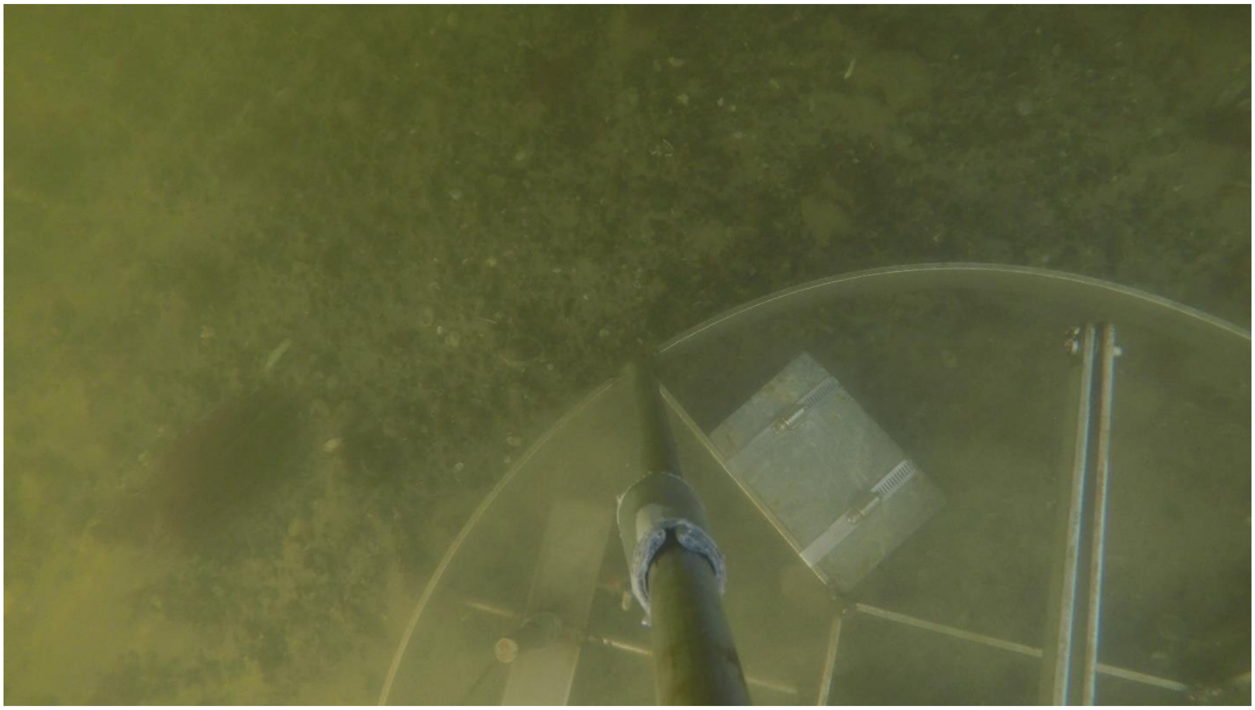

Figure A17. *GoPro Screen capture from station BH_17*

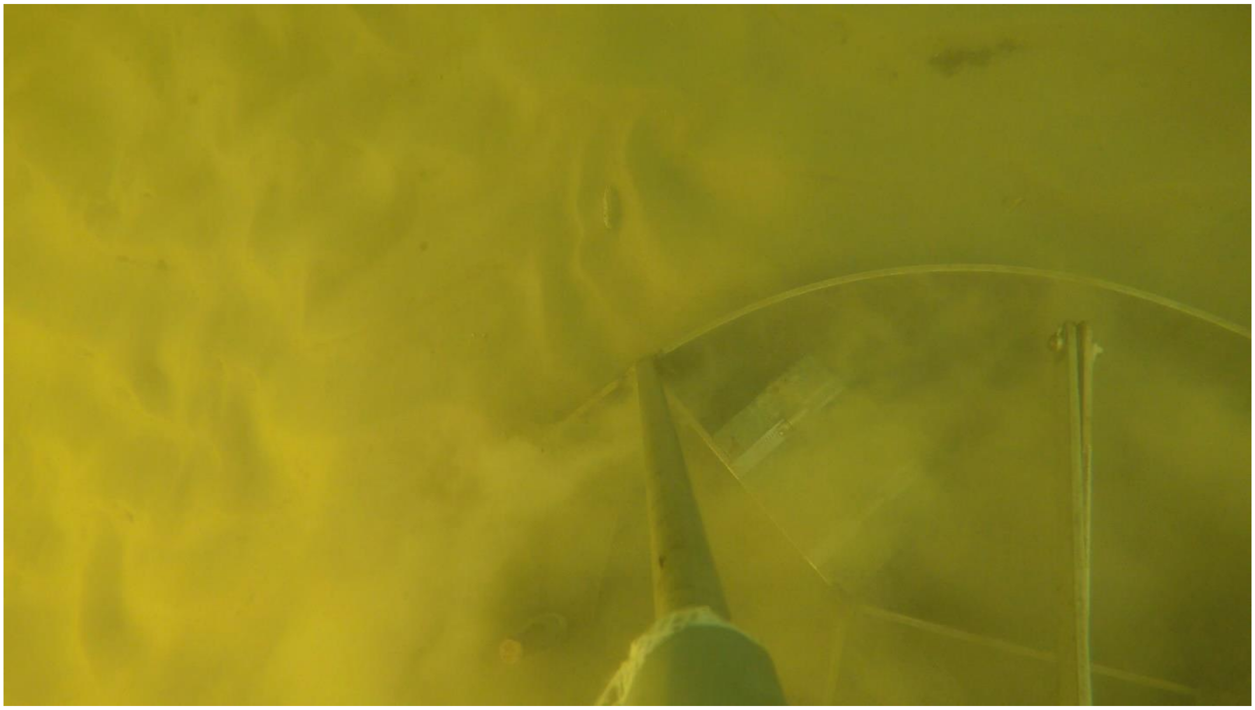

Figure A18. *GoPro Screen capture from station BH_18*

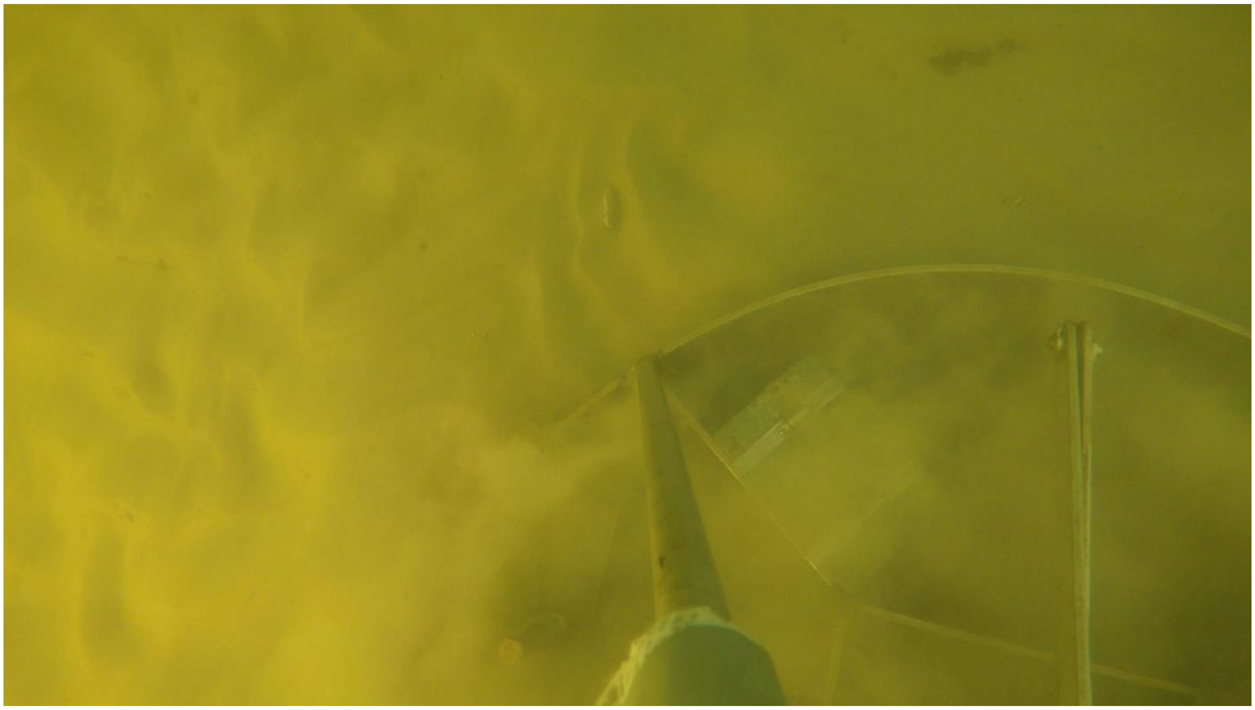

Figure A19. *GoPro Screen capture from station BH_19*

Figure A20*. GoPro Screen capture from station BH_20 (poor image due to shallow water depths preventing the camera from being fully submerged).*

