Fishery resource utilization of a restored estuarine borrow pit: A beneficial use of dredged material case study

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Marine Pollution Bulletin xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Fishery resource utilization of a restored estuarine borrow pit: A beneficial use of dredged material case study

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ARTICLE INFO

Keywords:
Fisheries hydroacoustics
Benthos
Essential fish habitat
Borrow sites
Habitat restoration

ABSTRACT

Numerous pits in coastal waters are subject to degraded water quality and benthic habitat conditions, resulting in degraded fish habitat. A pit in Barnegat Bay, New Jersey (USA) was partially filled with dredged sediment to increase flushing, alleviate hypoxia, and enhance benthic assemblages. Restoration objectives were assessed in terms of benthic community parameters and fishery resource occupation. Restoration resulted in increased benthic diversity (bottom samples) and the absence of water column stratification. Fisheries resources occupied the entire water column, unlike pre-restoration conditions where finfish tended to avoid the lower water column. The partial restoration option effectively reproduced an existing borrow pit configuration (Hole #5, control), by decreasing total depth from −11 m to −5.5 m, thereby creating a habitat less susceptible to hypoxic/anoxic conditions, while retaining sufficient vertical relief to maintain associations with juvenile weakfish and other forage fishes. Partially filling pits using dredged material represents a viable restoration alternative.

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1. Introduction

Sand borrowing for beach nourishment in estuarine and coastal waters creates depressions on the underwater landscape. Variously referred to as borrow pits or dredged holes, these depressions often differ from dredged navigation channels in many respects, including volume, size, shape, and depth and are frequently much deeper than the surrounding ambient bottom. Borrow pits also tend to be disconnected, isolated features, which have implications for their ecology. Short term effects generally consist of localized, temporary increases in turbidity and sedimentation. However, long-term impacts of altered bathymetry such as reduced hydrodynamic flow, poor tidal flushing, and water column stratification can lead to degraded water and sediment quality, from the accumulation of fine grained sediments and organic material, and depressed dissolved oxygen (DO) concentrations leading to stagnation. These factors contribute to reduced ecological function, characterized by a highly stressed benthic community, and reduced finfish utilization, typically in the lower reaches of the borrow pit.

Restoration of estuarine and coastal habitats has been the subject of interest in recent years, although the focus has generally been on wetland, shellfish, and seagrass habitats. The potential beneficial use of dredged material to partially or completely return borrow pits to historical depth contours has been identified as a restoration alternative by Dial and Deis (1986), Yozzo et al. (2004), as well as by several Districts of the Army Corps of Engineers. Aside from the engineering aspect, decisions on the efficacy and desirability of filling pits have hinged upon ecological issues. On one end of the spectrum, returning subtidal bottoms in the estuary to their historical depth contours could re-establish pre-existing habitat attributes and functions. Detractors opposed to filling dredged holes claim that existing pits provide valuable recreational fishing areas and critical over-wintering habitat for various fishery resources. Potential benefits and detriments of borrow pits are reviewed in Yozzo et al. (2004). Previous characterizations of benthic resources in borrow pits include Murawski (1969), Jørgensen (1980), Cerrato and Scheier (1984), and Cerrato et al. (1989). Likewise, regional fishery resource use of borrow pits and surrounding open-water habitats have previously been assessed by Conover et al. (1985) and Woodhead and McCafferty (1986).

In 2006, the Dredging Operations and Environmental Research (DOER) Program began to retrospectively assess the potential benefits of using dredged material to create or restored essential fish habitat. Several projects were selected for study to include a borrow pit restoration project and fishery utilization of both an offshore dredged material mound and an artificial reef built from dredged rock. In 2005, two dredged holes, identified as #5 (control) and #6, located in Barnegat Bay, NJ was selected for study. Dredged Hole #6, had been filled the previously year to a target elevation of −5.5 m (original depth = 11.5 m) MLW by placing dredged material derived from the Double Creek Channel using a hydraulic pipeline

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0025-326X/$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.marpolbul.2013.05.031

cutterhead dredge. The final design included formation of six mounds in the elevated basin of the hole to add relief and increase the bathymetric complexity of the borrow pit basin. By mounding the sediments during the dredge and fill operation, it was theorized that the tops and sides of the mounds would provide conditions suitable to sustain and support a healthy and diverse benthic invertebrate community. Dredged sediments consisted primarily of sandy material (70–90% coarse fractions). Approximately 96,000 cubic meters (125,000 cubic yards) of dredged material was pumped into Dredged Hole #6. A minimum of 1 m (~3 ft) of sand was placed over the underlying fine-grained sediment as a foundation for creation of sand mounds. For purposes of comparison a nearby un-restored borrow site (Dredged Hole #5) was left at its existing depth of −5.5 m (−18 ft) MLW. The success of restoration efforts was assessed in terms of overall "health" of each borrow pit by examining water quality, sediment characteristics, benthic invertebrate communities, and fishery assemblages both between borrow pits and to baseline (pre-restoration) data results.

