AN ASSESSMENT OF THE ECOLOGICAL CONDITION OF BENTHIC COMMUNITIES IN NEW HAVEN HARBOR IN RELATION TO SELECTED ENVIRONMENTAL FACTORS AND HABITAT STRUCTURE

QUINNIPIAC RIVER FUND PROJECT FINAL REPORT
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Introduction

The Quinnipiac River Watershed (QRW) drains into New Haven Harbor (NHH), thus the harbor receives many potential contaminants that enter the watershed from the watershed's varied urban, suburban and agricultural landscapes. The long history of such inputs into NHH has resulted in contaminated sediments and indications of impaired overall ecological health (e.g. Applequist et al. 1972, Gronlund et al. 1991, Rozan and Benoit 2002). Concurrently, the harbor has experienced extensive human development and activity which has reshaped and altered its coastline and varied sea floor habitats. However, the harbor remains an important natural resource in terms of, for example, providing habitat for both resident and migrating fish, as settlement area for oysters (which are eventually relayed to deeper waters), and as a overwintering feeding area for migrating birds. Much of the habitat value of the harbor is tied to its benthic communities and the sedimentary characteristics and features that comprise its sea floor. Surprisingly, relatively little quantitative research has been done on assessing the ecological health of benthic communities in NHH. Surveys were done in the 1970s and early 1980s as a part of the monitoring program for United Illuminating (McCusker and Bosworth 1979, 1981, 1985) and a spatially limited study by Rhoads and Germano (1982) related to these surveys. There have also been some consultant reports related to specific projects and a few scatted sampling efforts by researchers and students at the University of New Haven and Yale University in the 1990's and early 2000's. A study of winter flounder diets conducted in part of NHH also provided data on benthic communities (Carlson et al. 18997). As such, we have a very limited knowledge of this critical component of the NHH ecosystem.

Benthic populations and communities are excellent indicators of environmental conditions and are regularly used for environmental assessment in estuarine and coastal waters (e.g. Pearson and Rosenberg 1978, Rhoads et al. 1978, Zajac and Whitlatch 2001, Mangi 2003). Often community and/or population data are combined with other ecologic metrics such as dissolved oxygen in an index of ecological health. Given their relatively sedentary life style within or on the sediments, benthic organisms integrate potential sediment and water quality impacts expressed through their ecological characteristics (e.g. abundance, growth, survival). Many environmental indices used to assess the degree and nature of environmental impacts have been developed based on marine macrobenthic taxa and communities because of this (e.g. Weisberg et al. 1997, Borja et al. 2000). For marine and estuarine systems, many indices are based on a conceptual models (Fig. 1) developed from observational and experimental studies of temporal and spatial benthic population and community dynamics in relation to certain types of environmental disturbances, particularly organic enrichment and physical disturbances (e.g., Pearson and Rosenberg 1978, Rhoads et al. 1978, Rhoads and Germano, 1982). These models state that benthic populations and communities respond to improvements in habitat quality (following either reductions in organic enrichment (Pearson and Rosenberg, 1978) or dredge material disposal (Rhoads et al. 1978) in several progressive successional, or recovery, stages, and as the abundance and species diversity of the benthos increases, dominant organisms change from more pollution-tolerant to pollution-sensitive species. Also, as benthic habitat quality improves, small and near-sediment surface dwelling species become less dominant in the system and thre is an increase or replacement by larger, deeper-dwelling species whose feeding activities can have large influences on the chemical and physical properties of the sediment (Fig. 1). These activities, in turn, may facilitate the recruitment of other benthic species.

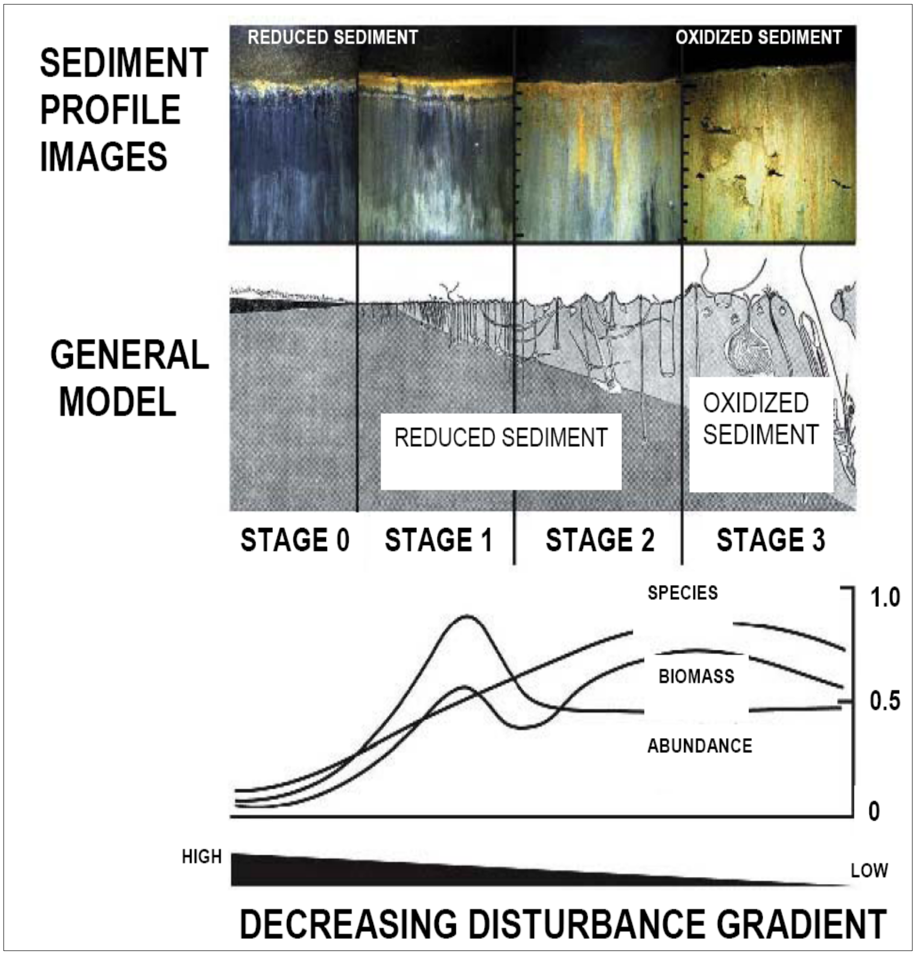


Figure 1. The Pearson and Rosenberg (1978) and Rhoads et al. (1978) model of macrobenthic succession in relation to a gradient of increasing disturbance (modified from Nilsson and Rosenberg 2000 and Norkko et al. 2006). There are three stages of benthic recovery and succession following a disturbance (running left to right). The photographs are examples of sediment-profile images showing changes in sediment texture, changes in the depth of the sediment oxic layer and effects of benthic organism activity in altering the sediment fabric and depth of the oxic sediment layer. Below the photographs is the general disturbance-recovery model illustrated in Pearson and Rosenberg (1978) which depicts how the type and functional groups of benthic organisms change as the successional process proceeds from left to right following the abatement of a organic enrichment disturbance. Initial colonizers tend to be small, near-sediment surface tube-dwelling species. As succession proceeds, larger and deeper-dwelling species begin to dominate and their feeding activities increase the depth of oxygen penetration into the sediment. The lowest panel of the figure describes how species diversity, biomass and abundance of the benthos are predicted to change following a disturbance

Using benthic communities as indicators of coastal environmental conditions, and application of indices based on macrofauna, has provided insights into coastal and estuarine conditions and has focused our approach to coastal environmental assessment and management. There can, however, be significant mis-classifications and as such there is a continued need to question the underlying basis of these paradigms (Norkko et al. 2006), and to determine the performance and sensitivity of those indices and other assessment approaches in different types of coastal environments (e.g. Zajac and Whitlatch 1982, Zajac 2001). This is especially so if there is an uncritical use of indices relative to conditions and stressor(s) for which the indicators were not originally developed. Mis-classifications can be the result of several factors such as distinctness of the species pool, specific physical and chemical characteristics of the system generating complex gradients, differences in species responses to different classes of stressors. Also, long-term allogenic (i.e. directional) succession of the system in the face of environmental change may result in the establishment of suites of species that may or may not respond to environmental conditions within the ranges that were used to develop benthic indices.

Given the paucity of information that is available for the benthic communities in NHH, and the need to establish a contemporary baseline of ecological conditions that can be used to assess future ecological changes in NHH, potentially through the application of a benthic index, the objectives of this project were to:

* assess the ecological characteristics of the benthic communities in New Haven Harbor and the lower Quinnipiac River and how these characteristics may vary spatially in the harbor relative to habitat structure,

* assess the status of benthic communities relative to disturbance / impacts models and which benthic indices might be best applied for benthic community assessment in NHH, and

* develop recommendations for future monitoring / research on the benthic communities in order to better understand potential impacts and changes that may be associated with local human actives and larger scale phenomena such as climate change.

Materials and Methods

This project comprised three sets of activities in terms of data collection and analysis. These included a) data mining for previous reports and data on the benthic ecology of New Haven Harbor, b) collection of sediment samples in the harbor in order to characterize the benthic community, and c) collection of underwater video data for characterization of habitat complexity and to provide additional information on benthic communities. Photos of field sampling and equipment are provided in the appendix to this report.

Data Mining

Data searches focused primarily on benthic community studies conducted previously in New Haven Harbor. Much of this focused on retrieving the raw data that were available in paper files associated with work done for the United Illuminating (UI) company that were deposited at the Connecticut DEP Long Island Sound Resource Center at the Avery Point campus of the

University of Connecticut (Groton, CT). Specifically, we were able to obtain raw data from the 1983 survey, and summary results from surveys conducted in the 1970s. The raw data records were reviewed and relevant information was transcribed into digital Excel files for subsequent analyses. The field sampling methods that were used by the UI consultants, the Normandeau Group, differed from those that this study employed. Their surveys used a 0.053 m^2 Ponar grab sampler and the whole sample was sieved through a 1.0 mm mesh sieve. The details of how we statistically compared our data that collected for UI are given in the results section.

Benthic Community Characterization and Assessment

Field sampling to collect data on benthic communities and sediment characteristics was conducted in New Haven Harbor between July and October 2009. Benthic infaunal and sediment samples were collected in six study areas (Figure 2). There were three shallow subtidal (~ 0.5 m deep) and six subtidal (~1 to 7 m deep) study areas. Benthic core samples, were taken at 5 random positions within each study area using a 5 cm diameter x 15 cm deep plastic tube. In the shallow subtidal areas, benthic cores were obtained by hand, and at subtidal sites a 0.06 m^2 Ponar benthic grab sampler was used to obtain a large sediment sample that was then sub-sampled using the core. Core sample depth averaged between 7-9 cm, except in few areas that had dense shell hash and sand in which cases core depth was ~ 3 -4 cm. At each study area, we also collected data on water temperature, bottom water dissolved oxygen, salinity and collected three additional sediment cores for sediment analysis. Benthic community samples were fixed (4% formalin) and stained with rose Bengal. These samples were subsequently sieved using a 300 µm sieve, and preserved in 70% ethanol. Samples were sorted using a dissecting microscope and individual organisms identified to the lowest possible taxonomic level. Samples for sediment analyses, including grain size and total organic carbon, were frozen until analyzed.

Several types of univariate and multivariate statistical analyses were conducted to determine differences within and among the study areas in New Haven Harbor with respect to habitat diversity and structure, and benthic community characteristics and their relationship to habitat structure. Details are given in the Results section.

Video Data Collection and Habitat Assessment

In order to characterize the bottom habitats of New Haven Harbor and assess habitat diversity and the relationship to benthic community structure, we collected video data using a high-definition drop video camera. Video data were collected between June and September 2010. Video data has been collected at the same study sites as for benthic characterization (Fig. 2), as well as over a broad area of the western portion of New Haven Harbor in order to track changes in an extensive bed of *Ulva*, a macroalgae and have potentially significant habitat affects on benthic fauna. At each study area, video was collected at 5 to 6 randomly spaced sites, within the general location where sediment samples were taken previously. The camera system was slowly lowered to the bottom, and any disturb sediment was allowed to be carried away by currents before running the video recorder. We recorded at least two minutes of video at each video sample location, but generally longer runs of video were obtained in order to collect data on epifaunal communities. In the lab, the videos were analyzed to collect data on various bottom features / habitat components, using CPCe software (Kohler and Gill, 2006) and analyzed using several multivariate statistical routines. Data were collected in 1 -2 minute video segments from ~ 5-7 video runs at each study area. Details are given in the results section.