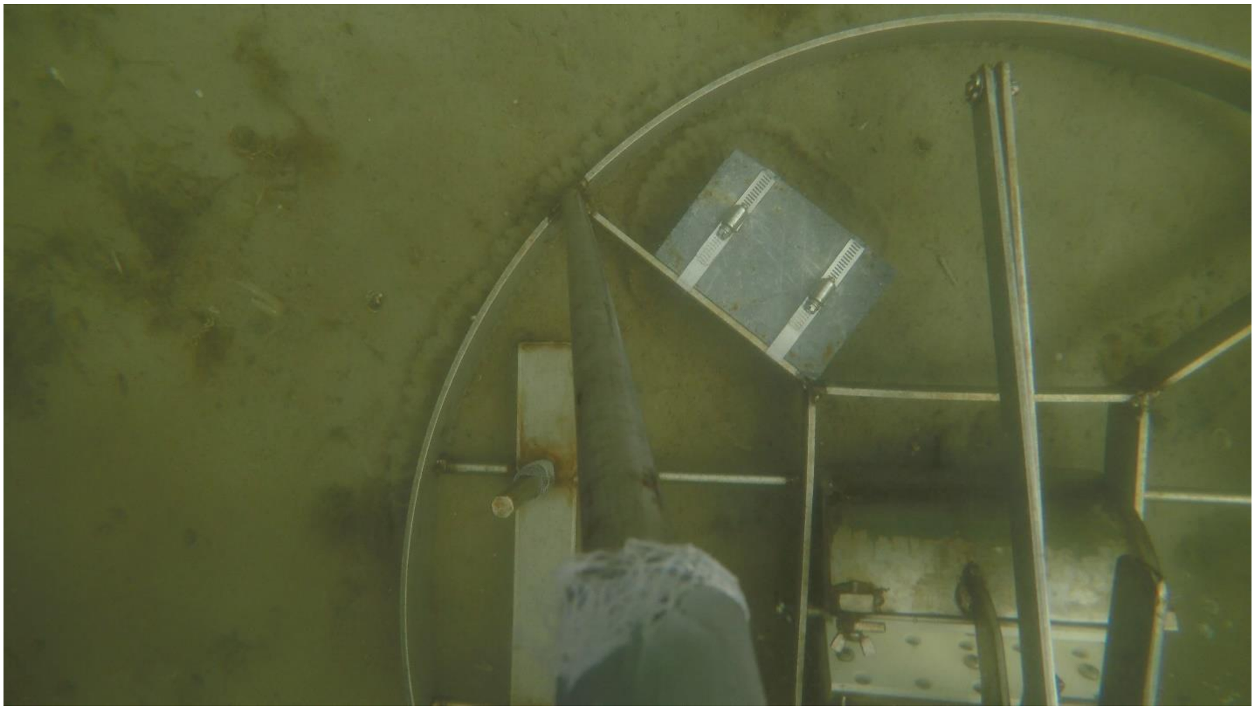

Figure A21. *GoPro Screen capture from station BH_21*

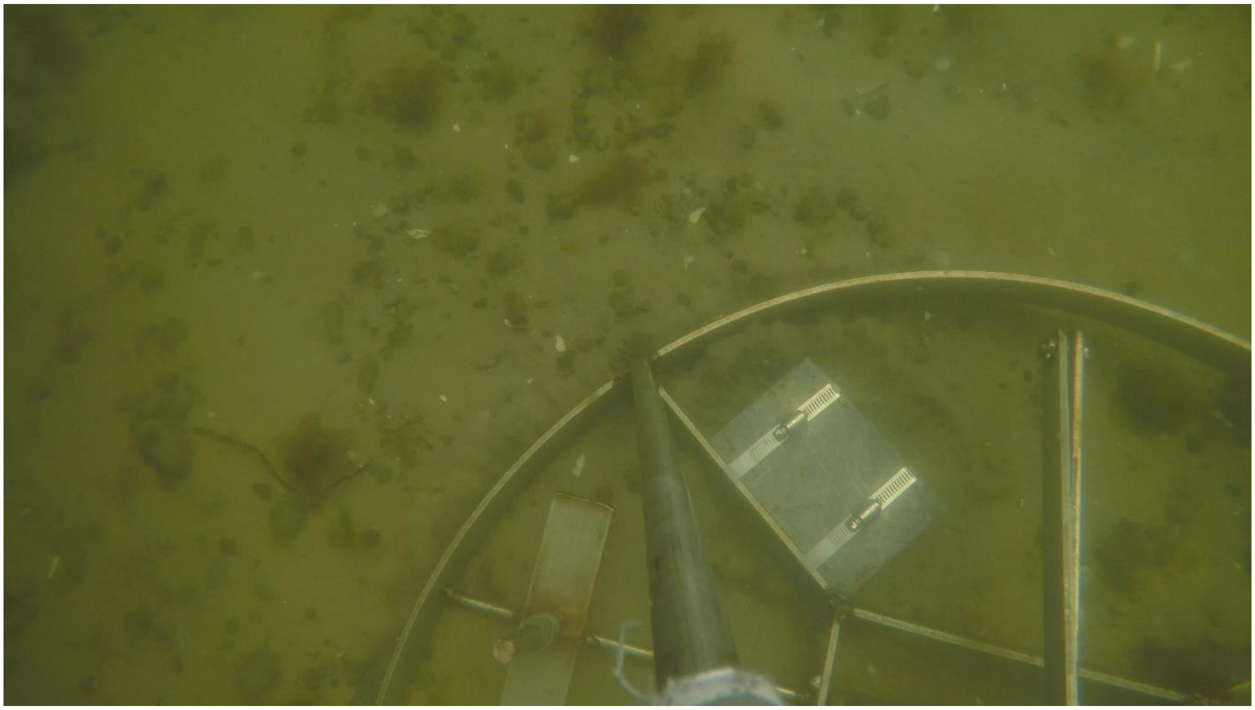

Figure A22. *GoPro Screen capture from station BH_22*

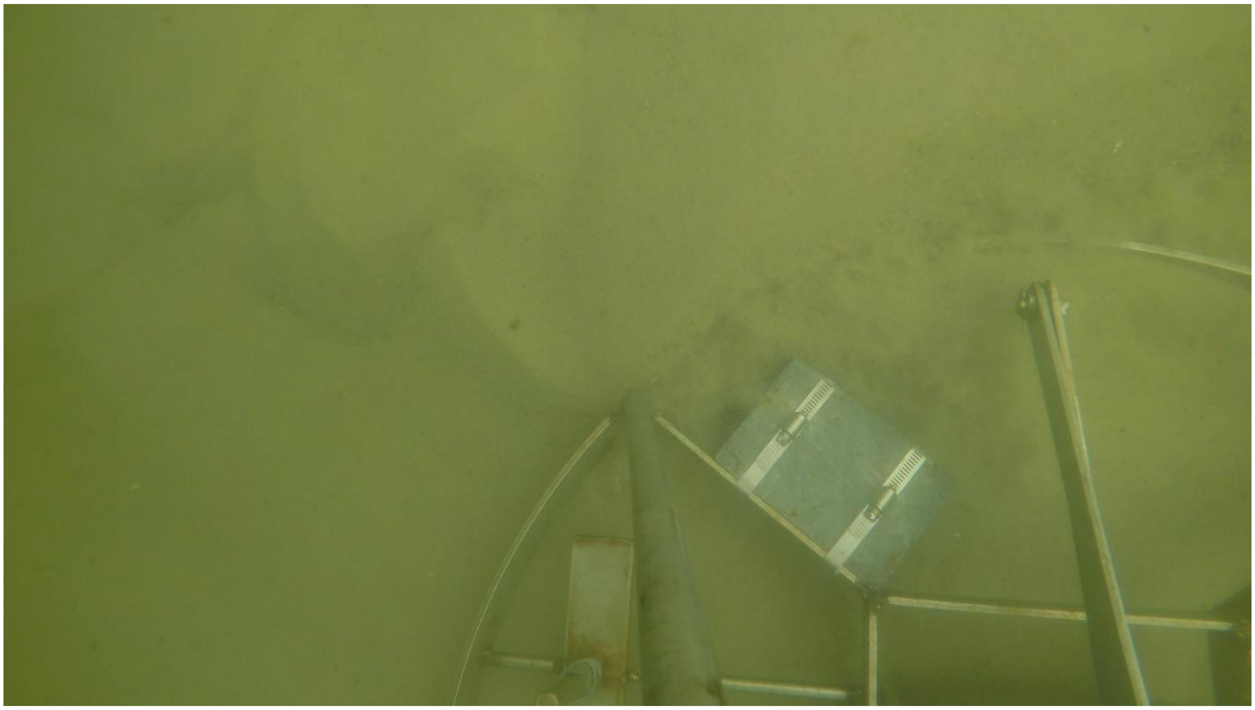

Figure A23. *GoPro Screen capture from station BH_23*

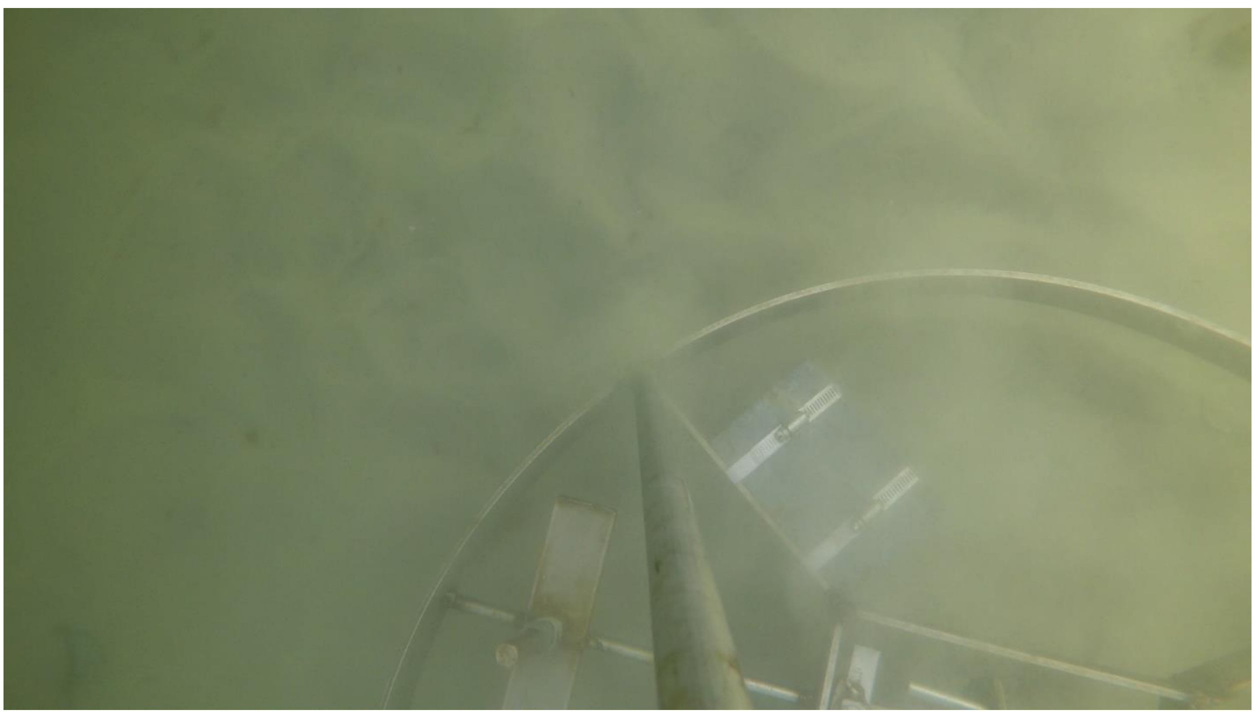

Figure A24. *GoPro Screen capture from station BH_24*

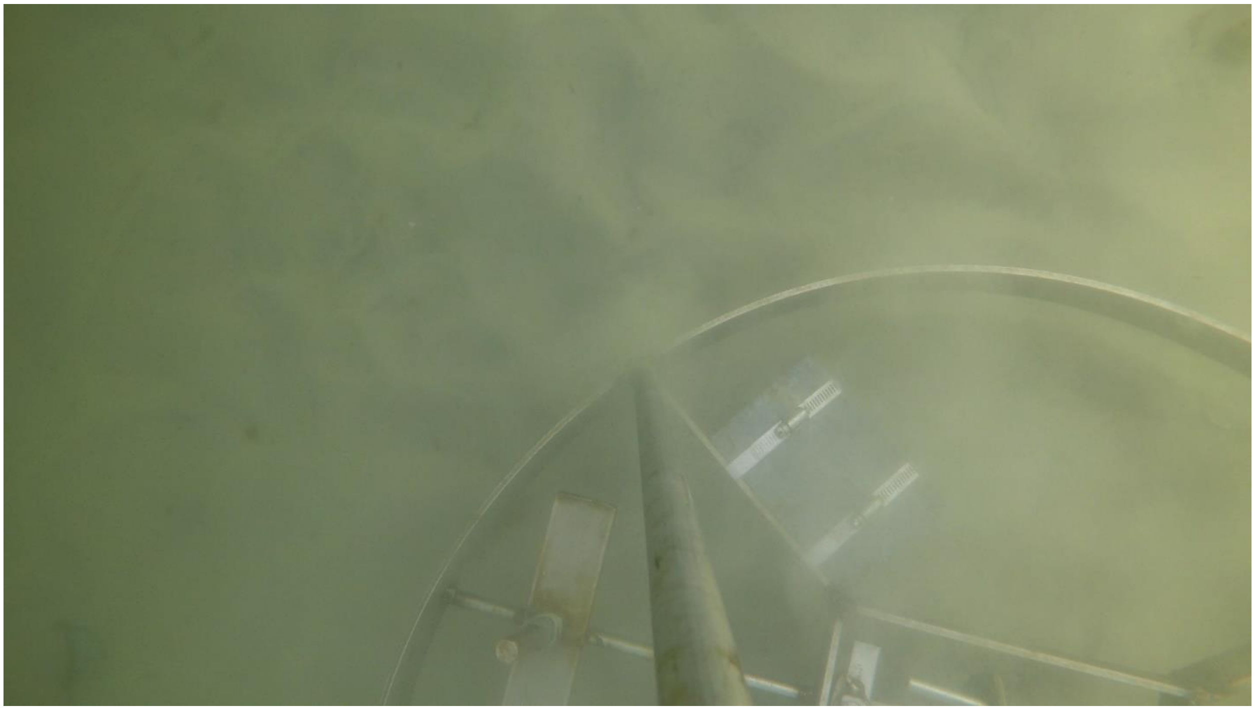

Figure A25. *GoPro Screen capture from station BH_25*

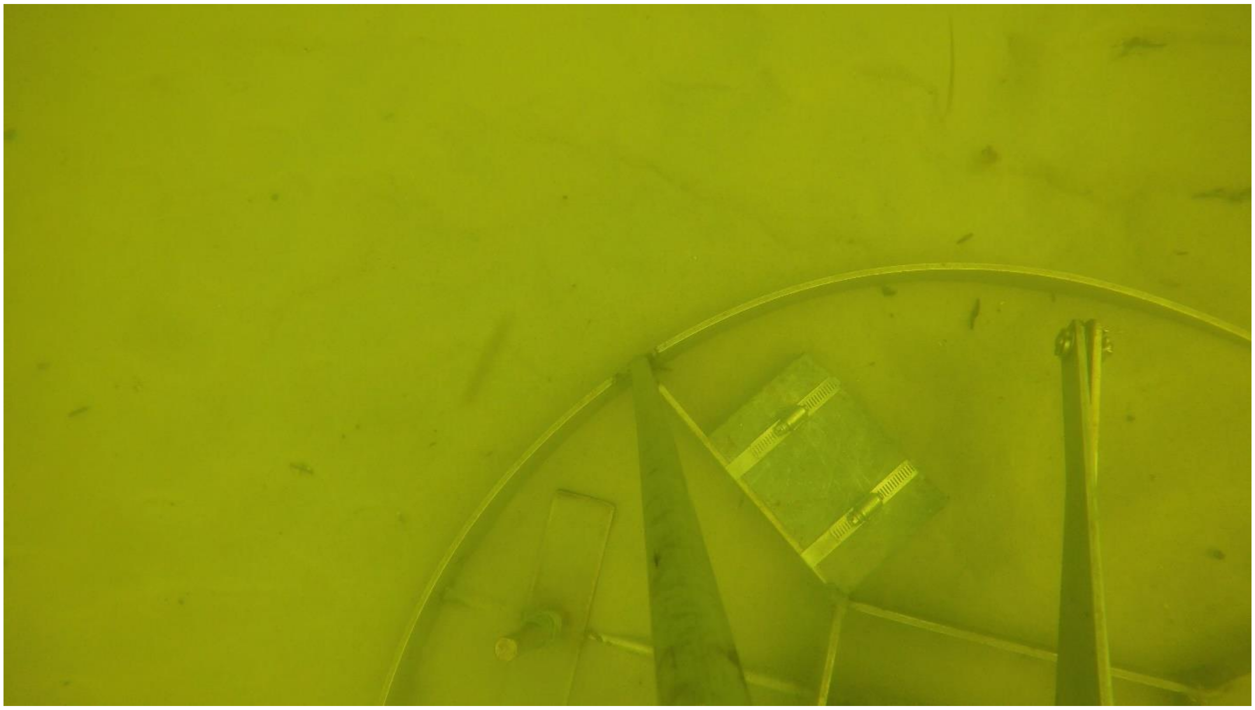

***Figure A26**. GoPro Screen capture from station BH_26*

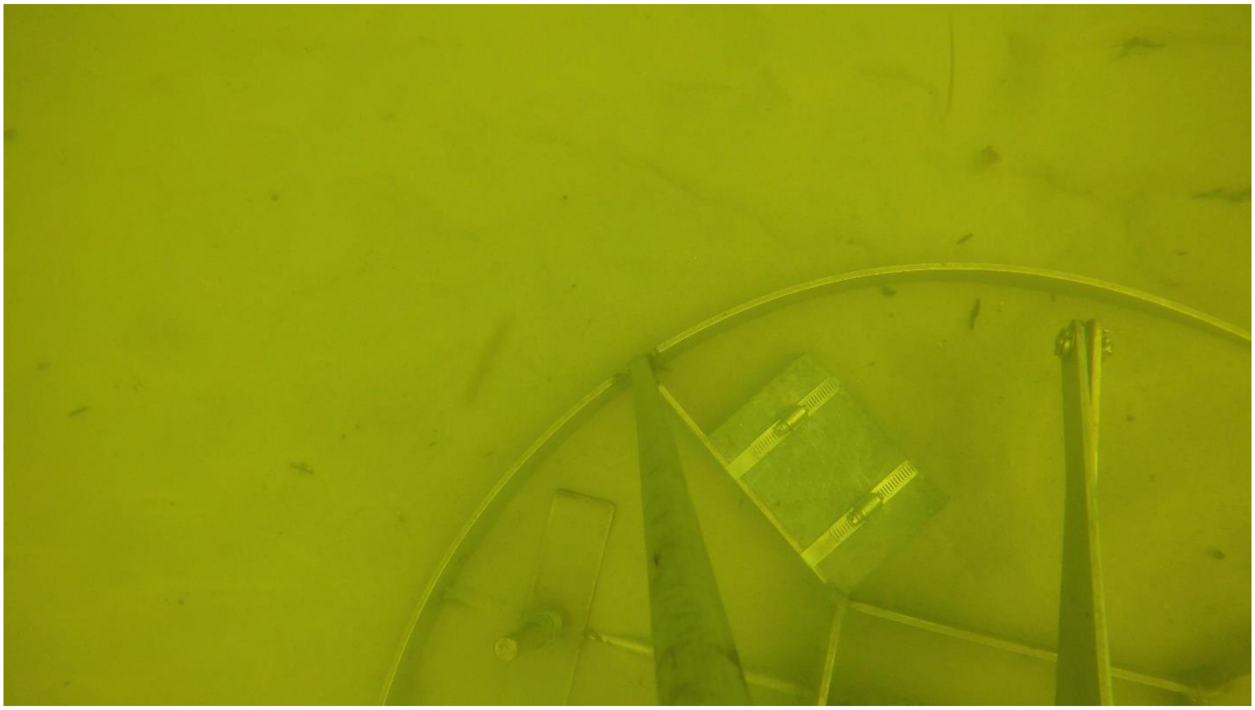

***Figure A27**. GoPro Screen capture from station BH_27*

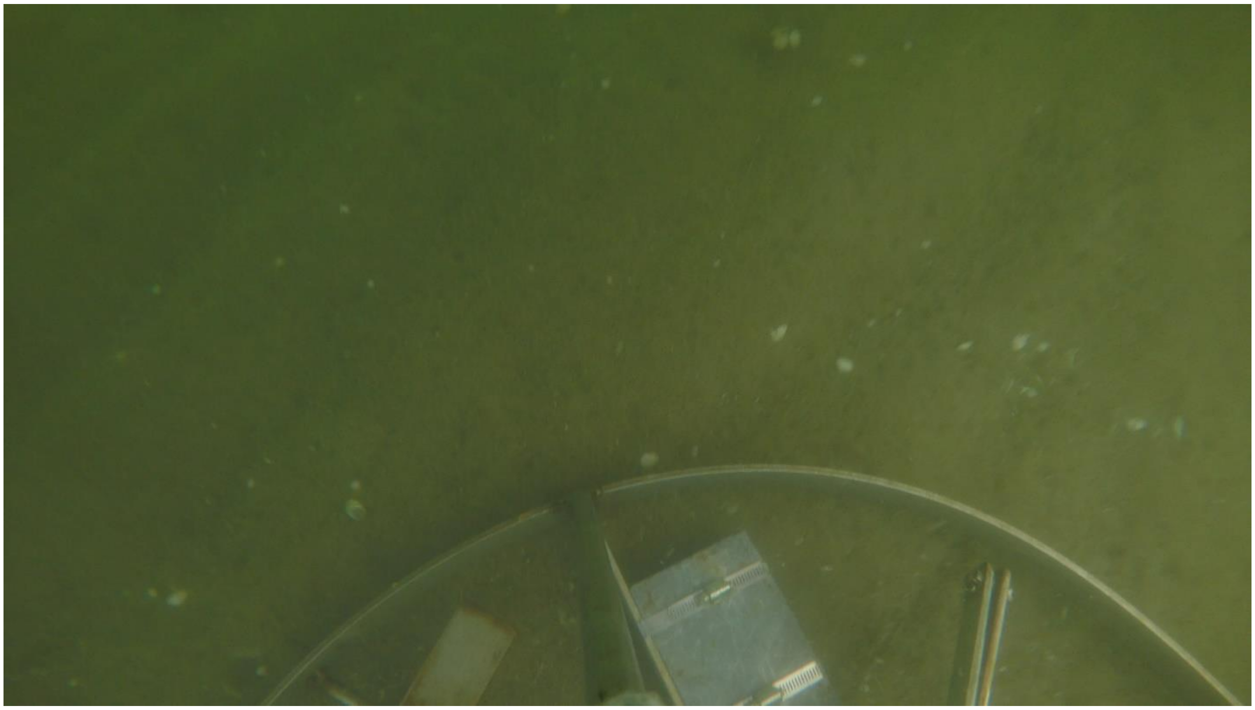

***Figure A28.** GoPro Screen capture from station BH_28*

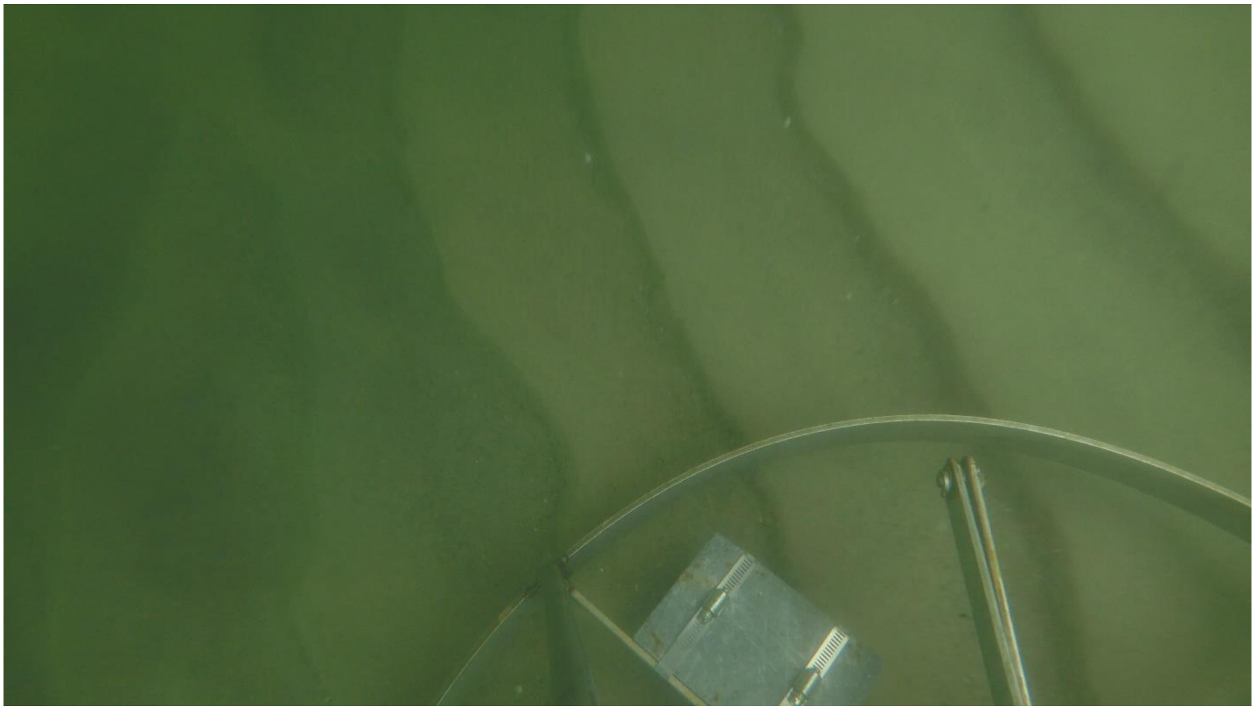

Figure A29. *GoPro Screen capture from station BH_29*

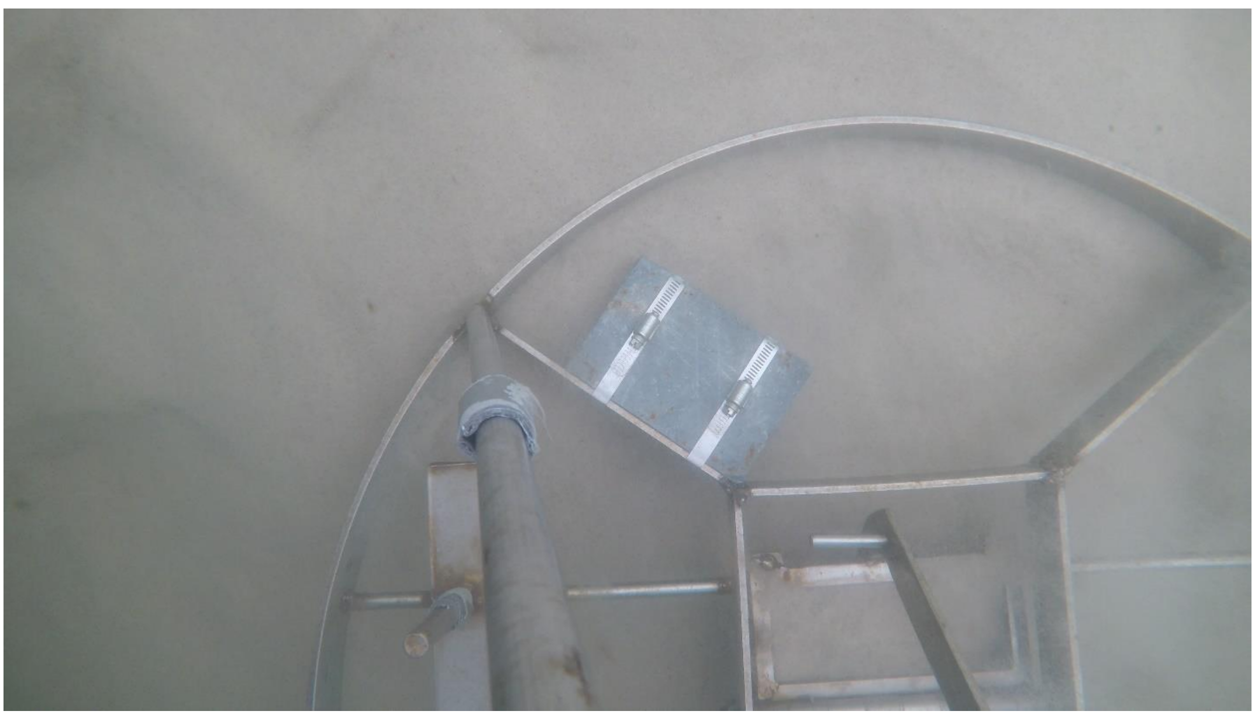

Figure A30. *GoPro Screen capture from station BH_30*

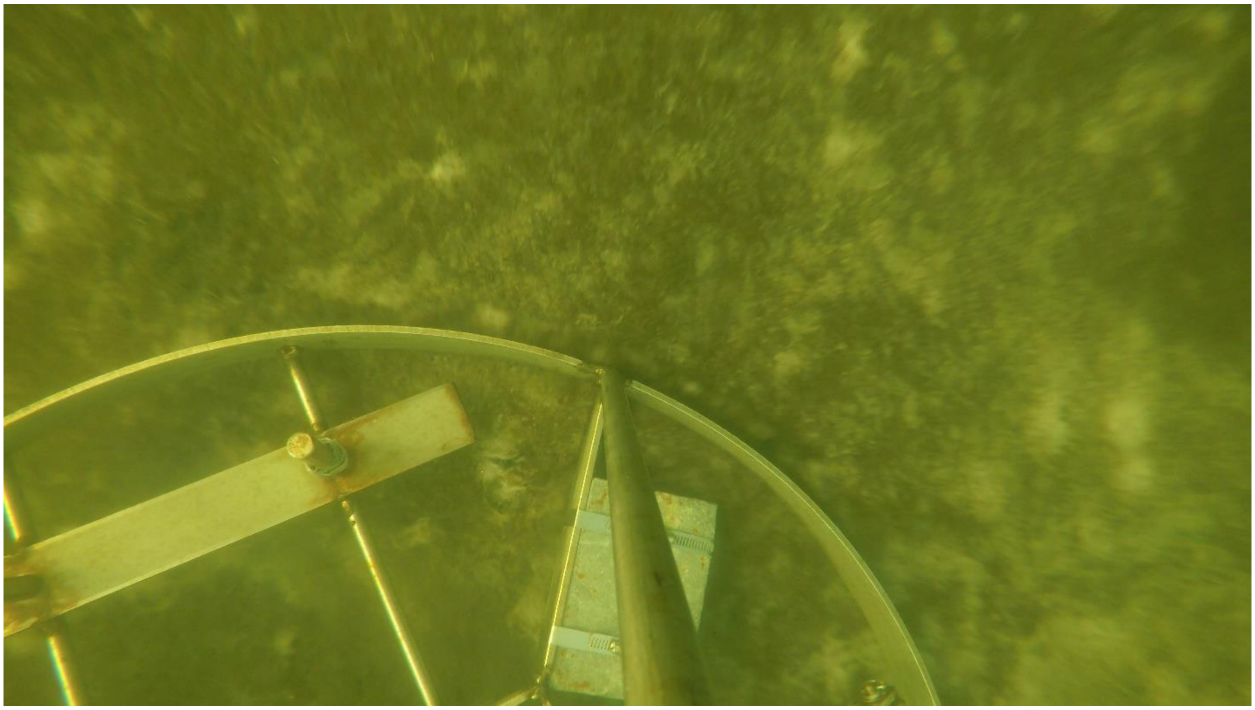

Figure A31. *GoPro Screen capture from station BH_31*

Table A1. *Summary of screen capture analysis by station.*

Station	Shell (%)	Algae (%)	Woody Debris (%)	Sand (%)	Mud (%)	Gravel (%)
01	0	0	0	100	0	0
02	0	0	0	100	0	0
03	0	0	0	100	0	0
04	0	0	0	100	0	0
05	0	0	0	100	0	0
06	12	43	42	3	0	0
07	0	0	0	100	0	0
08	0	0	0	100	0	0
09	2	0	0	98	0	0
10	0	0	0	100	0	0
11	0	0	0	100	0	0
12	4	0	0	96	0	0
13	0	0	0	100	0	0
14	0	10	0	90	0	0
15	0	0	0	100	0	0
16	0	0	0	100	0	0
17	0	13	0	28	0	59
18	0	6	0	94	0	0
19	0	0	0	100	0	0
20	0	16	0	84	0	0
21	0	22	0	54	0	25
22	0	0	0	100	0	0
23	0	0	0	100	0	0
24	0	0	0	100	0	0
25	0	0	0	100	0	0
26	0	13	0	85	0	2
27	2	0	0	98	0	0
28	0	0	0	100	0	0
29	0	0	0	99	0	1
30	0	0	0	100	0	0
31	0	0	0	0	100	0

7. Appendix B – CMECS Biotic Components