2. Methods

2.1. Study site

Barnegat Bay (39° 43.9′ N, 74° 9.1′ W) is a 75 square mile shallow estuary located in Ocean County, New Jersey. Situated behind a barrier spit and Long Beach Island, the estuary's primary connection to the ocean is via Barnegat Inlet (Fig. 1). Dredged Holes #5 and #6 are located less than 30.5 m (100 ft) from shore along the western side of Long Beach Island. Dredged Hole #5 is located adjacent to the Town of Loveladies, and covers an area of approximately 2.8 hectares (7 acres). Dredged Hole #6 is located in the Borough of Harvey Cedars, approximately 1.6 km (1 mile) south of Dredged Hole #5, and covers an area of approximately 4.9 hectares (12 acres).

2.2. Water quality

A calibrated YSI (Model 6920 V2) water quality sonde was used to measure DO concentration (mg/l), temperature (°C), and salinity

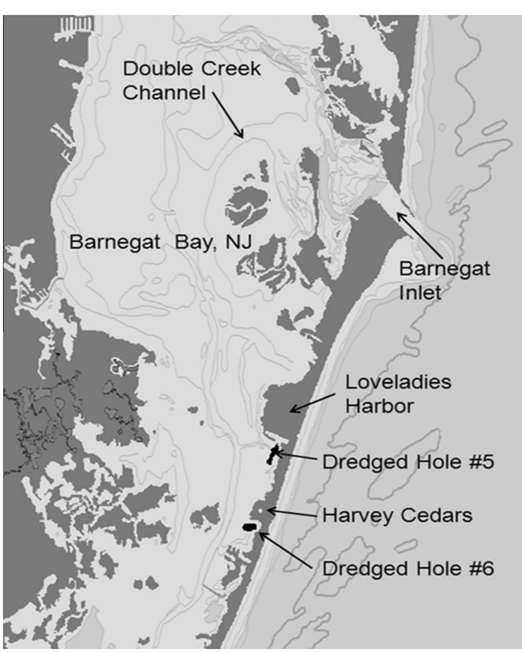

Fig. 1. Location of study borrow pits in the Barnegat Bay Estuary.

(ppt) at surface, mid- and bottom depths at seven stations in each dredged hole during each sampling event.

2.3. Sediments

Representative stations were sampled by Young grab during the May and November 2007 surveys for sediment grain size analysis. Grab samples were processed using a combination of wet-sieving and flotation procedures (Folk 1968; Galehouse, 1971). Sediment data analysis was conducted using Gradistat 4.0 (Blott, 2000). Sediment analyses were supplemented with visual observations of materials present in the grab samples.

2.4. Benthic sampling

Benthic macroinvertebrates were sampled in August 2006, and May and November 2007 at sites previously established during baseline collection efforts by Versar (1999), to evaluate recruitment and community structure in each dredged hole and to determine if benthic conditions were altered by restoration. In Hole #6, samples were collected from each of the tops, sides, and troughs of six mounds using a 0.044-m^2 stainless steel Young Grab Sampler, for a total of eighteen samples. In Hole #5, twelve samples were collected from the bottom and sides of the unaltered pit. Six samples were collected in a nearby reference area at each site in the natural bay bottom. A successful sample required a minimum penetration depth into the bottom sediment of at least 6 cm. Samples were sieved in the field using 0.5 mm mesh screening, preserved in 10% buffered formalin, and stained with rose Bengal for laboratory processing.