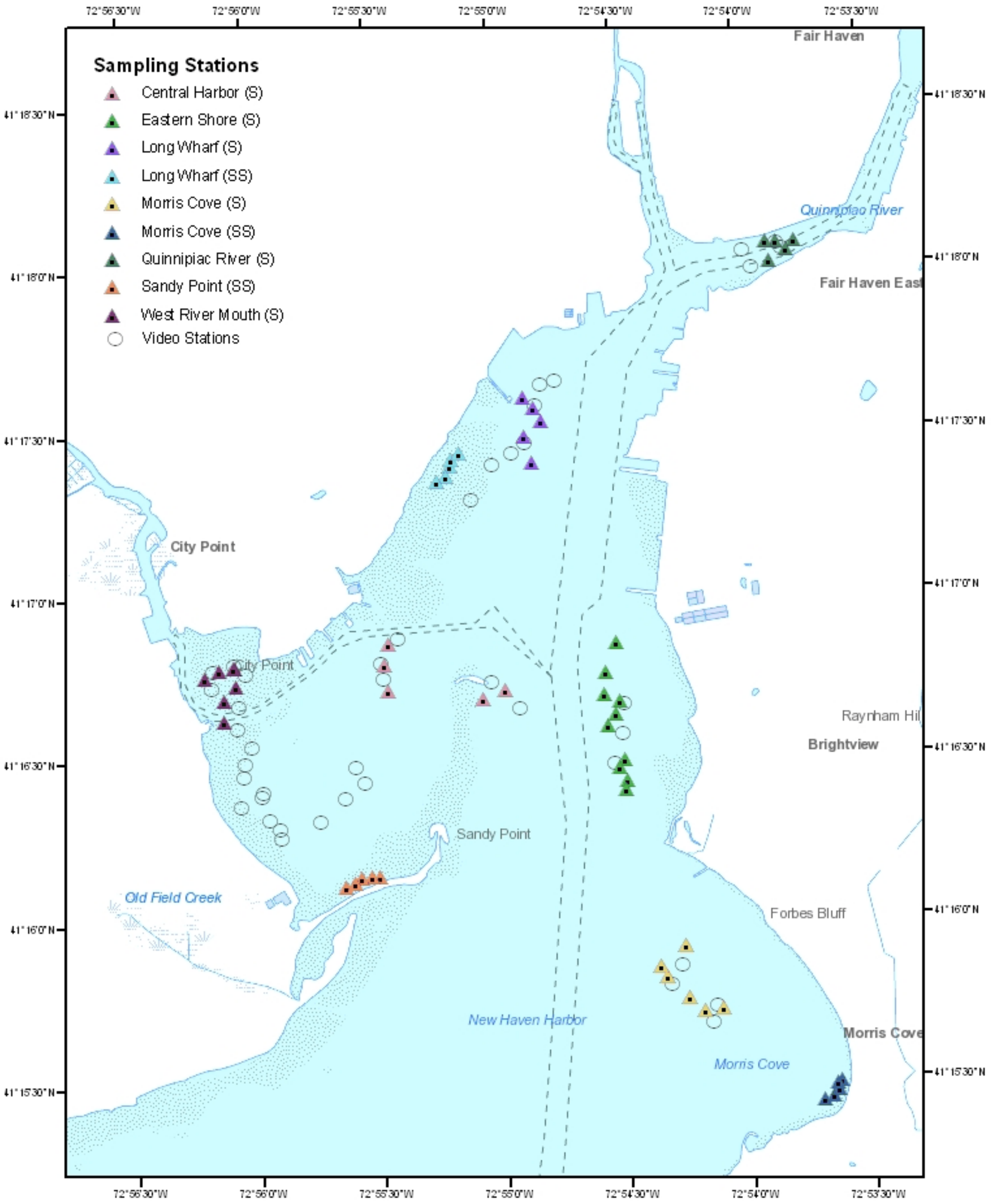


Figure 2. Location of benthic sampling cores and video samples in the New Haven Harbor study areas. SS= shallow subtidal; S = subtidal

Results

Benthic Community Structure

A total of 101 taxa were found in all of our New Haven Harbor samples. The highest number of species was found in the class Polychaeta, followed by Crustacea, Gastropoda and Bivalvia. The highest mean number of taxa was found in an area at the mouth at the Quinnipiac River north of the I-95 Bridge (Fig. 4), likely due to the heterogeneous bottom habitats in this area consisting of shell hash and mixed sands and muds (see below). Differences in mean taxonomic richness among study areas was significant. We also measured diversity using the Shannon-Wiener index H´ which is a metric combining both taxonomic richness and the evenness in the relative abundances among taxa in a sample. There were also significant differences in diversity among study areas (One way ANOVA, p<0.001, Fig. 5), however in this case the highest diversity was found in the shallow and deeper subtidal habitats of Long Wharf, indicating that the relative abundances of the taxa found that these sites were more similar to each other, whereas at the other sites there were larger differences in the relative abundances of the species and a stronger dominance structure and overall species composition.

To assess differences in community structure among study areas, several types of multivariate and univariate statistical analyses were used. Non-metric multidimensional scaling was used to assessed general

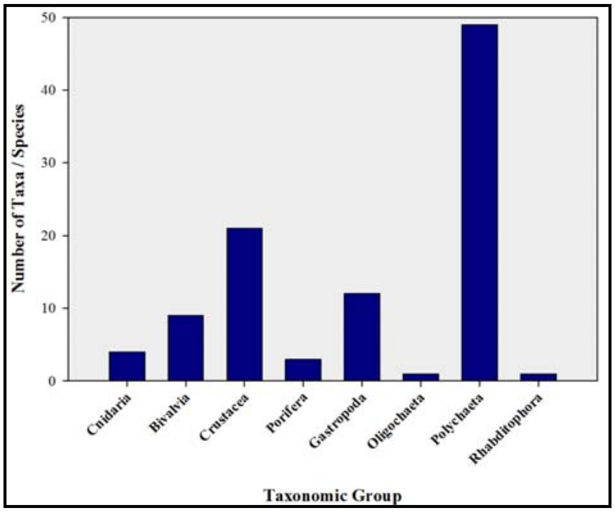


Fig. 3. Taxonomic richness among major groups of benthic fauna in New Haven Harbor**.**

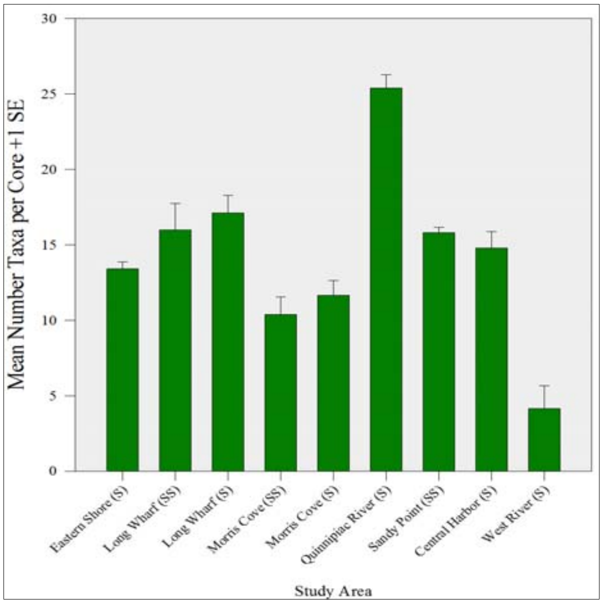


Fig. 4. Average per core abundance at each NHH study area

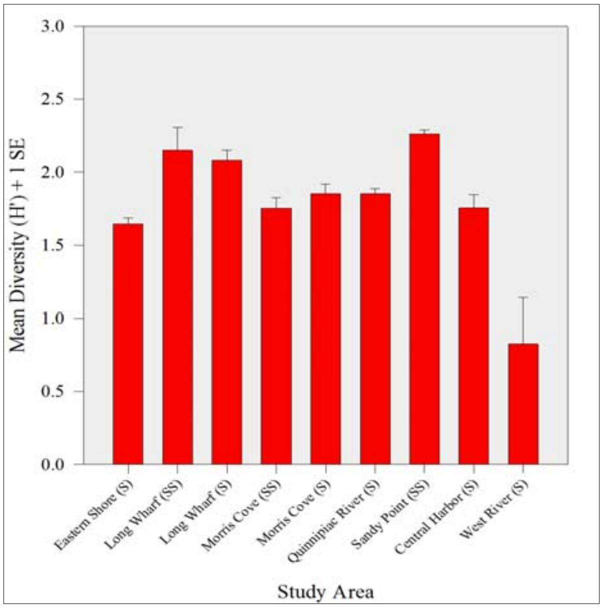


Fig. 5. Mean diversity (Shannon-Wiener H) at eaxch NHH study area.

differences in community structure (Fig. 6). This analysis indicated that shallow subtidal benthic communities at Sandy Point and Morris Cove and subtidal communities at the mouth of the West River were release similar to the other study areas. The Long Wharf study areas as well as the Central Harbor and Eastern Shore are most similar to each other. An analysis of similarities test (ANOSIM) indicated that there were statistically significant differences in community structure the study areas among (Global R = 0.87; p<0.001); even communities that were similar based on the MDS analysis had differences that were statistically discernable.

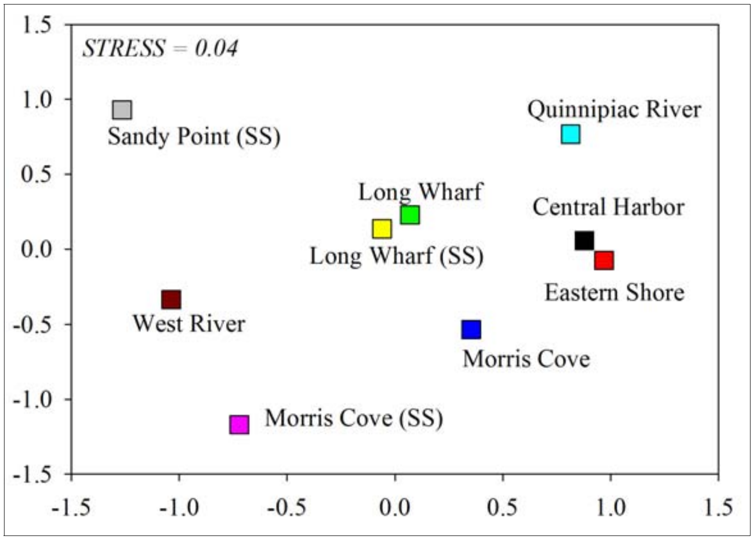


Fig. 6. nMDS plot of study area benthic community structure based on averaged core abundances. Distances among sites indicate level of similarity; sites with more similar benthic communities are closer together in the ordination space. Stress refers to the goodness of fit of the ordination to the data; in this case stress equals 0.04 indicating a excellent fit.

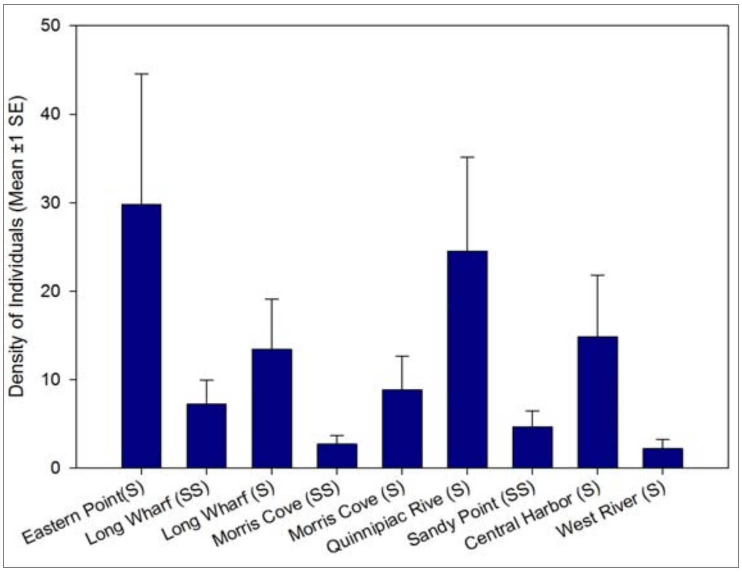


Fig. 7. Mean total abundance at each study area in New Haven Harbor

Several community characteristics differed among the study areas. Mean total abundance was relatively high in the Eastern Point study area, at the mouth of the Quinnipiac River and in the Central Harbor (Fig. 7). Relatively low abundances were found in the Morris Cove and Sandy Point shallow subtidal areas and in the area where the West River enters New Haven Harbor. A principal components analysis (PCA) was conducted to assess which species are contributing to these differences. The analysis indicated that several polychaete taxa and oligochaetes (all annelids) contributed the most to community differences Fig 8). These included *Mediomastus ambiseta*, *Streblospio benedicti*, *Cossura longocirrata*, *Sabellaria* and several oligochaete species. The abundances of these tax differed among study areas (Fig. 9). *Cossura* and *Mediomastus* were very abundant at Eastern Point. *Mediomastus* was also abundant in the Central Harbor and Quinnipiac River sites. *Streblospio* was abundant at the Long Wharf and Quinnipiac River sites. The Morris Cove and Sandy Point shallow subtidal sites has overall low abundance of these taxa that were dominant numerically at the other study areas.

An analysis of species similarities (SIMPER) provides more detailed insights into differences in species composition within and among study areas (Table 1). The dominant taxa noted above generally were the most abundant at each site and contributed most to within site similarity, but in different relative amounts. Study sites where a more diverse set of species contributed to with site community similarity included the shallow subtidal at Long Wharf where the bivalves *Macoma* and *Tellina* were abundant as well as the gastropod *Illyanassa* and the polychaete *Tharyx*. This polychaete and the cumacean *Oxyurostylis* were abundant in subtidal area of Long Wharf. The Morris Cove shallow subtidal site had high abundances of the polychaetes *Ophelia* and *Capitella*. In the Quinnipiac River site , another polychaete, *Sabellaria*, was found in relatively high abundance. This worm attaches to hard surfaces such as the shell hash that was found at this site (see below).

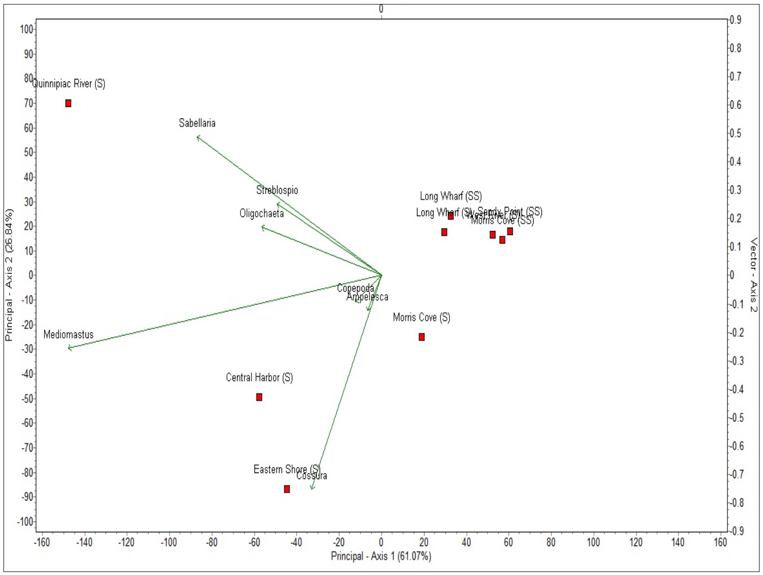


Fig. 8. Results of PCA on New Haven Harbor benthic samples.