Table B1. *List of taxa present in Barnstable Harbor. (*) indicates invasive/cryptogenic species according to the Massachusetts Office for Coastal Zone Management Marine Invasive Species Program.*

Phylum	Class	Order	Genus	Taxon	AphiaID
Mollusca	Gastropoda	Cephalaspidea	Acetocina	*Acetocina canaliculata*	160065
Annelida	Polychaeta	Phyllodocida	Alitta	*Alitta succinea*	234850
Mollusca	Bivalvia	Cardiida	Ameritella	*Ameritella agilis*	878476
Arthropoda	Malacostraca	Amphipoda	Ampelisca	*Ampelisca abdita*	158020
Arthropoda	Malacostraca	Amphipoda	Ampelisca	*Ampelisca macrocephala*	101908
Arthropoda	Malacostraca	Amphipoda	Ampelisca	*Ampelisca vadorum*	158022
Arthropoda	Malacostraca	Amphipoda		Amphipoda	1135
Mollusca	Bivalvia	Arcida	Anadara	*Anadara transversa*	156734
Cnidaria	Anthozoa	Actiniaria	Anemonia	*Anemonia* spp.	100695
Annelida	Polychaeta	Eunicida	Arabella	*Arabella iricolor*	129854
Annelida	Polychaeta		Arenicola	*Arenicola* spp.	129206
Mollusca	Gastropoda	Neogastropoda	Astyris	*Astyris lunata*	160102
Mollusca	Gastropoda	Caenogastropoda	Bittiolum	*Bittiolum alternatum*	160172
Mollusca	Bivalvia			Bivalvia	105
Arthropoda	Malacostraca	Decapoda		Brachyura	106673
Mollusca	Gastropoda	Neogastropoda	Buccinum	*Buccinum undatum*	138878
Annelida	Polychaeta	Scolecida		*Capitellidae* spp.	921
Arthropoda	Malacostraca	Amphipoda	Caprella	*Caprella linearis*	101839
Arthropoda	Malacostraca	Amphipoda	Caprella	*Caprella penantis* *	101846
Cnidaria	Anthozoa	Spirularia		Cerianthidae	100684
Arthropoda	Malacostraca	Isopoda	Chiridotea	*Chiridotea coeca*	157842
Annelida	Polychaeta		Clymenella	*Clymenella torquata*	130279
Arthropoda	Malacostraca	Amphipoda		*Corophiidae* spp.	101376
Arthropoda	Malacostraca	Decapoda	Crangon	*Crangon septemspinosa*	158355
Mollusca	Bivalvia	Ostreida	Crassostrea	*Crassostrea virginica*	140657