2.5. Fishery hydroacoustics

Fishery hydroacoustic surveys were conducted in August 2006, and May and November 2007. Acoustic backscatter data were collected with a BioSonics DT 6000 digital echosounder equipped with 200-kHz split-beam transducer (6-degree conical beam angle at −3 dB). Targets satisfying single target criteria with target strength (TS) above −52.6 dB (equivalent to a length of 4 cm) was accepted. The acoustic resolution (minimum target separation distance) of single targets was determined to be 0.23 m following $R = c\tau/2$ (Simmonds and MacLennan, 2005), where c = speed of sound in water (1500 m s^{-1}) and τ is pulse length duration (0.3 ms). Water temperature, salinity and depth were measured at stations in each borrow pit for correct calculation of speed of sound and absorption coefficients. Before each sampling period the hydroacoustic equipment was calibrated using a tungsten carbide sphere (38.1 mm diameter) standard target of known acoustic TS (~39.2 dB in seawater). The calibration was stable over all sampling periods.

The transducer was mounted in a downward, vertical orientation on an adjustable aluminum frame affixed to the gunnels of the survey vessel. Acoustic data were collected and stored on a laptop computer running BioSonics Acquisition Program (version 4.1) software. Post-processing analyses were performed using Hydroacoustic Data Analysis Software (HADAS), developed by the US Army Engineer Research and Development Center (ERDC). Data were collected during mobile surveys with boat speed limited to 5 km h^{-1}. Each site was divided into parallel transects, spaced at 30 m intervals, covering the full north to south footprint of each dredged hole. Transects extended the full width (shoal to shoal) of each borrow site. Fifteen transects (mean length = 235 m) were occupied at Hole #6 and 22 transects (mean length = 135 m) at Hole #5. Total survey distance was 2.5 km (Hole 5) and 3.5 km (Hole 6), respectively. To equalize effort among sampling units, individual transects were divided into 10 m segments, referred to

as elementary sampling distance units (ESDUs). This approach has been widely used in fisheries hydroacoustic studies as a basis for statistical analyses and comparisons (e.g., Gangl and Whaley, 2004). During each seasonal survey, all transects were surveyed during both day- and nighttime hours and during flood and ebb tidal stages. Relative fish density was estimated using standard echo-integration techniques, which process the 20logR Time Varied Gain (TVG) signals. To determine absolute fish density values, the contribution of single fish (average backscattering cross section or σ) was measured. This value (σ) corresponds to the acoustic equivalent of the length of the insonified fish after conversion to target strength (TS). TS values (dB) were converted to fish length using a BioSonics variant of the dorsal-aspect equation developed by Love (1971). Based on the total and the mean echo per fish, the absolute number of fish can be calculated in the area insonified. Thus every ping transmitted by the sounder provides a measurement of fish density in fish per cubic meter (scaled to fish per 100 m^3).

2.6. Conventional fisheries gears

Otter trawls and gill nets were used to examine fish assemblage taxonomic composition, and to provide ground truth data for the hydroacoustic surveys. Triplicate fish trawls using a 5-m otter trawl were conducted seasonally within the deepest portion of each hole. The trawl had 1-inch stretch mesh on the wings and a cod end liner with quarter inch mesh. Trawl depths varied from 4 to 6 m. Experimental gill nets equipped with mesh sizes from 5.1 to 22.9 cm (2–9 in.) were deployed for 5 h in each hole. All fish collected by both gear types were identified to species, counted, and total length (TL) measured to the nearest mm.

3. Statistical analyses

3.1. Univariate methods

Fisheries acoustics: Total fish counts were analyzed by Analysis of Variance (ANOVA) using square-root transformed data. ANOVA was performed using a four-way factorial design: Site (Hole 5 or Hole 6), Sample Date (August 2006, May 2007, and November 2007), Time of Day (Day or Night), and Tide (Ebb or Flood). Initial results suggested that tide was not a significant factor. Therefore the data were re-analyzed using a three-way factorial design (Site, Date, and Day/Night). The presence of significant Site X Date and Date X Day/Night interaction factors prevented interpretation of the Date or Site factors, thus requiring separate two-way analyses for each sampling event to detect potential differences among sites or day/night collections.