Within study area, similarity was highest at Sandy Point and Central Harbor; moderate levels in the Quinnipiac River, Eastern Shore and Long Wharf; low levels, <50%, at both Morris Cove sites, the shallow subtidal of Long Wharf at the West River (Table 1). The relative magnitude of community variation within sites was determined by using the Index of Dispersion which measures the geometric separation of samples at a site based on their positions in ordination space, in this case nMDS. The most variable locations were the West River, Morris Cove and Long Wharf shallow subtidal (Fig. 10), suggesting higher spatial variation on benthic community structure at these sites.

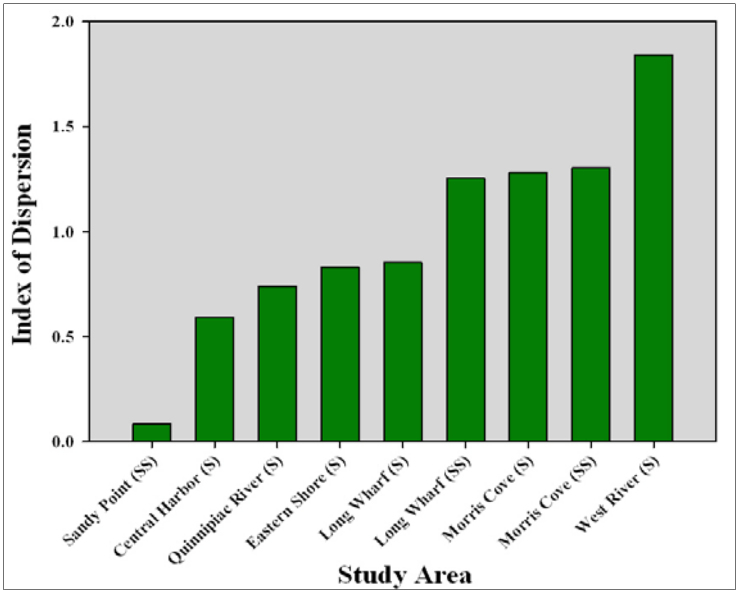


Fig. 10. Index of multivariate dispersion for New Haven Harbor study areas. Higher values indicate greater community variation within sites.

Table 1. Results of similarity percentage analysis (SIMPER). Table shows the percent contribution of each species to the total similarity within a specific study area. Av.Abund = average abundance per core at the site; Av.Sim = average similarity among replicates at the site; Sim/SD = Similarity standard deviation; Contrib% = percent contribution to within site similarity; Cum.% = cumulative similarity.

Group Eastern Shore (S)
Average similarity: 67.14

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Cossura	108.60	26.89	4.36	40.05	40.05
Mediomastus	97.20	23.87	5.58	35.55	75.61
Ampelisca	21.80	6.14	3.26	9.14	84.75
Oligochaeta	29.00	4.97	1.54	7.40	92.15

Group Long Wharf (SS)
Average similarity: 47.88

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Streblospio	43.80	16.35	1.01	34.14	34.14
Oligochaeta	27.40	9.11	1.01	19.03	53.18
Macoma	11.00	4.60	1.56	9.60	62.78
Tellina	5.00	3.01	3.83	6.29	69.07
Tharyx	5.00	2.99	2.14	6.25	75.32
Ilyanassa	5.00	2.52	2.85	5.27	80.58
Mediomastus	12.60	2.45	0.95	5.13	85.71
Balanus	4.40	1.38	1.06	2.88	88.59
Capitella	6.00	1.12	0.62	2.33	90.92

Group Long Wharf (S)
Average similarity: 64.06

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Streblospio	58.75	20.49	2.26	31.99	31.99
Oxyurostylis	31.75	15.16	6.38	23.67	55.66
Tharyx	24.25	10.66	5.04	16.64	72.30
Cossura	15.13	4.89	2.03	7.63	79.94
Mediomastus	15.50	3.54	0.81	5.53	85.47
Oligochaeta	12.38	2.68	0.97	4.18	89.65
Hydrobia	4.63	1.73	2.06	2.70	92.35

Group Morris Cove (SS)
Average similarity: 43.72

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Streblospio	8.20	10.77	2.67	24.63	24.63
Ophelia	10.20	10.62	1.03	24.29	48.92
Capitella	11.40	9.26	2.38	21.19	70.11
Mediomastus	4.20	5.99	3.24	13.70	83.81
Gemma	2.20	2.21	3.00	5.06	88.87
Nereis	1.00	1.38	1.10	3.15	92.02

Table 1 continued

Group Morris Cove (S)
Average similarity: 47.41

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Cossura	46.50	13.55	2.54	28.59	28.59
Streblospio	18.50	9.66	2.05	20.37	48.97
Capitella	14.67	9.57	1.58	20.19	69.15
Mediomastus	36.83	7.43	0.80	15.68	84.83
Hydroides	5.50	2.96	1.64	6.25	91.08

Group Quinnipiac River (S)
Average similarity: 62.37

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Mediomastus	143.00	19.97	1.63	32.01	32.01
Sabellaria	120.20	17.45	3.40	27.98	60.00
Streblospio	78.40	9.41	7.93	15.09	75.09
Oligochaeta	78.60	8.63	2.44	13.83	88.92
Eteone	8.40	1.39	3.51	2.24	91.16

Group Sandy Point (SS)
Average similarity: 80.62

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Tellina	30.60	30.67	13.19	38.04	38.04
Polydora	9.20	8.24	4.86	10.22	48.26
Oligochaeta	11.00	7.68	5.06	9.53	57.79
Glycera	7.00	6.06	2.98	7.51	65.30
Gemma	6.40	5.60	4.91	6.95	72.25
Tharyx	5.80	5.50	5.34	6.82	79.06
Eteone	4.20	3.25	2.66	4.03	83.10
Pygospio	3.60	2.79	2.44	3.46	86.56
Sphaerosyllis	3.00	2.31	4.36	2.87	89.43
Scolelepis	2.80	2.13	13.22	2.64	92.06

Group Central Harbor (S)
Average similarity: 71.05

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Mediomastus	117.40	30.09	6.19	42.35	42.35
Cossura	56.60	14.65	4.49	20.62	62.98
Copepoda	40.00	10.14	6.03	14.28	77.26
Streblospio	36.40	6.94	1.11	9.77	87.03
Oligochaeta	23.60	6.18	3.15	8.70	95.73

Group West River (S)
Average similarity: 8.77

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Oligochaeta	13.14	4.97	0.60	56.73	56.73
Streblospio	5.71	1.74	0.40	19.85	76.58
Notoacmea	2.86	0.82	0.22	9.31	85.89
Mediomastus	5.43	0.69	0.35	7.84	93.73

Habitat Structure in New Haven Harbor

Research on habitat structure was conducted along several lines, including analysis of environmental data collected in the field (e.g. salinity, temperature), image analysis of sediment structural components from core samples, sediment grain-size distributions and total organic carbon of sediment core samples, and image analysis of video data collected in the field.

Temperature and salinity did not vary to any great extent at the times sediment samples were being collected (July - October). Water temperature varied between 17 - 18 °C and sediment temperature between 17 - 20.6 °C; salinity varied between 27 - 31.5 psu. Sediment composition varied considerably among the study sites (Fig. 11), as did total organic carbon (Fig. 12). Coarse sediments characterized the Morris Cove and Sandy Point shallow subtidal sites, sands in the Quinnipiac River, Eastern Shore, Central Harbor and Long Wharf shallow subtidal sites, whereas silt-clays and clays comprised much of the sediments in the Long Wharf, Central Harbor, West River and Morris Cove sites. TOC was at about 1% by weight at most of the study sites, although somewhat higher at the Central Harbor, Long Wharf Quinnipiac River and West River sites, TOC was low in the sandy Morris Cove hallow subtidal sediments.

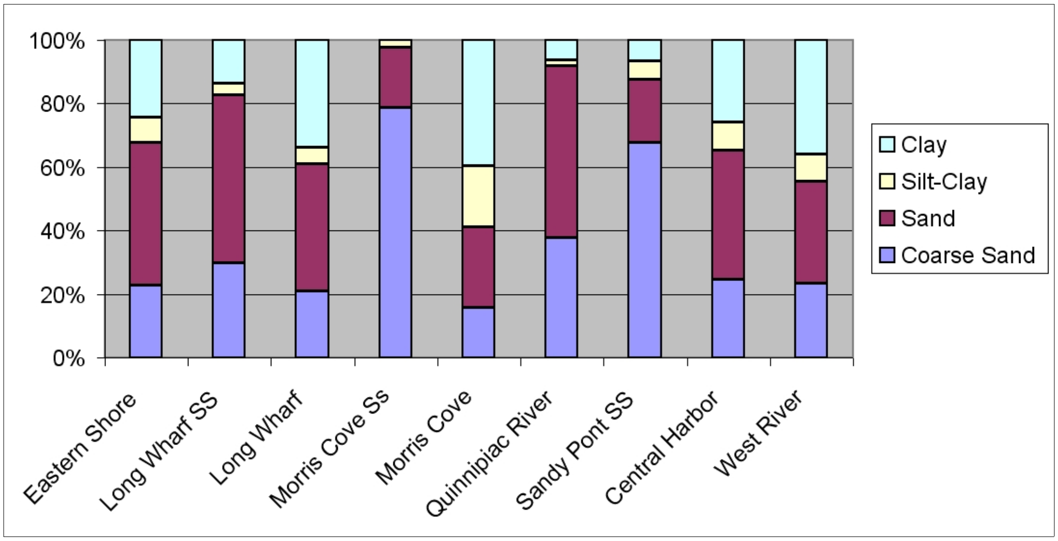


Fig. 11. Mean grain size composition by weight at each NHH study site. Grain size composition was determined using a partial wets sieving / dry sieving technique given in Holme and McCintyre (1984). Coarse Sand: ≥0.500 µm; Sand: < 0.500 µm ≥0.110 µm; Silt-Clay: <0.110 µm ≥0.064 µm; Clay: < 0.64 µm

We used image analysis of the benthic sample cores to obtain additional data on structural habitat elements (i.e. features that generate habitat in benthic environments). After the sediment samples taken to enumerate benthic organisms were sorted to remove the organisms, the core materials were spread out in a shallow pan and photographed. Image analysis was then used to determine the percent occurrence of habitat features using CPCe software (see above) based on 30 random points on each photograph. These habitat features differed considerable among the study sites (Fig. 13). Apart from sediments, shell hash (whole and fragmented shells)

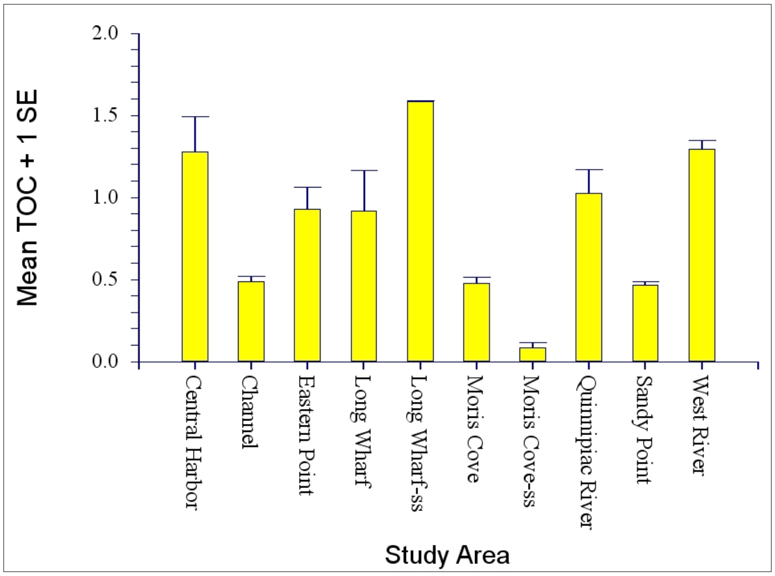


Fig. 12. Mean total organic carbon (TOC) at each NHH study site as determined by weight loss on ignition following procedures in Holme and McIintyre (1984).

constituted the most significant habitat element at most sites, except the West River, which was primarily just sediment. Organic structural elements (in this case algae) were also high at the West River and the Quinnipiac River sites. Animal tubes were prevalent at the Morris Cove and Central Harbor subtidal sites. Multivariate analyses of these data revealed that there were statistically distinct differences among the sites, as determined by randomizations tests of cluster analyses (Fig. 14). Two main groups of sites were distinguished. One group comprised the Eastern Shore, and the shallow subtidal sites at Sandy Point, Long Wharf and Morris Cove, which were all characterized to varying degrees by relatively large percentages of rock, and or shell in addition to bare substrate. The other group was comprised of subtidal sites at Morris Cove, Central Harbor, West River and the Quinnipiac River, and these were statistically distinct among themselves as well. This group was characterized by bare sediments but also relatively large percentages of shell, tubes and organic material / vegetation.