Mollusca	Gastropoda	Littorinimorpha	Crepidula	*Crepidula fornicata*	138963
Mollusca	Gastropoda	Littorinimorpha	Crepidula	*Crepidula plana*	160230
Arthropoda	Malacostraca	Cumacea		*Cumacea* spp.	1137
Arthropoda	Malacostraca	Isopoda	Cyathura	*Cyathura polita*	157847
Arthropoda	Malacostraca	Amphipoda	Dexamine	*Dexamine thea*	102136
Annelida	Polychaeta	Terebellida	Dodecaceria	*Dodecaceria* spp.	129246
Annelida	Polychaeta	Eunicida	Drilonereis	*Drilonereis longa*	157357
Arthropoda	Malacostraca	Isopoda	Edotia	*Edotia triloba*	157885
Arthropoda	Malacostraca	Amphipoda	Elasmopus	*Elasmopus levis*	421508
Mollusca	Bivalvia	Adapedonta	Ensis	*Ensis leei*	876640
Annelida	Polychaeta	Phyllodocida	Eteone	*Eteone longa*	130616
Mollusca	Gastropoda	Littorinimorpha	Euspira	*Euspira heros*	160315

Phylum	**Class**	**Order**	**Genus**	**Taxon**	**AphiaID**
Arthropoda	Malacostraca	Amphipoda	Gammarus	*Gammarus mucronatus*	158094
Arthropoda	Malacostraca	Amphipoda	Gammarus	*Gammarus* spp.	101537
Mollusca	Bivalvia	Venerida	Gemma	*Gemma gemma*	156803
Annelida	Polychaeta	Phyllodocida	Glycera	*Glycera americana*	157388
Annelida	Polychaeta	Phyllodocida	Glycera	*Glycera capitata*	130118
Annelida	Polychaeta	Phyllodocida	Glycinde	*Glycinde solitaria*	157396
Arthropoda	Malacostraca	Amphipoda		Haustoriidae	101384
Annelida	Polychaeta	Phyllodocida	Hediste	*Hediste diversicolor*	152302
Mollusca	Gastropoda	Littorinimorpha	Hydrobia	*Hydrobia* spp.	138081
Arthropoda	Malacostraca	Amphipoda	Idunella	*Idunella* spp.	101581
Mollusca	Gastropoda	Neogastropoda	Ilyanassa	*Ilyanassa obsoleta*	467490
Mollusca	Gastropoda	Neogastropoda	Ilyanassa	*Ilyanassa trivittata*	467492
Echinodermata	Holothuroidea	Apodida	Leptosynapta	*Leptosynapta tenuis*	158485