Benthos: Community level variables including taxa per sample, total numerical abundance per sample, Shannon–Weiner diversity index (H′), and Pileou's (J) evenness index were calculated from the infaunal data and subjected to ANOVA. Values for numerical abundance were $\log_{10}(X+1)$ transformed prior to analysis to adjust for non-normality and insure homogeneity of variance. Because shallow depth (Top of constructed mounds) samples could only be taken post-restoration the ANOVA had to be performed in two steps. First, all data except the shallow depth samples were analyzed using a three-way factorial design (Site (Borrow Area) X Habitat (Depth) X Before/After) to determine if differences occurred between sites or habitats as a result of the filling operation. A second, one-way ANOVA was performed among all site-habitat combinations (e.g. Hole 5 Bottom, Hole 6 Top) for the post-restoration samples (May 2006–November 2007) to determine if the shallow depth samples differed from the bottom, mid, or reference area values. Where significant differences ($p < 0.05$) were detected either a Student's *T* test or Tukey's Honestly Significant Difference (HSD) test was conducted between pairs of factor means or multiple factor means respectively.

3.2. Multivariate methods

Conventional fisheries data were analyzed by a combination of multivariate methods including hierarchical clustering and non-Metric Dimensional Scaling (nMDS). Hierarchical clustering is a technique that associates pairs of samples based on the similarity of their species composition and abundances. Samples with the highest degree of similarity are successively combined and the final result presented as a dendrogram in which the degree of similarity of sample is indicated by links in the diagram. The Bray–Curtis Index was used as the similarity index and samples were combined by group averaging. All data were fourth-root transformed prior to analysis to reduce the influence of extremely abundant species. SIMPROF (Similarity Profile), a bootstrapping technique, was performed on the nodes (sample groups) generated by clustering to determine the likelihood that individual groups were generated purely by chance.

Trawl data were also analyzed by nMDS, an ordination technique that compares species composition among sample pairs and projects the results in two- or three-dimensional space (Clarke and Warwick, 2001). nMDS results are interpreted by examining the degree of difference in the spread of data points across axes with the proximity of any two data points being a measure of the degree of similarity between them. Goodness-of-Fit of the plot is measured by a stress value as indicated in the upper right corner of each plot. Stress values of 0.1 or less indicate a high degree of fit (and therefore interpretation with relatively high confidence), while those with stress levels ranging between 0.1 and 0.2 should be interpreted with caution. Plots with stress values of 0.2 or greater should not be interpreted. Simultaneous plotting (biplots) of nMDS and clustering results permits comparison of the results. If the plots are similar it is assumed that the patterns are robust. Data were also analyzed by ANOSIM (Analysis of Similarity), a nonparametric test analogous to Analysis of Variance, to determine if patterns of sample groupings detected in the clustering-nMDS biplots were statistically significant. Two pairs of ANOSIM tests were performed. The first examined differences between plots by sampling date while the second reassigned sampling dates to before and after restoration to allow a Before/After-Control/Impact (BACI) comparison. In addition, species' contributions to sample similarities were evaluated using the SIMPER technique. All multivariate techniques employed in this study (Clustering, SIMPROF, NMDS, ANOSIM, and SIMPER, were performed using PRIMER (Version 6.0) statistical software following interpretive guidance found in Clarke and Warwick (2001). Infaunal data was analyzed in an identical manner to that of the trawl data.

4. Results

4.1. Water quality

Water quality measurements taken in during August 2006, and May and November 2007 in Dredged Holes #5 and #6 indicated that DO concentrations were relatively high, ranging from 7.4 to 9.4 mg/l and were generally at or above saturation even in the deepest portions of the pit basins. No evidence of a halocline was observed during any sampling period. Salinities ranged from 26 ppt (spring) to 29 ppt (summer and fall). No thermoclines were observed as the water column appeared to be well-mixed. Water temperatures were relatively uniform within each borrow pit;

although were periodically as much a 1° cooler in Hole #5 when compared to Hole #6.

4.2. Sediment grain size analysis

Sediments in all bottom samples taken from the two borrow pits can be characterized as sandy silt, with percent clay/silt fraction ranging from 59% to 82.7%. Mean grain size for bottom samples averaged 24 μm. Pre-restoration results from baseline sampling conducted in 1999 indicated percent clay/silt fraction as high as 94%. Mid-depth stations were characterized as either silty-sand to sandy-silt. In Dredged Hole #5 the silt/clay percentage ranged from 14.8% for silty-sand to 84% for sandy-silt. Samples taken from the top of mounds created during restoration in Dredged Hole #6 were similar to mid-depth stations both in sediment type and percent clay/silt fractions. Samples from adjacent shoals ranged from sandy silt to sand with clay/silt fractions of less than 24%. The sand fraction tended to be very fine or medium-fine at the silty stations, coarse at the shallow stations, and medium in the remaining silty-sand samples.