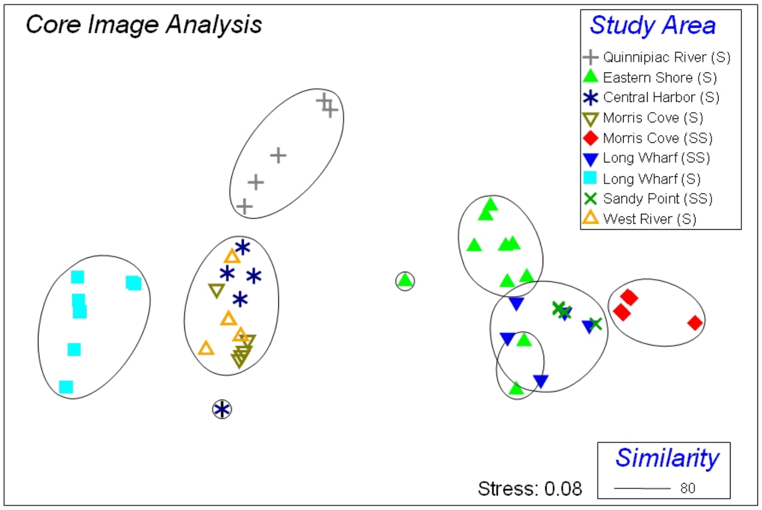


Figure 14. nMDS analysis of sample core habitat components based on image analysis. Circles around point indicates groups that were clustered together at a 80% level of similarity.

A significant component of our study of benthic habitats in NHH utilized underwater video to obtain data on habitat structure as well as on epibenthic fauna that may not be sampled by the grabs and cores. The video records (Fig. 15) were scored for a variety of habitat variables including both biogenic and non-biogenic variables, as well as for epibenthic organisms. There were clear differences in habitat components among the subtidal study sites (Fig. 16). Bare substrate (sediment) was the predominate feature at Long Wharf and Central Harbor, and to a lesser extent Quinnipiac River sites. Each of these site however did have 30% - 40% of the bottom also comprised of a variety of other features. The Quinnipiac River site in particular had large percentages of shell hash and animal tubes. Morris Cove also had a large percentage of bare substrate, but the sediments are heavily bioturbated with many animal tracks

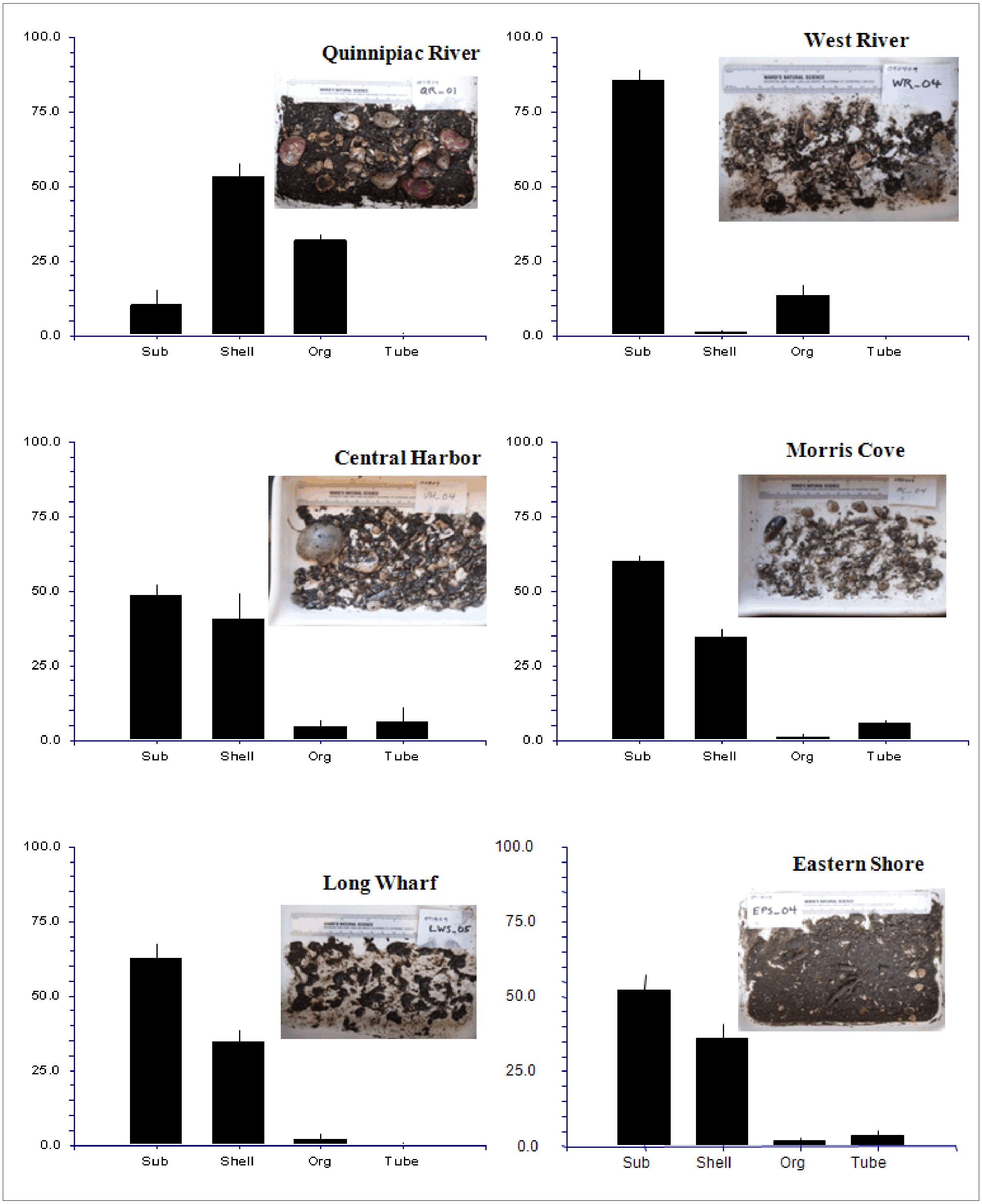
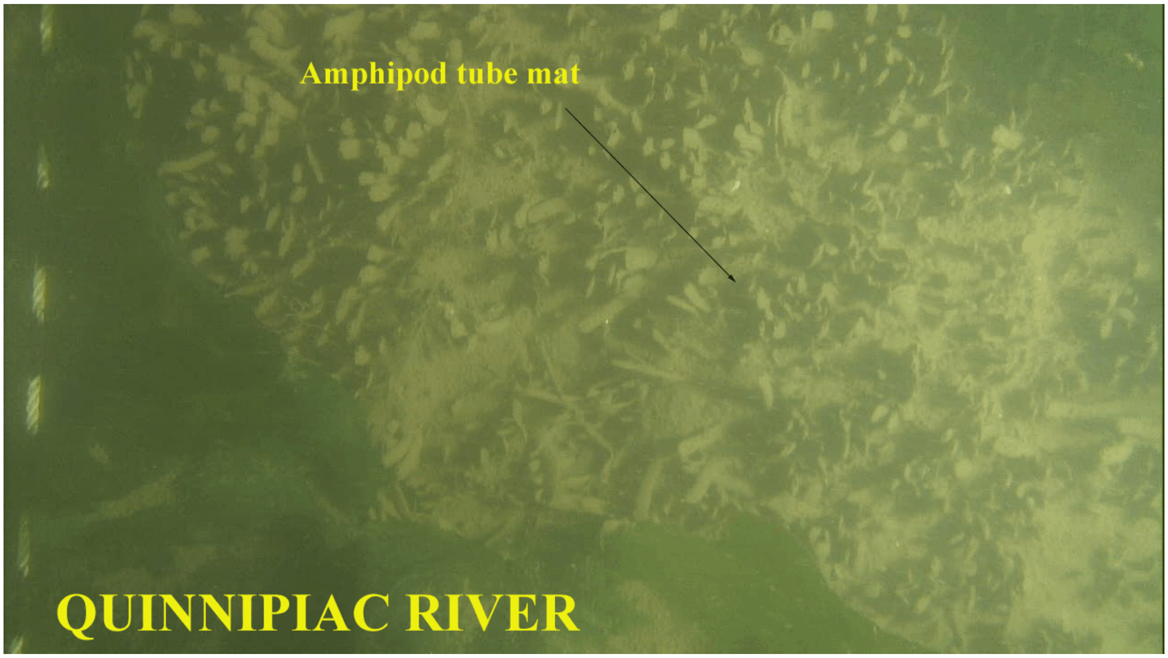


Fig. 13. Results of image analysis of sediment cores for habitat structural elements. Y -axis is mean percent composition (+1 SE); Sub = Sediment substrate (sand + mud); Shell = whole shells and fragments; Org = organic material (e.g. algal strands); Tube = tubes constructed by animals in the sediments. Images show representative examples of sediment habitat features at each site.



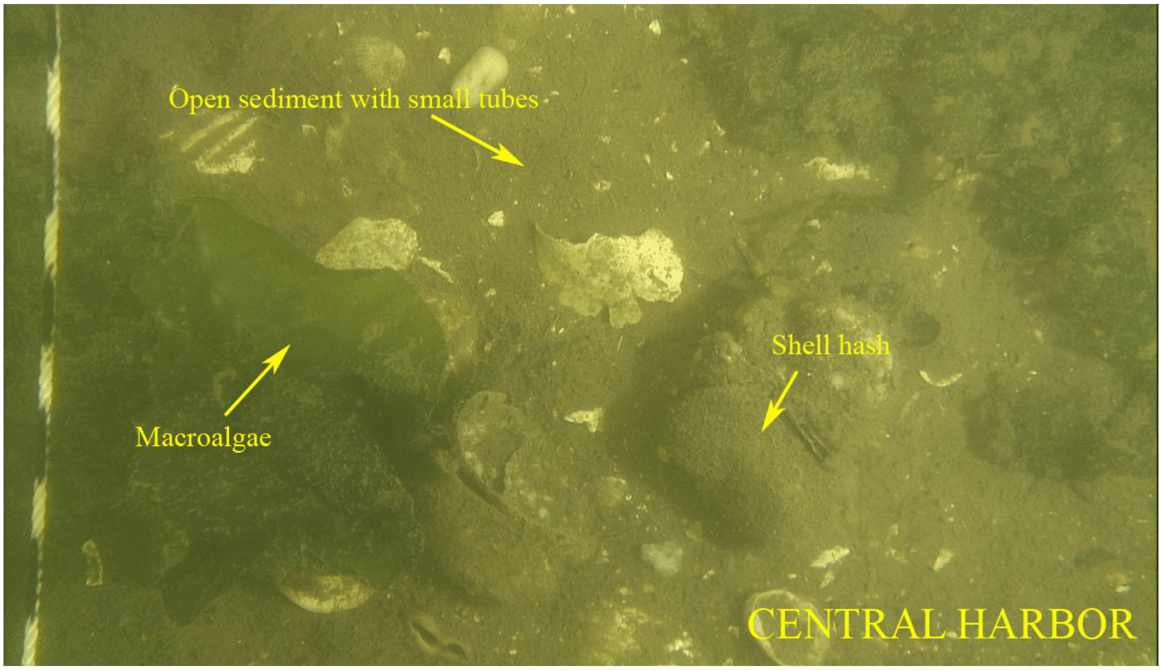


Figure 15. Representative images from video records collected in New Haven Harbor. Images are from43 of the study areas and show features that were enumerated for assessing habitat diversity. Black/white bands on left side of image are in 1 cm lengths. Field of view in the images is ~ 10 x 12 cm. See http://www.youtube.com/watch?v=9i1X3p0r5YM for video example.

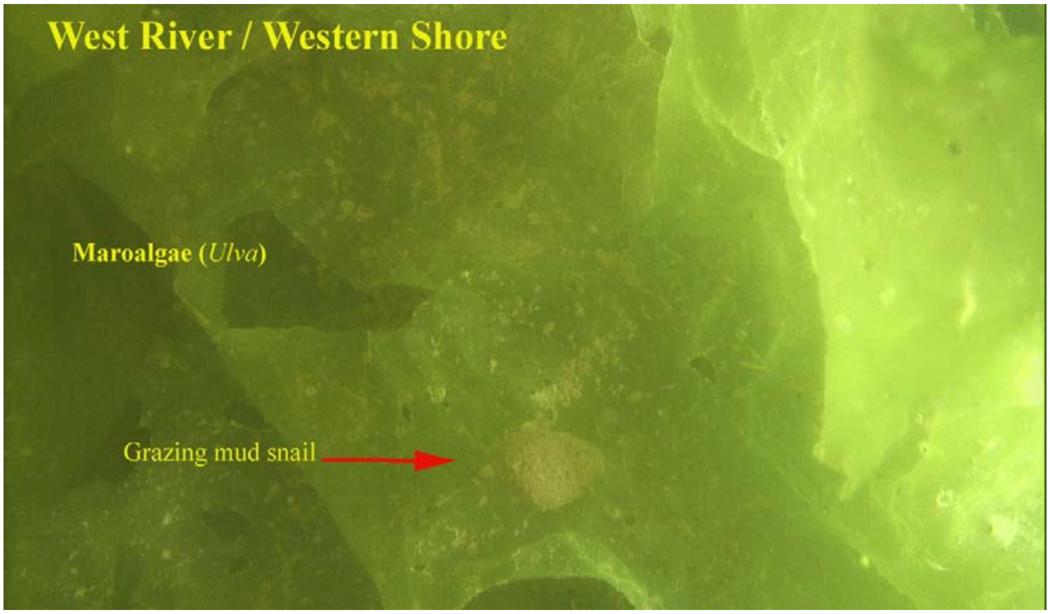


Figure 15. (Continued) Representative images from video records collected in New Haven Harbor. Images are from 4 of the study areas and show features that were enumerated for assessing habitat diversity. Black/white bands on left side of image are in 1 cm lengths. Field of view in the images is ~ 10 x 12 cm. See http://www.youtube.com/watch?v=9i1X3p0r5YM for video example.