Arthropoda	Malacostraca	Decapoda	Libinia	*Libinia dubia*	107335
Mollusca	Bivalvia	Cardiida	Limecola	*Limecola balthica*	880017
Mollusca	Gastropoda	Littorinimorpha	Littorina	*Littorina littorea* *	140262
Mollusca	Bivalvia	Anomalodesmata	Lyonsia	*Lyonsia hyalina*	156793
Arthropoda	Malacostraca	Amphipoda	Lysianopsis	*Lysianopsis alba*	158036
Arthropoda	Malacostraca	Amphipoda	Melita	*Melita nitida*	146922
Mollusca	Bivalvia	Venerida	Mercenaria	*Mercenaria mercenaria*	141919
Arthropoda	Malacostraca	Amphipoda	Microdeutopus	*Microdeutopus gryllotalpa* *	102048
Mollusca	Bivalvia	Mytilida	Modiolus	*Modiolus modiolus*	140467
Mollusca	Bivalvia	Myida	Mya	*Mya arenaria*	140430
Mollusca	Bivalvia	Mytilida	Mytilus	*Mytilus edulis*	140480
Nemertea				Nemertea	152391
Annelida	Polychaeta	Phyllodocida	Nephtys	*Nephtys picta*	157501
Annelida	Polychaeta	Phyllodocida	Nereis	*Nereis pelagica*	130404
Annelida	Polychaeta	Phyllodocida	Nereis	*Nereis* spp.	129379
Annelida	Polychaeta	Eunicida	Ninoe	*Ninoe nigripes*	130255
Mollusca	Gastropoda		Notoacmea	*Notoacmea* spp.	456334
Annelida	Clitellata			Oligochaeta	2036
Annelida	Polychaeta		Ophelia	*Ophelia* spp.	129413
Arthropoda	Malacostraca	Decapoda	Pagurus	*Pagurus arcuatus*	158402
Arthropoda	Malacostraca	Decapoda	Panopeus	*Panopeus herbstii*	158436
Annelida	Polychaeta	Scolecida	Paraonis	*Paraonis fulgens*	146932
Annelida	Polychaeta	Terebellida	Pectinaria	*Pectinaria gouldii*	334421
Mollusca	Bivalvia	Venerida	Petricolaria	*Petricolaria pholadiformis*	156961
Annelida	Polychaeta	Phyllodocida		Phyllodocidae	931
Annelida	Polychaeta	Scolecida	Phylo	*Phylo ornatus*	334519
Annelida	Polychaeta	Phyllodocida	Proceraea	*Proceraea cornuta*	131362
Annelida	Polychaeta	Spionida	Pygospio	*Pygospio elegans*	131170
Annelida	Polychaeta	Phyllodocida	Salvatoria	*Salvatoria clavata*	195986

Phylum	**Class**	**Order**	**Genus**	**Taxon**	**AphiaID**
Annelida	Polychaeta	Spionida	Scolelepsis	*Scolelepsis squamata*	157566
Annelida	Sipuncula			Sipuncula spp.	1268
Arthropoda	Malacostraca	Isopoda	Sphaeroma	*Sphaeroma quadridentatum*	157912
Annelida	Polychaeta	Spionida		Spionidae spp.	913
Annelida	Polychaeta	Spionida	Spiophanes	*Spiophanes bombyx*	131187
Mollusca	Bivalvia	Venerida	Spisula	*Spisula solidissima*	156996
Annelida	Polychaeta	Spionida	Streblospio	*Streblospio benedicti*	131191
Porifera	Demospongiae	Suberitida	Suberites	*Suberites ficus*	134285
Annelida	Polychaeta	Phyllodocida		Syllidae spp.	948
Arthropoda	Malacostraca	Amphipoda	Unciola	*Unciola* spp.	101474

Table B2. *Species distribution at stations 1-16 in Barnstable Harbor with total counts of each taxa and individuals at each station on the bottom rows. Numbers indicate individuals identified in three replicate grab samples. (*) indicates invasive/cryptogenic species according to the Massachusetts Office for Coastal Zone Management Marine Invasive Species Program*

Taxa	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Acetocina canaliculata	0	0	1	0	0	0	1	1	1	0	0	0	0	0	0	0
Alitta succinea	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Ameritella agilis	0	0	1	0	0	1	7	0	0	1	24	34	62	3	39	13
Ampelisca abdita	0	29	0	0	7	4	0	0	0	0	0	0	0	0	0	0
Ampelisca macrocephala	0	77	10	2	10	21	1	1	1	0	0	0	0	5	0	0
Ampelisca vadorum	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Amphipoda	0	0	1	0	0	16	0	0	0	4	0	0	0	0	0	0
Anadara transversa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Anemonia spp.	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Arabella iricolor	0	2	54	9	0	0	0	2	0	0	0	0	0	0	0	0
Arenicola spp.	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Astyris lunata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bittiolum alternatum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bivalvia	0	7	0	1	0	0	3	0	0	0	0	4	3	0	1	0
Brachyura spp.	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Buccinum undatum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Capitellidae spp.	0	259	434	211	251	442	1	46	13	33	0	0	1	4	0	0
Caprella linearis	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
***Caprella penantis* ***	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cerianthidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chiridotea coeca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Clymenella torquata	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
Corophiidae spp.	0	0	0	0	0	11	0	0	0	19	0	0	0	0	0	0
Crangon septemspinosa	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Crassostrea virginica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crepidula fornicata	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Crepidula plana	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0
Cumacea spp.	0	5	1	0	2	9	2	1	3	0	17	0	1	1	0	0
Cyathura polita	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Taxa	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16
Dexamine thea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dodecaceria spp.	0	0	6	0	0	0	0	13	1	1	0	0	0	18	0	0
Drilonereis longa	0	0	11	32	42	0	0	4	1	3	0	0	1	0	0	1
Edotia triloba	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Elasmopus levis	0	0	2	0	0	4	0	0	0	0	0	0	0	1	0	0
Ensis leei	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Eteone longa	1	61	46	18	43	11	2	3	8	2	0	0	1	4	1	0
Euspira heros	0	0	0	0	0	0	1	1	2	0	1	0	0	0	0	0
Gammarus mucronatus	0	0	1	0	0	5	0	0	0	1	0	0	0	0	0	0
Gammarus spp.	0	0	0	0	0	74	2	0	0	0	0	0	0	0	0	0
Gemma gemma	114	5423	46	97	17	28	1627	38	803	1	2	19	1039	12	303	68
Glycera americana	0	0	25	1	9	2	2	9	11	0	0	0	0	2	24	66
Glycera capitata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Glycinde solitaria	0	0	5	0	0	0	0	14	0	0	0	0	0	0	0	0
Haustoriidae sp. 1	0	0	0	0	0	0	0	1	5	1	3	0	0	0	0	10
Haustoriidae sp. 2	7	0	0	0	0	0	0	0	0	0	0	1	6	1	40	209
Hediste diversicolor	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Hydrobia spp.	0	152	0	2	0	0	2	1	128	0	0	0	0	0	0	0
Idunella spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ilyanassa obsoleta	0	3	0	0	0	0	0	0	0	0	0	0	0	11	0	0
Ilyanassa trivittata	0	0	47	22	16	0	0	2	14	5	0	0	0	2	0	0
Leptosynapta tenuis	0	0	0	0	2	0	0	0	1	0	2	0	0	0	0	0
Libinia dubia	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Limecola balthica	0	0	3	0	0	0	0	0	0	0	4	0	0	0	0	1
Littorina littorea *	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Lyonsia hyalina	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lysianopsis alba	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Melita nitida	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Mercenaria mercenaria	0	1	18	0	1	0	0	2	2	1	0	0	0	2	0	0
Microdeutopus gryllotalpa *	0	2	2	0	2	124	0	1	2	1	0	0	0	0	0	0
Modiolus modiolus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mya arenaria	9	22	5	31	10	4	0	4	7	3	0	2	1	1	0	0
Taxa	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**

Mytilus edulis	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Nemertea	5	0	0	0	0	0	0	0	0	0	2	6	0	0	0	0
Nephtys picta	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Nereis pelagica	0	7	5	0	0	0	0	0	3	0	0	0	0	11	0	2
Nereis spp.	0	0	1	2	0	0	0	0	0	0	0	6	0	0	0	2
Ninoe nigripes	0	0	0	0	0	0	0	0	0	0	0	3	0	0	1	0
Notoacmea spp.	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0
Oligochaeta spp.	0	222	0	0	299	2	0	0	0	21	0	0	0	0	1	0
Ophelia spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pagurus arcuatus	0	0	0	0	0	0	6	0	0	6	0	2	0	1	0	0
Panopeus herbstii	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
Paraonis fulgens	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
Pectinaria gouldii	0	0	1	0	1	1	0	1	1	0	0	0	0	2	0	0
Petricolaria pholadiformis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phyllodocidae spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
Phylo ornatus	138	26	0	0	0	0	0	2	0	4	23	1	49	4	0	0
Proceraea cornuta	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Pygospio elegans	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0
Salvatoria clavata	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Scolelepsis squamata	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
Sipuncula spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sphaeroma quadridentatum	0	5	1	1	1	12	2	1	3	0	0	0	0	0	0	0
Spionidae sp. 1	0	88	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spionidae sp. 2	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0
Spiophanes bombyx	0	2	1	0	0	0	0	1	0	5	0	0	0	5	0	0
Spisula solidissima	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Streblospio benedicti	0	0	0	70	368	175	0	0	0	0	0	0	0	0	0	0
Suberites ficus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Syllidae spp.	0	0	0	3	0	0	2	2	0	0	0	0	0	0	0	0
Unciola spp.	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
Number of individuals per station	275	6394	731	505	1081	974	1679	157	1011	114	80	79	1165	97	412	372
Number of taxa per station	7	20	27	18	17	27	20	24	21	20	10	11	11	23	10	9

Table B3. *Species distribution at stations 17-31 in Barnstable Harbor with total counts of each taxa and individuals at each station on the bottom rows. Numbers indicate individuals identified in three replicate grab samples. (*) indicates invasive/cryptogenic species according to the Massachusetts Office for Coastal Zone Management Marine Invasive Species Program*

Taxa	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Acetocina canaliculata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Alitta succinea	10	0	0	32	4	0	0	0	0	40	129	135	0	0	0
Ameritella agilis	5	3	4	5	35	22	21	0	0	102	23	86	0	0	0
Ampelisca abdita	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ampelisca macrocephala	2	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Ampelisca vadorum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amphipoda	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Anadara transversa	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Anemonia spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Arabella iricolor	0	0	0	58	0	0	0	0	0	92	44	2	0	0	0
Arenicola spp.	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Astyris lunata	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bittiolum alternatum	3	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Bivalvia	0	0	0	0	0	0	0	0	0	39	5	12	0	0	0
Brachyura spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Buccinum undatum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Capitellidae spp.	1	0	1	11	0	0	1	0	0	3	0	0	55	0	0
Caprella linearis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Caprella penantis *	10	0	0	0	8	0	0	0	0	0	1	0	0	0	0
Cerianthidae	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chiridotea coeca	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Clymenella torquata	0	0	0	5	0	0	0	0	0	111	8	0	0	0	0
Corophiidae spp.	5	0	0	0	2	0	0	0	0	4	2	0	0	0	0
Crangon septemspinosa	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Crassostrea virginica	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
Crepidula fornicata	11	0	0	0	1	0	0	0	0	3	2	0	0	0	0
Crepidula plana	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cumacea spp.	4	0	0	0	3	0	0	0	0	2	0	6	0	0	0
Cyathura polita	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Taxa	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Dexamine thea	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Dodecaceria spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Drilonereis longa	1	0	2	3	9	1	0	0	0	0	0	0	21	0	0
Edotia triloba	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Elasmopus levis	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Ensis leei	0	0	0	0	1	0	2	0	0	0	1	0	1	0	0
Eteone longa	0	2	0	6	0	0	0	0	0	1	1	3	0	0	0
Euspira heros	0	0	0	0	0	0	0	0	0	3	0	3	1	0	0
Gammarus mucronatus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gammarus spp.	10	0	0	0	3	0	0	0	0	0	0	0	0	0	0
Gemma gemma	7	0	32	2	2	3	4	0	0	7194	4145	5479	82	9	0
Glycera americana	5	0	39	13	4	0	12	10	1	4	12	0	0	0	0
Glycera capitata	0	0	0	15	0	0	0	0	0	0	0	6	0	0	0
Glycinde solitaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Haustoriidae sp. 1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
Haustoriidae sp. 2	1	57	1	0	0	125	218	8	156	0	0	0	32	0	0
Hediste diversicolor	14	0	0	0	2	0	0	0	0	11	48	123	0	0	0
Hydrobia spp.	0	0	0	0	0	0	0	0	0	22	427	2174	5	0	0
Idunella spp.	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Ilyanassa obsoleta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ilyanassa trivittata	0	1	0	0	3	0	0	0	0	2	0	3	0	0	0
Leptosynapta tenuis	0	0	0	0	0	0	0	0	0	4	21	2	8	1	0
Libinia dubia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Limecola balthica	0	0	0	2	0	0	7	7	3	0	6	0	0	0	0
Littorina littorea*	1	0	0	0	1	0	0	0	0	5	0	0	0	0	0
Lyonsia hyalina	0	0	0	0	0	0	0	0	0	3	3	4	0	0	0
Lysianopsis alba	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
Melita nitida	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mercenaria mercenaria	0	0	0	9	0	0	0	0	0	4	1	6	0	0	0
Microdeutopus gryllotalpa*	7	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Modiolus modiolus	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
Mya arenaria	0	0	0	3	0	1	2	0	0	24	21	3	0	0	0
Mytilus edulis	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