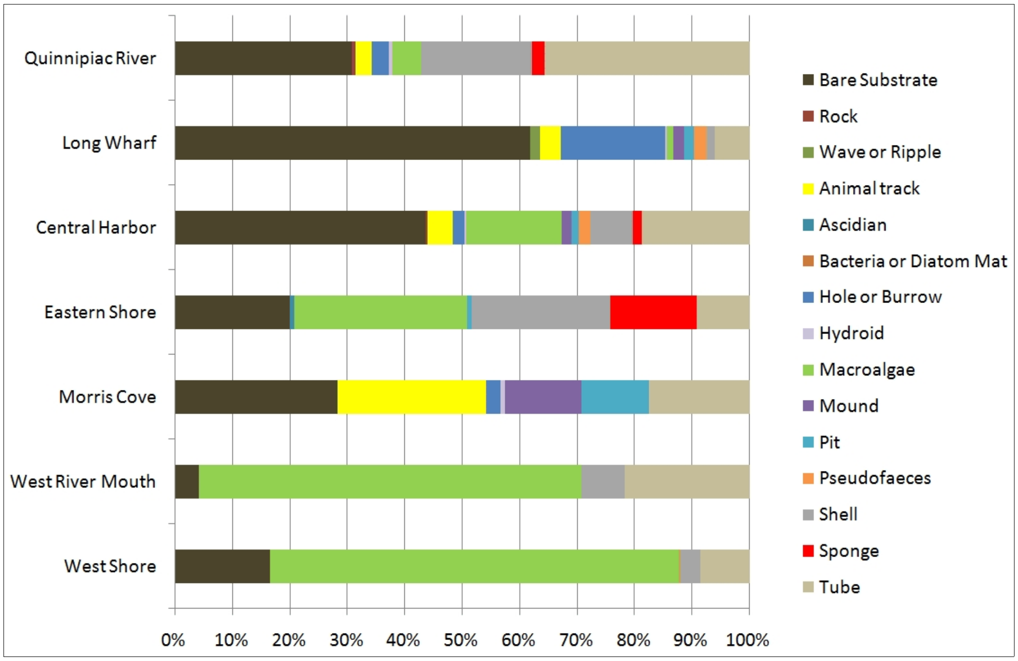


Figure 16. Mean percent composition of subtidal habitat features in New Haven Harbor as determined by video sampling and analysis.

mounds, pits and there was also a relatively large percentages of tubes created by the infauna. western position of the harbor and in the Long Wharf area. Drifting macroalgae was the predominate habitat feature at the mouth of the West River and along the western shore of NHH. These algal mats sit on top of bare sediments or in some areas a mixture of bare substrate and shell. There was also a relatively large percentage of animal tubes at the West River mouth area. In some cases, particularly close to the navigation channel in this area, these were created by amphipods and formed tubes mats, as was also seen at the Quinnipiac River site (Fig. 15).

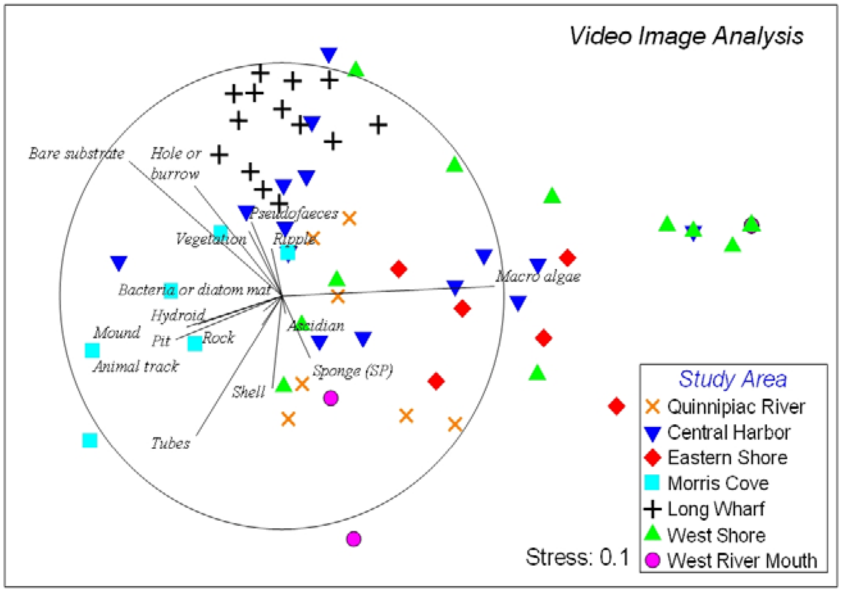


Figure 17. MDS analysis of habitat features in New Haven Harbor based on video imaging. Overlain are vectors from a principal components analysis (PCA) representing habitat factors and how they are influencing the nMDS ordination.

Although these sites were characterized by the suite of features shown in Fig. 16, there was a fair degree of variation in habitat features within sites as well (Fig. 17). The Long Wharf, Eastern Shore and West Shore areas had the least variation in habitat structure (MDS dispersion = 0.718, 0.975 and 1.009 respectively). The West River Mouth, Morris Cove, Quinnipiac River and Central Harbor areas had increasingly higher within-site habitat variation (MDS dispersion =1.106.

1.151, 1.157 and 1.225, respectively). An ANOSIM test indicated that there were statistically significant differences in habitat features among sites based on the video data (Global R = 0.458, $p < 0.001$). On a site by site basis, all sites differed among each other except West River Mouth and West Shore, and Central Harbor and Quinnipiac River sites. Also differences among Central Harbor and Morris Cove and Central Harbor and Eastern Shore were marginally significant ($p < 0.10$). As was noted above, the West Shore and several stations along the Eastern Shore were characterized by a large macroalgal component to habitat structure, whereas Morris Cove, Long Wharf and other Eastern Shore site habitats were primarily differentiated by bare substrates and associated biogenic features such as tubes, pits and mounds (Fig. 17).

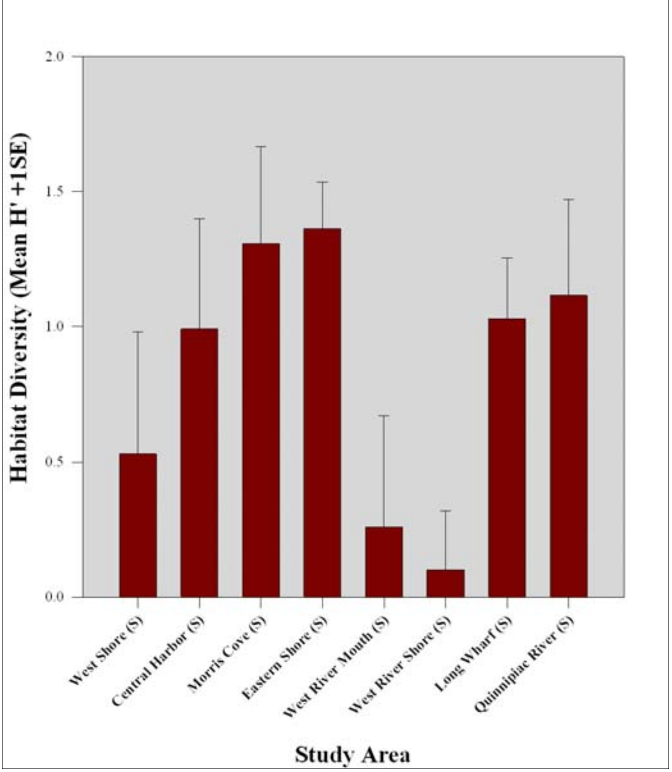


Figure 18. Habitat diversity (measured by the information theoretic index H') at each study area based on features (see Fig. 16) scored from video records.

Overall habitat diversity was assessed by calculating the Shannon-Wiener diversity index, H', for each video record at each site. There were significant differences in mean habitat diversity among sites (one way ANOVA, $p<0.001$). The lowest habitat diversity was in the western portion of the harbor where drift macroalgae comprised the most prevalent habitat component, whereas relatively high diversity was found in other areas where there were more even mixtures of habitat features (Fig. 18).

Habitat / Benthic Community Relationships

To assess which habitat features may be shaping differences in benthic community structure in NHH, we performed two sets of multivariate analyses focusing on habitat feature data collected from the core imaging and from underwater video records. In each case, multiple regression was first used to assess which habitat features explained most of the variation in species abundances. The features identified were then used in a canonical correspondence analysis (CCA) to assess patterns / differences of species abundances and distributions (community structure) among sites as constrained by their relationships to environmental variables. CCA explores community structure among different sites and helps to identify features that are determinants of the patterns found.

CCA using the core imaging data (Fig. 13) and several sediment variables (Fig. 11), revealed a distinct separation between the West and Quinnipiac River sites and the Morris Cove, Eastern Shore and Central Harbor sites, within the Long Wharf site having an intermediate position

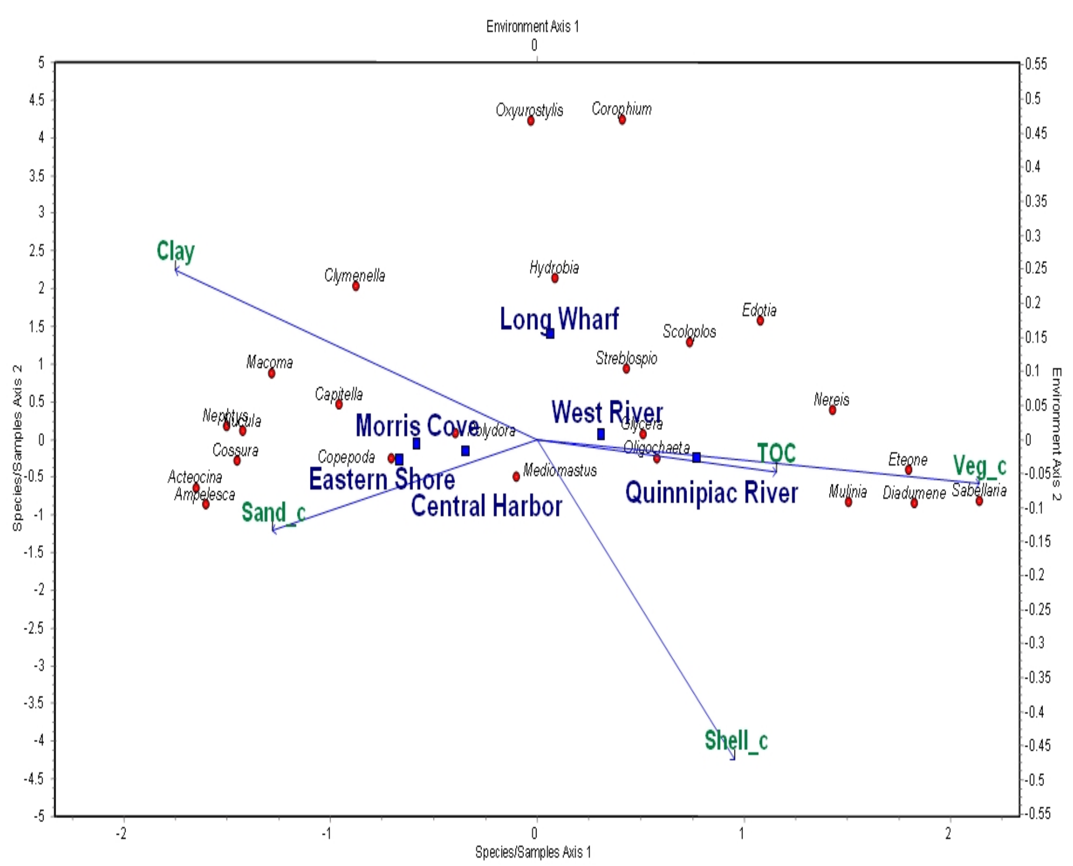


Figure 19. CCA ordination of subtidal sites in New Haven Harbor relative to sediment composition and habitat features determined with core imaging. Clay: % composition of clay sized particles in the sediments; TOC: % by weight total organic carbon in sediments; Sand_c, Shell_c and Veg_c: relative % occurrence of sand, shell and vegetation in the core samples.

along axis 1 and separated to some extent form all the other sire along axis 2 (Fig. 19). Overall, the ordination along the first two canonical axes explained 76.1 % of the variation in species / sites relative to the environmental variables considered (axis 1: 42.9%, axis 2: 33.2%). Increasing amount of TOC, shell and vegetation separated the West and Quinnipaic River sites, whereas increasing amounts of sand and clay in the sediments separated the Morris Cove, Eastern Shore and Central Harbor sites. Differences in species patterns generally reflect the community structure results presented above. The river sites had relatively larger abundances the bivalve *Mulinia* and the polychaetes *Eteone* and *Nereis*, and in the case of the Quinnipiac River the concretion forming polychaete *Sabellaria*.. Higher abundances of amphipods, *Ameplisca* and *Corophium*, the polychaetes *Cossura*, *Nephtys, Clymenella* and *Capitella*, the gastropod *Acteocina*, and the cumacean *Oxyurostylis* at the other sites. A Monte Carlo randomization test indicated that there is a very low probability ($p < 0.001$) that the ordination configuration shown in Fig. 19 occurred by chance alone.