Taxa	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Nemertea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nephtys picta	0	9	0	0	7	2	1	1	4	24	1	0	0	0	0
Nereis pelagica	5	0	1	26	0	1	0	0	0	0	0	21	0	0	0
Nereis spp.	0	0	0	0	0	0	0	4	0	0	0	0	3	0	0
Ninoe nigripes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Notoacmea spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oligochaeta spp.	23	0	0	0	0	14	0	291	0	30	27	651	1453	0	0
Ophelia spp.	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Pagurus arcuatus	15	1	0	1	4	0	0	0	1	0	1	0	0	0	0
Panopeus herbstii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Paraonis fulgens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pectinaria gouldii	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Petricolaria pholadiformis	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phyllodocidae spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phylo ornatus	1	5	0	0	0	33	0	0	0	4	0	0	0	0	0
Proceraea cornuta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pygospio elegans	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Salvatoria clavata	0	0	0	0	0	0	0	0	0	2	0	6	0	0	0
Scolelepsis squamata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sipuncula spp.	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Sphaeroma quadridentatum	0	0	0	0	1	1	0	18	1	4	26	408	1	5	0
Spionidae sp. 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spionidae sp. 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spiophanes bombyx	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0
Spisula solidissima	0	2	0	0	0	2	0	0	0	0	0	22	1	0	0
Streblospio benedicti	3	0	0	8	0	0	0	0	0	0	0	1	0	0	0
Suberites ficus	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Syllidae spp.	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unciola spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Number of individuals per station	154	81	82	207	98	205	269	339	167	7739	4960	9161	1664	15	0
Number of taxa per station	30	9	9	17	22	11	10	7	7	28	28	26	13	3	0

Table B4. Average species composition at each station. No animals were found at station 31.

Station	Amphipoda	Bivalvia	Gastropoda	Polychaeta	Echinodermata	Crustacea	Cnidaria	Porifera	other worms	Number of Individuals
01	2.3 ± 2.5	41 ± 6.6	28.7 ± 27.6	46.3 ± 11.9	0	0.3 ± 0.6	0	0	1.7 ± 2.8	118.7 ± 35.4
02	36.3 ± 22.4	1817.7 ± 175.4	32.3 ± 33.6	148.3 ± 115	0	3.3 ± 0.6	0	0	74 ± 68.4	2038 ± 273.8
03	5.3 ± 4.9	24.3 ± 12.3	14.3 ± 11.6	197 ± 12.5	0	0.7 ± 0.6	0	0	0	241.7 ± 11
04	1	43 ± 51.3	3.7 ± 1.5	115.7 ± 55.5	0	0.3 ± 0.6	0.3 ± 0.6	0	0	164 ± 36.6
05	6.3 ± 1.2	9.3 ± 2.3	6 ± 5.6	238 ± 70	0.7 ± 1.2	1 ± 1	0	0	99.7 ± 100.5	261.3 ± 61.2
06	88 ± 85.5	11 ± 3.5	2.7 ± 1.2	211.3 ± 72.4	0	8.7 ± 10	0	0	0.7 ± 1.2	321.7 ± 51.2
07	1 ± 1.7	545.7 ± 510.6	2 ± 1	8 ± 8.7	0	3.3 ± 0.6	0	0	0	560 ± 504.4
08	1 ± 1	14.7 ± 12	11.3 ± 17.9	34.3 ± 21.5	0	0.7 ± 1.2	0	0	0	62 ± 21.5
09	2.7 ± 0.6	270.7 ± 200.8	38.7 ± 63.5	12.7 ± 3.5	0.3 ± 0.6	2 ± 1	0	0	0	327 ± 160.5
10	9 ± 14.7	2 ± 1.7	0.7 ± 0.6	16 ± 6.2	0	2.3 ± 4.1	0	0	7 ± 8.2	30 ± 16.8
11	1 ± 1	10 ± 1.7	0	8.3 ± 6.1	0.7 ± 1.2	5.7 ± 3.5	0	0	0.7 ± 1.2	25.7 ± 4.9
12	0.3 ± 0.6	20 ± 2	0	3.3 ± 3.1	0	0.7 ± 0.6	0	0	2 ± 2.7	24.3 ± 2.3
13	2.3 ± 1.2	368.3 ± 421.7	2 ± 3.5	17.3 ± 8.1	0	0.3 ± 0.6	0	0	0	390.3 ± 424.9
14	2.3 ± 2.3	6.3 ± 4.1	2.3 ± 4.1	18.3 ± 11.4	0	0.7 ± 0.6	0	0	0	30 ± 17.4
15	13.3 ± 4.9	114.7 ± 34.6	0.3 ± 0.6	8.7 ± 6.4	0	0	0	0	0.3 ± 0.6	137 ± 29.3
16	73 ± 22.9	27.3 ± 12.7	5.3 ± 7.6	23.7 ± 2.5	0	0	0	0	0	129.3 ± 31.9
17	12 ± 8.7	4.7 ± 2.1	1 ± 1.7	13.7 ± 6.5	0	6.3 ± 1.5	0.3 ± 0.6	0.3 ± 0.6	7.7 ± 2.5	38.3 ± 14.6
18	19.3 ± 12.9	1.7 ± 1.1	0.3 ± 0.6	5.3 ± 3.1	0	0.3 ± 0.6	0	0	0	27 ± 14.4
19	0.3 ± 0.6	12 ± 1.7	0	15 ± 13.1	0	0	0	0	0	27.3 ± 15.4
20	0	7 ± 1	2 ± 2	61.7 ± 25.1	0	0.3 ± 0.6	0	0	0	71 ± 23.9
21	5.3 ± 5.5	14 ± 3.6	0	8.7 ± 5.1	0	2.7 ± 2.9	0	0	0	30.7 ± 8.1
22	41.7 ± 71.3	9.3 ± 5	0	12.3 ± 1.5	0	0.3 ± 0.6	0	0	4.7 ± 8.1	63.7 ± 65.3
23	72.7 ± 125	12 ± 7	0	4.7 ± 4.1	0	0 ± 0	0	0	0	89.3 ± 124.4
24	2.7 ± 2.1	2.3 ± 1.	0	5 ± 6.1	0	6 ± 9.5	0	0	97 ± 34.7	16 ± 5.6
25	52.3 ± 10.6	1 ± 1.7	9.3 ± 10.7	1.7 ± 1.2	0	0.7 ± 1.2	0	0	0	65 ± 11.1
26	0	2455.3 ± 804.1	12.7 ± 10.7	97.3 ± 52.1	1.3 ± 2.3	2 ± 2.7	0	0	10 ± 17.3	2570.7 ± 791.5
27	1.7 ± 1.5	1402 ± 587.3	723 ± 290.7	81.3 ± 43.5	7 ± 3.5	9.3 ± 9.7	0	0	9 ± 15.6	2224.3 ± 667.6
28	0.3 ± 0.6	1871 ± 534.4	138 ± 234.7	99.3 ± 56.4	07 ± 1.2	138.7 ± 72.5	0	0	217 ± 153.3	2248 ± 654.5
29	10.7 ± 2.9	28.3 ± 11.7	0.3 ± 0.6	26.3 ± 12.1	2.7 ± 3.8	0.3 ± 0.6	0	0	484.3 ± 288.9	68.7 ± 5
30	0	3 ± 2	0	0	0.3 ± 0.6	1.7 ± 1.5	0	0	0 ± 0	5 ± 1.7

Table B5. *CMECS Biotic Component classifications for Barnstable Harbor Stations 1-30. Asterisk (*) indicate species not yet part of the CMECS catalog. No animals were found at station 31.*

Station	Component	Biotic Setting	Biotic Class	Biotic Subclass	Biotic group	Biotic community	most abundant species
01	Biotic						*Phylo ornatus* *
02	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Clam bed	Gemma bed	*Gemma gemma*
03	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Small surface-burrowing fauna	Capitellid bed	Capitellidae spp.
04	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Small surface-burrowing fauna	Capitellid bed	Capitellidae spp.
05	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Small tube- building fauna	Streblospio bed	*Streblospio benedicti*
06	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Small surface-burrowing fauna	Capitellid bed	Capitellidae spp.
07	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Clam bed	Gemma bed	*Gemma gemma*
08	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Small surface-burrowing fauna	Capitellid bed	Capitellidae spp.
09	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Clam bed	Gemma bed	*Gemma gemma*
10	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Small surface-burrowing fauna	Capitellid bed	Capitellidae spp.
11	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Small surface-burrowing fauna	Tellina bed	*Ameritella agilis*
12	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Small surface-burrowing fauna	Tellina bed	*Ameritella agilis*
13	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Clam bed	Gemma bed	*Gemma gemma*
14	Biotic						Dodecaceria spp. *
15	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Clam bed	Gemma bed	*Gemma gemma*
16	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Mobile crustaceans on soft sediment	Haustoriid bed	Haustoriidae spp.
17	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Small Surface-Burrowing Fauna	Oligochaete Bed	Oligochaeta spp.
18	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Mobile crustaceans on soft sediment	Haustoriid bed	Haustoriidae spp.
19	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Larger Deep-Burrowing Fauna	Glycera bed	*Glycera americana*
20	Biotic						*Arabella iricolor* *
21	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Small surface-burrowing fauna	Tellina bed	*Ameritella agilis*
22	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Mobile crustaceans on soft sediment	Haustoriid bed	Haustoriidae spp.
23	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Mobile crustaceans on soft sediment	Haustoriid bed	Haustoriidae spp.
24	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Small Surface-Burrowing Fauna	Oligochaete Bed	Oligochaeta spp.
25	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Mobile crustaceans on soft sediment	Haustoriid bed	Haustoriidae spp.
26	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Clam bed	Gemma bed	*Gemma gemma*
27	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Clam bed	Gemma bed	*Gemma gemma*