Of the habitat features derived from the video data, variable selection analysis indicated that the presence of tubes, shell and sand waves accounted for 78.9 % of the variation in species abundances. These habitat features in addition to bare substrate and macroalgae were used in the CCA (Fig. 20), which indicated that increasing numbers of tubes and shell shaped the species community patterns at the West River and Quinnipiac River sites, whereas increasing cover of

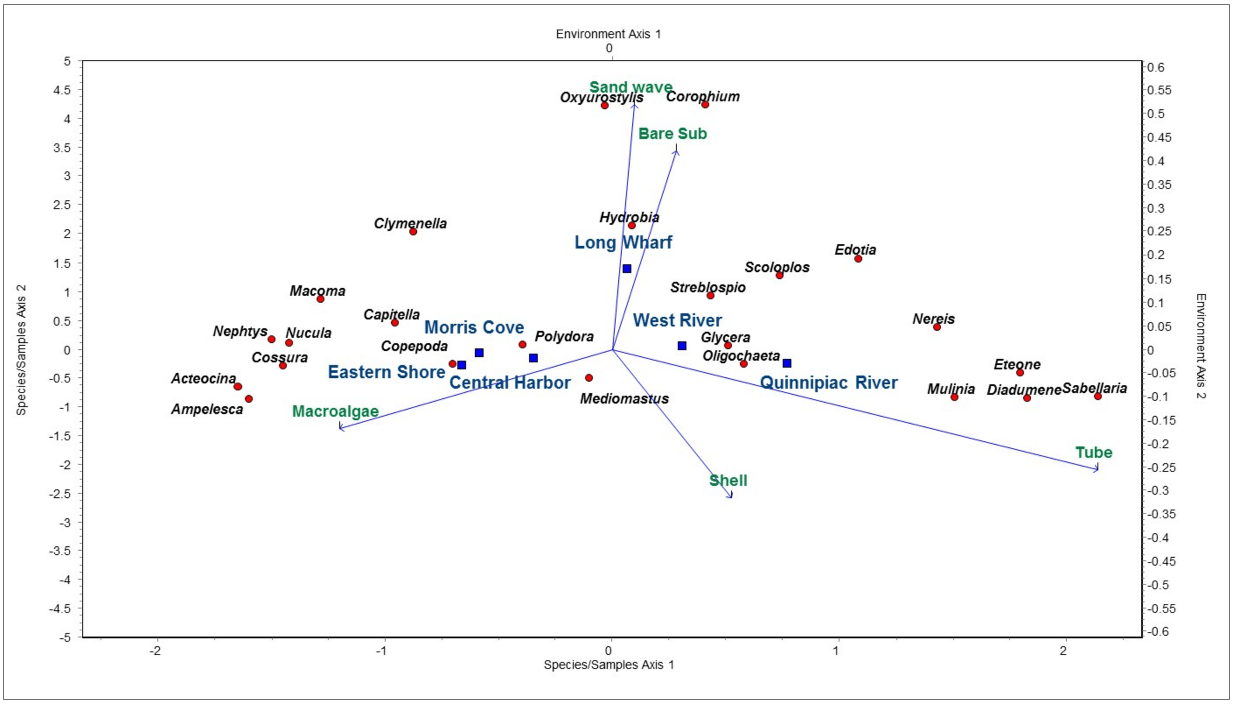


Figure 20. CCA ordination plot of sites and species in New Haven Harbor in relation to habitat features based on video data.

macroalgae was most associated with increases of some species at the Eastern Shore and Central Harbor sites. Increasing amounts of bare substrate and sand waves were associated with community patterns at the Long Wharf site. Note that while large amounts of drift macroalgae were found in the West River mouth area and along the western shore of NHH, the strongest positive relationship between benthic infauna and macroalgae were at locations (Eastern Shore, Central Harbor) where the amount of macroalgae increased from low to moderate levels. In contrast, high amounts of macroalgae at the West River site was associated with low abundances of the species that were found in this portion of the harbor.

Epifaunal communities

Our video analyses show that epifauna (organisms living on top of sediments and/or among surficial habitat features) constitute an important component of the benthic communities, especially gastropods and crustaceans (Fig. 21). The gastropods *Illyanassa obsoleta* and *Hydrobia ulvae* were commonly found as well as a variety of crustaceans, including several species of crabs (all grouped as Brachyura), such as the green crab *Carcinus meanus*, blue crabs (Callinectes sapidus), and mud crabs, hermit crabs *Pagurus spp*. (grouped as Paguroidea), various amphipods and isopods (grouped as Decapoda) and barnacles (Cirripedea). Gastropods and crustaceans were mostly prevalent along the West Shore as well as in the Central Harbor and Morris Cove study areas. Several other groups were found in low numbers at the other study sites including bivlaves (mussels), teleost fish, tunicates, anemones (Anthozoa), and sponges (porifera). A distance base redundancy analysis indicated that epifaunal communities were relatively distinct among the study sites , with three genera groupings, including a Central

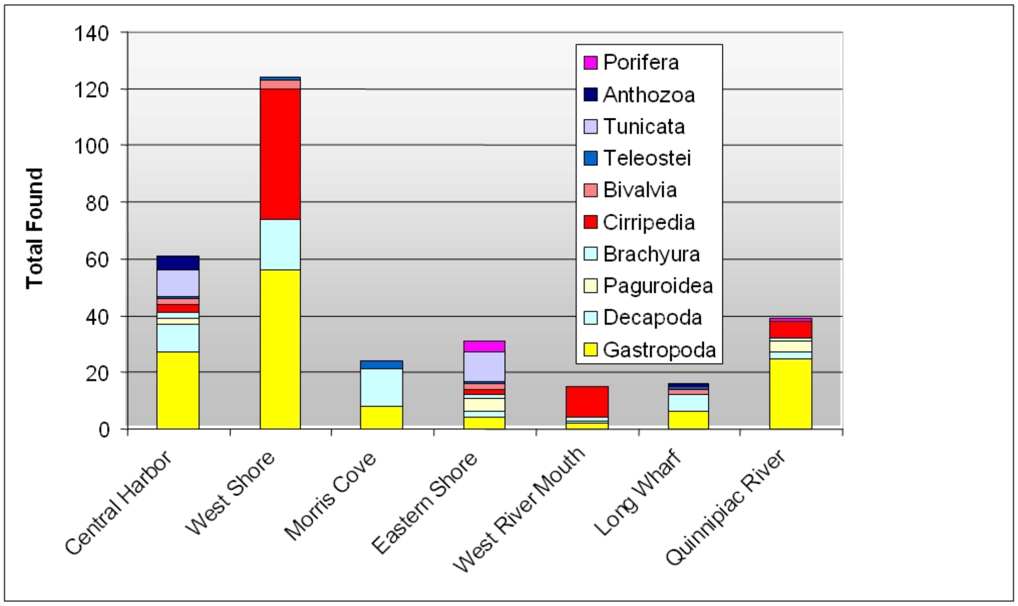


Figure 21. Total abundances of benthic epifauna observed in video data records collected in New Haven Harbor.

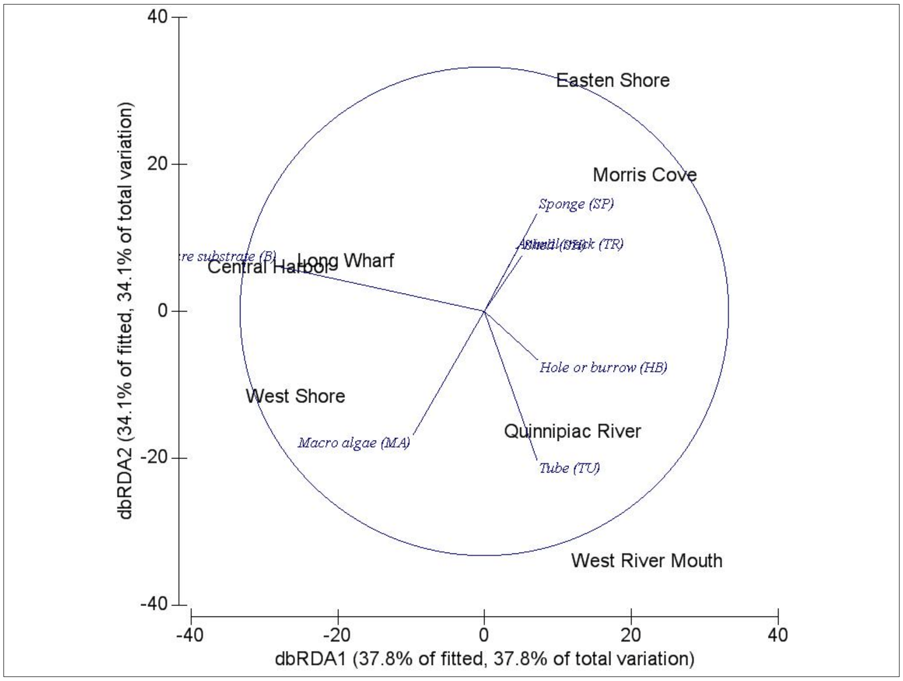


Figure 22. Distance-based redundancy analysis ordination of epifaunal communities at New Haven Harbor study sites relative to habitat features identified in video analyses.

Harbor, Long Wharf and West Shore group, a Morris Cove and Eastern Shore group and a Quinnipiac River , West River group (Fig. 21). The habitat features that appear to be shaping the epifaunal communities within these general groupings include burrows and tubes at The Quinnipiac and West River sites, bare substrate and macroalgae at the Central Harbor, Long Wharf and West Shore sites, and the presence of sponges, animal tracks and shell at the Morris Cove and Eastern Shore sites.

Potential long-term ecological trends in New Haven Harbor

We used data from a benthic survey conducted in New Haven Harbor in 1983 and our data to determine if there have been any discernable change sin the benthic communities in the harbor. Such comparisons can be difficult given methodological and potential taxonomic identification differences among studies. In terms of methodology, although both our and the UI study used the same type and size of grab sampler, the UI samples represent the fauna collected from the whole grab on a 1 mm sieve, and we obtained a core sub-sample from the grab and collected fauna on a 300 μm sieve. Faunal counts from our samples were extrapolated to numbers per m^2 to match the UI data. To reduce potential taxonomic differences on classification, we combined data for taxa at the genus level, and conducted the analyses at this taxonomic level. We also conducted analyses after converting genus-level abundances to presence / absence data to assess potential differences just based on species compositions. The analyses were limited to locations in the harbor that were common to both studies (Fig. 23). Several types of multivariate analyses were conducted.

Based on both genus level abundances and presence-absence, it appears that here has been a shift in benthic community structure in New Haven Harbor (Fig. 24). There is clear separation among the UI and UNH samples in both sets of analyses, and PERMOVA tests indicate significant differences among the UI and UNH data sets for analyses based on genus-level relative abundances and presence / absence (Table 2). These results suggest a long-term shift in benthic community structure in the harbor, at each of the sites considered in this comparison. The average similarities within sites among the 1983 and 2009 sampling years were higher for the presence/absence data than for the abundance based comparisons, but still revealed significant differences over this time period at each site (Table 2). Considering the abundance data, the change detected may be the result of changing abundances of several taxa including ampeliscid amphipods, oligochaetes and several polychaete genera, primarily *Mediomastus* and *Streblospio* (Table 3).

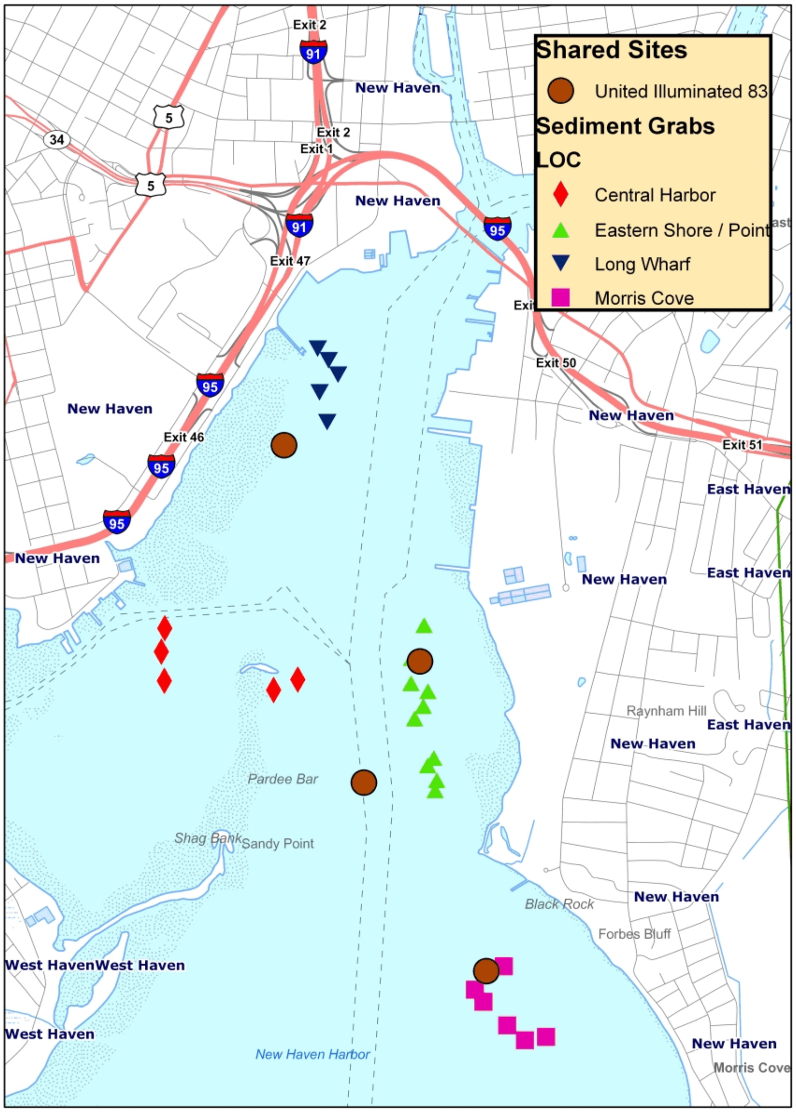


Figure 23. Locations of UNH and UI sampling in New Haven Harbor

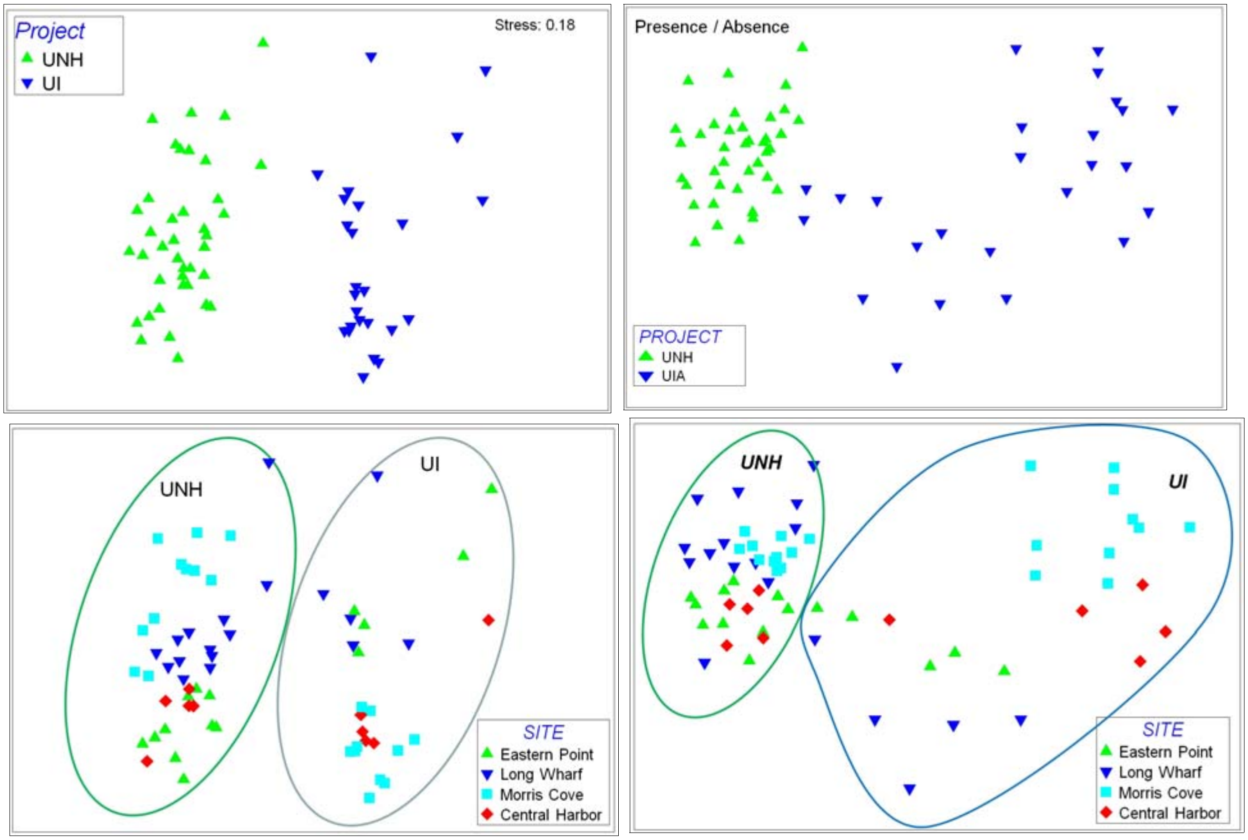


Figure. 24. Results of nMDS analyses of benthic community differences between 1983 (UI samples) and 2009 (UNH samples) in New Haven Harbor. Plots on the left show results using abundance data, plots on right are results using presence/ absence data.

Table 2. Results of PERMOVA analyses to test difference sin community structure among the UI and UNH data sets. The PERMOVA design was a two way analysis with replication, with data source (UI or UNH) and site (Eastern Point, Long Wharf, Morris Cove and Central Harbor) as the main factors. Test were done for differences for the main effects and well as comparisons of UI vs UNH data sets for each site separately.

	Abundance Data		Presence /Absence Data	
Overall Test				
Factor	*p-value*	*% variation*	*p-value*	*% variation*
Source	0.001	36.3	0.001	47.0
Site	0.001	10.1	0.001	9.0
Source x Site	0.001	25.9	0.001	24.6
Residual Variation		27.7		19.4
Differences among Sites based on Source (UI vs UNH)				
Site	*p-value*	*% similarity*	*p-value*	*% similarity*
Eastern Point	0.001	13.0	0.002	63.0
Long Wharf	0.002	21.0	0.001	58.9
Morris Cove	0.001	13.1	0.001	46.9
Central Harbor	0.013	16.8	0.009	46.8

Table 3. Results of SIMPER analysis comparing community differences in New Haven Harbor between 1983 (UI) and 2009 (UNH) based on genus level identification of taxa found. Av.Abund = Average abundance; Av.Diss = Average Dissimilarity; Diss/SD = Dissimilarity standard deviation, a measure of provides a measure of how consistently a given taxa contributes to the dissimilarity between UI and UNH samples; Contrib % = % contribution to dissimilarity; Cum. % = Cumulative % dissimilarity. Only taxa contributing to 90 %

Groups UNH & UI
Average dissimilarity = 90.23

Taxa	Group UNH Av.Abund	Group UIA Av.Abund	Av.Diss	Diss/SD	Contrib %	Cum. %
Ampelisca	1080.76	25249.90	26.84	1.05	29.75	29.75
Mediomastus	8492.33	6.77	16.72	0.95	18.53	48.28
Streblospio	4972.37	2678.62	10.70	0.95	11.86	60.14
Oligochaeta	2921.91	18.05	5.73	0.85	6.35	66.49
Maldane	25.63	4186.38	5.34	0.88	5.92	72.41
Capitella	1349.89	5.26	4.11	0.58	4.56	76.97
Cumacea	1281.54	0.75	2.90	0.50	3.21	80.18
Polydora	21.36	1357.36	2.49	0.54	2.77	82.95
Corophium	371.65	213.57	1.03	0.38	1.15	84.09
Macoma	337.47	150.40	1.01	0.40	1.12	85.21
Podarke	333.20	14.29	0.97	0.46	1.08	86.29
Glycera	341.74	84.22	0.90	0.55	1.00	87.28
Pagurus	4.27	437.66	0.81	1.02	0.90	88.19
Hydroides	260.58	104.53	0.81	0.52	0.90	89.08
Nereis	72.62	460.22	0.79	1.01	0.88	89.96
Scoloplos	59.81	442.93	0.79	0.56	0.87	90.83

Discussion

New Haven Harbor is characterized by an environmentally complex coastal landscape. Sections are heavily developed / industrialized, such as the various port and industrial facilities at the mouths of the Quinnipiac River, Mill Rivers and West River, and along parts of the eastern shore. Other areas are bordered by residential areas, marinas, small salt marshes, parks and beaches. Our study shows that the seafloor of NHH is also comprised of a set of heterogenous habitats. Previous studies have provided a broad understanding of the general benthic environments of the harbor. These are almost wholly comprised of fine-grained sediments (muds) with sandier areas near Long Wharf, Sandy Point and along ceratin parts of the NHH shoreline (Fig. 25). Our analyses of the detailed characteristics of these environments reveal a rich variety of habitats, ranging from areas that are primarily comprised of bare sediments with few features to those that are quite complex. Based on the analyses, there are combinations of sites that have similar habitat characteristics (Table 4). In terms of sediment grain-size, our data generally agree with the sediment distributions reported previously for the harbor (Fig. 25, Table 4), although our data suggest that sediment compositions are more heterogenous in the harbor than the general mapping shown in Fig. 25. For example, much of the lower Quinnipiac River was previously characterized as mud, but at the site we sampled the sediments were comprised of primarily of sand and coarse sand (Fig. 11). Similarly, other sites were more sandier than suggested in Fig 25. Although much of the harbor can be characterized as “mud,” moderate differences in the amount of sand and other sediment grain-size fractions can potentially result in varying benthic communities. Our benthic community analyses revealed relatively distinct communities across the harbor (Table 4, Fig. 6), indicating that additional habitat factors and environmental conditions are shaping the distribution and characteristics of these communities. The habitat characteristics quantified from the core and video imaging indicate that across these general sedimentary environments, there are sets of features that increase the diversity of habitats both within and across the different sediment types. Habitat features identified via core imaging grouped the intertidal sites and Eastern Shore, and the other sites formed another group. These two groups varied based on higher amounts of shell and coarser sediments found with depth in the sediment, and higher numbers of tubes and organic fragments, respectively. The video imaging revealed a wider diversity of habitat characteristics among the sites sampled (Table 4, Fig. 17). Based on the video habitat features, the West River,

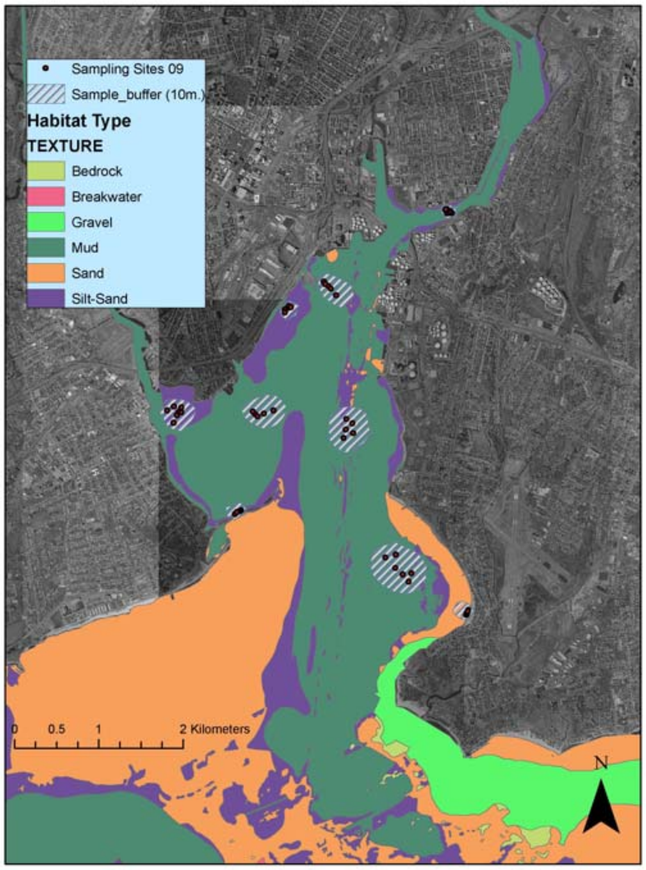


Figure 25. Spatial distribution of general bottom types in New Haven Harbor based on USGS data.

Table 4. Summary of analyses of benthic habitats and communities in New Haven Harbor. For each component, locations that had similar characteristic are grouped. MC$_{ss}$, LW$_{ss}$, and SP$_{ss}$ are the Morris Cove, Long Wharf and Sandy Point shallow subtidal / intertidal sites, respectively. The subtidal, deeper water sites are: ES = Eastern Shore, QR = Quinnipiac River, MC = Morris Cove, CH = Central Harbor, WR= West River, LW = Long Wharf, WS = Western Shore.

<table>
<tr><td>Sediment Grain-Size</td><td colspan="3">ES, QR, MC$_{ss}$, LW$_{ss}$, SP$_{ss}$
(<i>sands, sandy muds</i>)</td><td colspan="4">MC, CH, WR, LW
(<i>muddy sand, mud</i>)</td></tr>
<tr><td>Sediment TOC</td><td colspan="3">MC$_{ss}$, SP$_{ss}$, MC, ES
(<i>lower</i>)</td><td colspan="4">CH, LW, WR, QR
(<i>higher</i>)</td></tr>
<tr><td>Core Imaging Habitat Characteristics</td><td colspan="3">ES, MC$_{ss}$, LW$_{ss}$, SP$_{ss}$
(<i>shell, coarse sediments</i>)</td><td colspan="4">MC, CH, WR, QR, LW
(<i>shell, tubes, organic material</i>)</td></tr>
<tr><td>Video Imaging Habitat Characteristics</td><td>MC
(<i>Biogenic</i>)</td><td>WS
(<i>algae</i>)</td><td colspan="2">LW, CH, ES
(<i>shell, biogenic, algae</i>)</td><td>QR
(<i>shell, tubes</i>)</td><td colspan="2">WR
(<i>algae</i>)</td></tr>
<tr><td>Infaunal Communities</td><td>SP$_{ss}$</td><td>WR</td><td>MC$_{ss}$</td><td>LW, LW$_{ss}$</td><td>CH, ES,</td><td>MC</td><td>QR</td></tr>
<tr><td>Infauna / Habitat Relationships</td><td colspan="3">MC, ES, CH
(<i>sand, clay, algae</i>)</td><td colspan="4">LW, WR, QR
(<i>TOC, shell, tubes, algae</i>)</td></tr>
<tr><td>Epifauna</td><td colspan="2">ES, MC</td><td colspan="2">CH, LW, WS</td><td colspan="3">QR, WR</td></tr>
</table>

west shore of the harbor, Quinnipiac River and Morris Cove had relatively distinct habitat characteristics, whereas the Cental Harbor, Long Wharf and Eastern Shore sites were relatively more similar to one another. Habitat characteristics within many sites were quite variable as indicated by the separation of individual sample locations at specific sites on the ordination plot (Fig. 17) and the dispersion statistics calculated. Habitat characteristics at the Long Wharf and Morris Cove sites were relatively consistent. Although the west shore area had a relatively lower multivariate dispersion value as a majority of the sample sites were similar, other areas of the West Shore differed considerably as seen in the ordination plot. These differences were primarily based on whether there was drift macroalgae or not at the site. The Quinnipiac River site was also less variable than some of the other sites with shell hash, coarse sediments and tubes being found at most locations sampled at this site. On an overall basis, based on video imagine analysis, habitat diversity was high at most sites, except for those in the western portion of the harbor. The diversity found was comprised of both physical (e.g. sand ripples) and biogenic elements (e.g. pits, mounds, shell hash).

Given the variety of habitats found in NHH, and the physical (e.g. tidal currents, freshwater inflow, temperature) and chemical (e.g. salinity) environments gradients from the outer to the inner harbor, it is perhaps not surprising that NHH supports a relatively diverse benthic fauna. We found 101 benthic taxa during this study. In comparison, Zajac (1998) found a total of 144 benthic taxa in several open water areas of LIS in the areas of Stratford Shoal and south of Norwalk, CT. Thus, the benthic communities of NHH do not appear to be impoverished with respect to species richness. Diversity was relatively similar among the study sites (Fig. 5), with the highest levels being found in the Long Wharf area, and the lowest in the West River area.