28	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Clam bed	Gemma bed	*Gemma gemma*
29	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Small Surface-Burrowing Fauna	Oligochaete Bed	Oligochaeta spp.
30	Biotic	Benthic/Attached Biota	Faunal Bed	Soft sediment fauna	Clam bed	Gemma bed	*Gemma gemma*

8. Appendix C – CMECS Substrate Components

Table C1. *CMECS Substrate Component classifications for Barnstable Harbor Stations 1-31.*

Station	Component	Substrate Origin	Substrate Class	Substrate Subclass	Substrate Group
01	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand
02	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Muddy Sand
03	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Muddy Sand
04	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Muddy Sand
05	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Muddy Sand
06	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Muddy Sand
07	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
08	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand
09	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
10	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand
11	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand
12	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand
13	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand
14	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
15	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
16	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
17	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
18	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
19	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
20	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand
21	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
22	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
23	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand
24	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
25	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly

26	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
27	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
28	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
29	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
30	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly
31	Substrate	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Mud

9. Appendix D – CMECS Geoform

Table D1. *CMECS Geoform classifications for Barnstable Harbor Stations 1-31*

Station	Tectonic Setting	Physiographic Setting	Geoform Origin	Geoform	Geoform Type* (CCS internal)	Geoform Type (CMECS)
01	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
02	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
03	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
04	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
05	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
06	Passive Continental Margin	Embayment/Bay	Geologic	Channel	Basins Channels	Tidal Channel/Creek
07	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Subtidal Flat	Tidal Flat
08	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
09	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
10	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
11	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Subtidal Flat	Tidal Flat
12	Passive Continental Margin	Embayment/Bay	Geologic	Channel	Basins Channels	Tidal Channel/Creek
13	Passive Continental Margin	Embayment/Bay	Geologic	Slope	Bedform Shallow Slopes	
14	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
15	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
16	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Subtidal Flat	Tidal Flat
17	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Subtidal Flat	Tidal Flat
18	Passive Continental Margin	Embayment/Bay	Geologic	Slope	Margins and Deeper Slopes	
19	Passive Continental Margin	Embayment/Bay	Geologic	Slope	Bedform Shallow Slopes	
20	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
21	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Subtidal Flat	Tidal Flat
22	Passive Continental Margin	Embayment/Bay	Geologic	Slope	Bedform Shallow Slopes	
23	Passive Continental Margin	Embayment/Bay	Geologic	Slope	Bedform Shallow Slopes	
24	Passive Continental Margin	Embayment/Bay	Geologic	Slope	Margins and Deeper Slopes	
25	Passive Continental Margin	Embayment/Bay	Geologic	Channel	Basins Channels	Tidal Channel/Creek

26	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
27	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
28	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
29	Passive Continental Margin	Embayment/Bay	Geologic	Flat	Intertidal Flat	Tidal Flat
30	Passive Continental Margin	Embayment/Bay	Geologic	Slope	Bedform Shallow Slopes	
31	Passive Continental Margin	Embayment/Bay	Anthropogenic	Harbor	Harbor	

10. Appendix E – Grain Size

Table E1. *Grain size metrics. Median and Mean are in mm. Sorting, Skewness and Kurtosis are dimensionless. Gravel, Sand, Mud and Organic Matter are in percent (%).*

Station	Median	Mean	Sorting	Skewness	Kurtosis	Gravel	Sand	Mud	Organic Matter
1	404	412	217	0	3	0	0.951	0.049	0.327
2	155	178	137	2	12	0	0.811	0.189	2.355
3	174	219	178	2	8	0	0.848	0.152	1.506
4	171	179	105	1	3	0	0.838	0.162	1.673
5	190	210	136	2	9	0	0.897	0.103	1.048
6	266	361	367	2	10	0.004	0.825	0.171	5.497
7	681	783	554	1	3	0.018	0.936	0.045	2.375
8	233	294	214	2	8	0	0.941	0.059	0.628
9	535	729	576	1	3	0.023	0.936	0.041	0.684
10	306	461	439	2	5	0	0.943	0.057	0.853
11	498	587	397	1	5	0	0.966	0.034	0.525
12	618	711	454	1	3	0	0.965	0.035	0.502
13	751	718	402	0	2	0	0.969	0.031	0.492
14	180	281	392	7	69	0.012	0.965	0.023	0.818
15	384	473	331	4	26	0.005	0.994	0	0.487
16	370	485	422	5	40	0.013	0.987	0	0.363
17	656	1417	1603	2	5	0.224	0.775	0	0.445
18	334	398	319	6	50	0.011	0.989	0.001	0.377
19	445	571	429	5	56	0.009	0.991	0	0.418
20	208	252	188	5	55	0.002	0.986	0.012	0.963
21	384	568	527	3	17	0.025	0.973	0.001	0.522
22	666	799	471	3	14	0.024	0.976	0	0.444
23	288	325	202	7	82	0.003	0.997	0.001	0.397
24	788	980	672	3	18	0.062	0.938	0	0.309
25	462	518	269	7	84	0.005	0.995	0	0.381
26	740	957	876	2	10	0.099	0.9	0.001	1.214
27	977	1183	780	3	18	0.09	0.91	0	0.73
28	760	849	431	2	13	0.02	0.98	0	0.502
29	943	1235	928	3	14	0.116	88.4	0	0.345
30	694	760	312	5	50	0.007	0.993	0	0.218
31	30	47	57	3	18	0	0.178	0.822	12.011

Table E2. CMECS Substrate Component

Station	Substrate Origin	Substrate Class	Substrate Subclass	Substrate Group	Substrate Subgroup
01	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand	Medium Sand
02	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Muddy Sand	Silty Sand
03	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Muddy Sand	Silty Sand
04	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Muddy Sand	Silty Sand
05	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Muddy Sand	Silty Sand
06	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Muddy Sand	Silty Sand
07	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand
08	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand	Fine Sand
09	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand
10	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand	Medium Sand
11	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand	Medium Sand
12	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand	Coarse Sand
13	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand	Coarse Sand
14	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand
15	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand
16	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand
17	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Muddy Sand
18	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand
19	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand
20	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand	Fine Sand
21	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand
22	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand
23	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Sand	Medium Sand
24	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand
25	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand
26	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Muddy Sand
27	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand
28	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand

29	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Muddy Sand
30	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand
31	Geologic Substrate	Unconsolidated Mineral Substrate	Fine Unconsolidated Substrate	Mud	Silt

11. Appendix F – Water Column Data

Table F1. *CMECS Water Column Subcomponent classifications for Barnstable Harbor Stations 1-30. (*) indicates that no information on dissolved oxygen could be obtained due to equipment malfunction.*

Station	pH	Dissolved Oxygen (%)	Temperature (°C)	Salinity (ppt)	Temperature Subcomponent	Salinity Subcomponent	Layer Subcompoment
01	7.93	106.80	19.60	24.49	Moderate	Lower polyhaline	Estuarine Coastal Surface Layer
02	8.08	109.70	19.60	27.05	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
03	8.18	105.70	18.90	28.82	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
04	8.12	92.70	19.30	28.16	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
05	7.68	*	16.95	28.73	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
06	7.32	*	16.98	28.17	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
07	7.84	*	16.96	28.37	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
08	7.98	*	16.86	28.76	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
09	7.09	*	16.67	28.35	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
10	8.14	87.00	19.40	28.17	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
11	8.15	112.30	19.30	28.47	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
12	7.36	*	16.76	29.26	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
13	7.46	*	16.93	29.10	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
14	7.73	*	16.67	30.19	Moderate	Euhaline	Estuarine Coastal Surface Layer
15	8.16	103.00	18.60	28.99	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
16	8.13	106.20	18.60	28.52	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
17	7.97	90.10	18.00	28.34	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
18	8.02	92.10	18.20	28.41	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
19	8.25	106.50	19.50	29.43	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
20	7.88	98.00	18.17	30.55	Moderate	Euhaline	Estuarine Coastal Surface Layer
21	8.31	101.40	18.40	29.03	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
22	8.04	106.00	18.40	30.74	Moderate	Euhaline	Estuarine Coastal Surface Layer
23	8.12	96.30	18.30	29.22	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
24	8.18	85.00	18.20	29.72	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer

25	8.20	98.70	18.10	29.94	Moderate	Upper polyhaline	Estuarine Coastal Surface Layer
26	8.12	114.90	18.54	31.13	Moderate	Euhaline	Estuarine Coastal Surface Layer
27	8.14	110.60	18.53	31.32	Moderate	Euhaline	Estuarine Coastal Surface Layer
28	8.14	104.60	18.30	31.45	Moderate	Euhaline	Estuarine Coastal Surface Layer
29	8.14	102.90	18.20	31.48	Moderate	Euhaline	Estuarine Coastal Surface Layer
30	8.16	106.70	18.37	31.45	Moderate	Euhaline	Estuarine Coastal Surface Layer
31	7.22	-	16.92	23.29	Moderate	Euhaline	Estuarine Coastal Surface Layer