Benthic communities varied across the harbor, with differences among sites both in the abundances of the dominant species and species composition. The polychaete annelids found in high abundance throughout the harbor, including *Streblosio benedicti*, *Mediomastus ambiseta* and oligochaetes, are commonly found in estuaries and embayments along the LIS Coast and elsewhere and can reach seasonally high abundances during periods of maximum recruitment (e.g. Zajac and Whitlatch 1982, 2000). Apart from these species, the study sites each had varying numbers of species that were only found or mainly found at that site. For example, at the Quinnipiac River site this included *Sabellaria* which constructed small concretions of tubes along the sediment surface, and at the other sites several species of bivalves or other polychaetes (Table 1). Overall, the mix of species in NHH includes those are typically found in estuarine embayments and coastal areas.

The benthic communities were well-developed in most locations. However, the western portion of the harbor in the area just south of the mouth of the West River appears to have a reduced benthic community, and habitat diversity here and areas along the western shore as revealed by the video data is also low. The low abundances of organisms and apparent low habitat diversity are likely due to the extensive mats of the macroalgae *Ulva spp*. that were consistently found in this area throughout the summer and early fall while collecting benthic samples in 2009 and in the video records collected in 2010 (Figure 14). Mats of *Ulva* are known to smother sediments by causing hypoxic or anoxic conditions due their respiratory demands at night and to extirpate or reduce benthic communities (e.g. Norkko and Bonsdorff 1996). However, these drifting mats of algae may harbor transient communities that live within the mat (e.g. Norkko et al. 2000), and/ or organisms that use the mat temporarily to forage in or as protective cover. We believe that the mats may shrink or disappear during the fall and winter and their spatial extent, and potential impacts on benthic communitiesare greatest during the spring and summer. We are investigating the effects of the algal mats on benthic communities in New Haven Harbor in more detail via experimental and observational studies that were initiated in 2010 (comprising a significant portion of D.S. Brown’s thesis work at UNH). The extensive production of nuisance algae and drifting algal mats, such as we have found in NHH, are impacting many coastal areas globally and are related to eutrophication of these environments (e.g. Vahteri et al. 2000). The dynamics and impacts of these mats in NHH are currently being researched and monitored in more detail in our lab, as they appear to cover a large area of the western harbor, and may be having a significant negative impact on the ecology of this portion of the harbor. Patches of drifting algae (predominantly *Ulva*) were also observed in the other study areas, but their spatial extent and incidence in the video records was lower.

Although the benthic communities in many areas of New Haven Harbor are currently numerically dominated by species that are often considered opportunistic and potentially indicators of impacted conditions, such as the polychaetes *Streblospio benedicti* and *Mediomastus ambiseta*, the overall diversity is relatively high, with high abundances of non-opportunistic species in some areas. These include for example, the bivalve *Tellina*, and the polychates *Glycera*, *Spiochaetopterus* and *Sabellaria*. In some areas large (> 5 cm wide) quahog clams, *Mercenria mercenaria* were found in the grab samples (see APPENDIX) that were obtained and sub-sampled with the core samplers (these large clams were not readily sampled by our 5 cm cores). One of the dominant species found, *Cossura longicirrata*, has not previously identified in the harbors and embayments of Long Island Sound, but is known from offshore habitats of LIS (Zajac 1998), and deeper Atlantic waters. It is not clear how its presence in the harbor is related to conditions in the harbor or some larger regional factor that may be changing its distribution, or whether it simply has not been found in previous studies.

Comparison to studies conducted in 1983 suggests that there has been a shift in benthic community structure in NHH over the past 29 years. Although the sampling methods differed, we took several analytical approaches to make the data comprable and less affected by such differences. Both the analyses based on presence/absence and relative abundances at the genus level indicated a shift in benthic community structure (Fig 24). Considering the abundance-based comparisons, the main differences were decreases in amphipod abundances over the time period and increases in the abundances of oligochaetes and the polychaetes *Mediomastus* and *Streblospio,* and to a lesser extent *Capitella*. These species are often considered disturbance / pollution indicators, and typical of stage 1 benthic communities (Fig.1) that may be found in areas impacted by, for example, elevated organic levels or low dissolved oxygen. Based on presence/absence analyses, the shift is not due to relatively distinct sets of fauna in 1983 and 2009, but the regularity with which fauna common to both time periods were found at the sites and sample locations within sites. For example several amphipod taxa were found in almost every UI sample in 1983 (*Ampelisca*, *Corophium*), but only in a portion of samples from these sites in 2009. Likewise, taxa found consistently in samples in 1983, but sparsely in 2009 included the polychaetes *Maldane, Polydora, Euclymenela, Nephtys,* and *Scoloplos*, and several bivalves incuding *Mulinia* and *Macoma*. Overall however, given the differences in sampling and sieve sizes used between the two studies, these differences should be considered with caution, until additional confirming studies have been conducted. In this case, such studies should try to match the sampling procedures used in the UI studies to the extent possible at a selected set of sites to assess if such differences are contributing at all to the apparent change in benthic communities revealed by our studies.

The main objective of this study was to develop a contemporary baseline for the benthic communities of NHH. As such, we employed procedures (e.g. finer sieve size) that we feel would provide detailed information on certain suites of species that have been characterized as pollution / stress indicators under certain situations (see above). However, they can also be found in high abundances as part of the naturally occurring and not necessarily impacted communities in estuarine areas. These species were abundant at many sites in 2009, thus suggesting that benthic conditions over the past 25 years have deteriorated to some extent as reflected in the apparent increased abundance of these species since 1983. However, we also found a variety of other species along with these potential indicators, and in some areas a relatively diverse associated community. Under impacted conditions, species such as *Streblospio* and *Mediomastus* are often the only species found, and that was generally not the case that most of the sites that we sampled. Therefore, it may be possible that the UI sampling underestimated many of the small sized species that were abundant at the time we sampled (they used a 1 mm sieve to collect fauna fom thier samples), and that these species have been seasonally abundant within New Haven Harbor over the years and are not necessarily indicating a deteriorated condition. Zajac (2000) has argued that situations such as these reflect a dynamic the benthic community structure is comprised of species with many different life histories and life modes. In order to better assess these contrasting interpretations it will be necessary to resemble several sites using both sampling procedures as noted above.

Summary

Our study provides the basis for an overall assessment of ecological conditions in NHH and the potential connections to human activities around the harbor and in the watersheds contributing inputs into the harbor. We found an array of diverse habitats across multiple spatial scales in the harbor, both among and within sites we sampled. Associated with these diverse habitats was a relatively diverse set of benthic communities that although sharing certain common characteristics across the harbor, display local differences. The complex and diverse nature of the benthic communities suggests that the application of existing benthic indices may not be warranted, as these may be too limited or simple to accurately assess ecologoical health under these circumstances. New Haven Harbor is a highly developed, urban coastal environment, and has areas that are heavily impacted. This includes, for example, the confluence of the Quinnipiac and Mill Rivers where they enter the harbor and where the main port facilities are located and related activities occur. Previous sampling of benthic environments in this area have shown the sediments to be highly liquefied, anoxic and generally devoid of fauna (Zajac personal observations, Ignudo unpublished UNH research project). We also found that in portions of the western area of the harbor, extensive algal beds may be having a negative effect on benthic communities. However, much of the rest of the harbor supports complex, well-developed benthic communities. Indeed the level of overall taxonomic diversity is somewhat surprising relative to diversity levels found in Long Island Sound. In light of these findings, it is important not to consider the harbor as impacted on some overall basis, and to acknowledge and incorporate the presence of diverse habitats and communities within the context of environmental planning, conservation and management in the harbor. Habitat diversity on multiple spatial scales is being increasingly recognized as a critical factor that shapes benthic community structure and the health of coastal ecosystems, and that habitat diversity can be impacted various ways by human activities, thus compromising overall biodiversity (Thrush and Dayton 2002, Hewitt et al 2005, Thrush et al. 2006, Zajac 2008a,b). Any future activities and development in New Haven Harbor will need to consider not only impacts on benthic communities but also on the habitats found in the harbor and the physical and biological determinants of those habitats.

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APPENDIX

Appendix Table 1. Taxa / species identified in New Haven Harbor duirng 2009 sampling program

Acarina
- *Halacalus sp.*

Anthozoa
- *Diadumene leucolena*
- *Diadumene lineata*
- *Ceriantheopsis americana*
- *Bowerbankia gracilis*

Bivalvia
- *Bowerbankia gracilis*
- *Gemma gemma*
- *Macoma tenta*
- *Mercenaria mercenaria*
- *Mulinia lateralis*
- *Mya arenaria*
- *Nucula proxima*
- *Pandora gouldiana*
- *Pitar morrhuanus*
- *Tellina agilis*

Gastropoda
- *Acteocina canaliculata*
- *Bittium varium*
- *Crepidula convexa*
- *Hydrobia totteni*
- *Ilyanassa obsoleta*
- *Nassarius vibex*
- *Notoacmea testudinalis*
- *Prunum roscidum*
- *Rictaxis puctostriatus*
- *Turbenilla sp.*
- *Urosalpinx cinerea*

Polychaeta
- *Ampithoe valida*
- *Aricidea catherinae*
- *Autolytus cornutus*
- *Capitella capitata*
- *Chaetozone setosa*
- *Clymenella torquata*
- *Cossura longocirrata*
- *Diopatra cuprea*
- *Dodecaceria corallii*
- *Drilonereis longa*
- *Eteone heteropoda*
- *Eteone lactea*
- *Euclymene collaris*
- *Glycera americana*
- *Glycera capitata*
- *Glycera dibranchiata*
- *Goniadella gracilis*
- *Heteromastus filiformis*
- *Hobsonia florida*
- *Hydroides dianthus*
- *Laonice cirrata*
- *Leitoscoloplos fragilis*
- *Lumbrineris tenuis*
- *Maldane sarsi*
- *Mediomastus ambiseta*
- *Melinna cristata*
- *Nephtys incisa*
- *Nephtys picta*
- *Nereis succinea*
- *Ophelia acuminata*
- *Polydora cornuta*
- *Polydora ligni*
- *Polydora websteri*
- *Polygordius appendiculatus*
- *Polyphysia crassa*
- *Pygospio elegans*
- *Sabellaria vulgaris*
- *Scolelepis viridis*
- *Scoloplos robustus*
- *Scoloplos squamata*
- *Sphaerosyllis erinaceus*
- *Spio setosa*
- *Spiochaetopterus oculatus*
- *Streblospio benedicti*
- *Syllis gracilis*
- *Tharyx acutus*
- *Paranaitis speciosa*
- *Pectinaria gouldii*
- *Phyllodoce mucosa*
- *Podarke obscura*

Oligochaeta
- *Paranais litoralis*
- *Tubificoides benedeni*

Rhabditophora
- *Stylochus ellipticus*

Hydrozoa
- *Obelia dichotoma*

Merostomata
- *Limulus polyphemus*

Malacostraca
- *Americamysis bigelowi*
- *Ampelesca abdita*
- *Chirodotea caeca*
- *Corophium bonelli*
- *Corophium insidiosum*
- *Edotia lactea*
- *Eurypanopeus depressus*

- *Gammarus faciatus*
- *Heteromysis formosa*
- *Idotea balthica*
- *Neomysis americana*
- *Oxyurostylis smithi*
- *Pagarus longicarpus*
- *Palaemonetes pugio*
- *Stenothoe minuta*
- *Unciola irrorata*
- Xanthidae

Cirripedea

- *Balanus improvisus*

Demospongiae

- *Cliona celata*
- *Haliclona loosanoffi*
- *Microciona prolifera*

Hemichordata

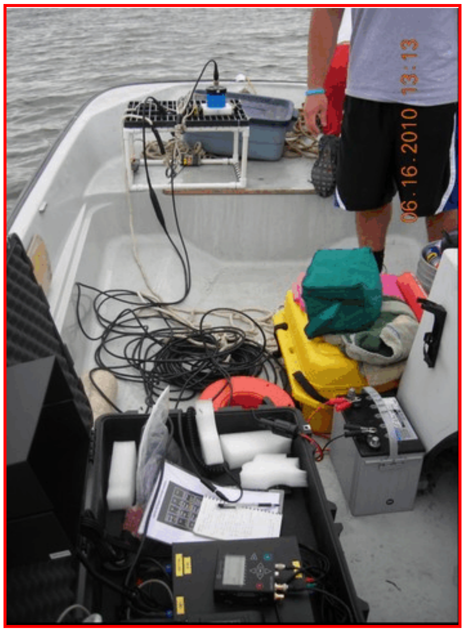
Saccoglossus kowalewskii

APPENDIX - Photographs of field sampling

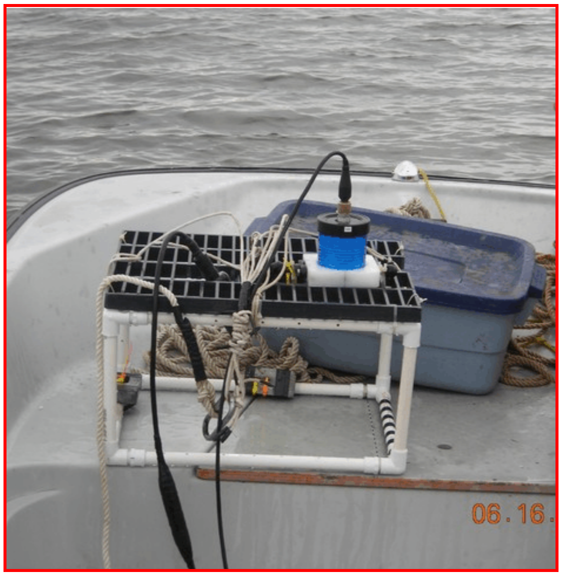
A-1. Benthic Ponar grab sampler being prepared for deployment.

A-2. Example of sample obtain by grab sampler. Note worm tubes

A-3. Large quahogs, *Mercenaria*, found in one sample



A-4. Video Camera system; electronic control system in foreground; video camera in background.



A-5. Close-up of video camera system. Camera (blue) on right and light system on left.

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