4.3. Benthic community

Species Composition: A total of 151 macroinvertebrate taxa were collected during the course of the study, including 71 polychaete taxa, 21 amphipods, 17 bivalves, 11 gastropods, 4 isopods, 3 mysid shrimps, 3 cumaceans, and 21 miscellaneous taxa. The amphipod *Ampelisca spp.* was the most abundant taxa comprising nearly 43% of all specimens collected (Table 1). This taxa was composed of two species (*A. abdita* and *A. vadorum*) with the preponderance of specimens being too small to accurately identify to the species level. This genus was also the most abundant taxon at all sampling sites with the exception of the bottom samples of both borrow areas prior to restoration (where it was second most abundant taxon) and Dredged Hole #6 Reference also prior to restoration. The second most abundant taxa, the polychaete *Mediomastus ambiseta* reached maximum abundances during the post-restoration time period at middle depth stations of both dredged holes, the shallow (Top) stations of Dredge Hole #6 and to a lesser extent the reference stations of both sites where it was the third most abundant taxon. The third most abundant taxa overall, the amphipod *Rudilemboides naglei* was also most numerous during the post-restoration time period and was an important constituent at all stations. Another taxa that warrants special mention is the amphipod *Microdeutopus gryllotalpa* which was the single most abundant taxa at bottom stations and second most abundant in middle depth stations and the Dredged Hole # 6 Reference stations prior to restoration. It was present during the post-restoration time period but was less abundant.

Community Structure Parameters: *Taxa Richness, Abundance, Diversity and Evenness*: Mean numbers of taxa were highest at reference stations and lowest at bottom stations in both borrow areas and during both time periods (Fig. 2). Mid-depth values were intermediate to these as were samples from the top of the Dredged Hole #6 mounds. Mean numbers of taxa/sample at both bottom and mid depth stations were also greater after restoration than before. Average numbers of animals/sample followed a similar pattern to that of taxa/sample with the exception that post-restoration abundances at the reference sites were also higher than pre-restoration values (Fig. 2). Shannon–Weiner diversity index values followed an identical pattern to that of abundance/sample (Fig. 2). Values for Pielou's evenness index were relatively uniform among sites, stations, and over time (Fig. 2). The highest index values occurred at mid depth and reference area stations prior to restoration at Dredged Hole #6.

Univariate Statistics: The three-way factorial ANOVA for mean taxa per sample was significant ($p < 0.05$) for only two factors: Habitat and Before/After. Tukey's HSD test indicated that each of the three habitat depths was significantly different ($p < 0.05$) from one another with the highest average number of taxa occurring in

Table 1
Taxa comprising 5% or more of specimens collected by sampling event.

Taxa	Taxon[i]	H5[a]	H6[b]	H5	H6	H5	H6	H5	H6	H5	H6	H6	H5	H6	Total
		Bt[c]	Bt	Md[d]	Md	RA[e]	RA	Bt	Bt	Md	Md	Tp[f]	RA	RA	
		BR[g]	BR	BR	BR	BR	BR	AR[h]	AR	AR	AR	AR	AR	AR	
Ampelisca (*LPIL*[j])	A	26.1	22.3	78.7	53.8	65.6	3.57	70.1	41.6	51.1	56.7	50.1	36.5	26.2	42.9
Mediomastus ambiseta	P	2.2	–	1.6	0.8	6.2	3.2	0.2	3.0	20.2	11.1	15.1	11.7	10.8	11.1
Rudilemboides naglei	A	–	–	–	–	0.3	4.7	10.7	13.8	4.9	2.5	3.7	15.2	20.4	9.9
Sarsiellidae (*LPIL*)	O	–	–	–	–	–	–	2.1	6.5	2.1	5.7	3.0	5.3	6.0	3.9
Myocopodina (*LPIL*)	O	–	–	–	–	–	–	0.8	1.1	4.3	7.3	2.3	0.5	4.4	3.6
Eobrolgus spinosus	A	–	–	0.7	–	0.1	5.8	0.1	2.9	1.3	0.9	2.0	6.3	6,2	3.5
Oligochaeta (*LPIL*)	O	4.4	–	1.6	7.9	2.6	18.7	1.1	0.8	2.9	0.1	0.5	5.3	3.2	3.3
Exogone dispar	P	–	–	0.2	0.4	0.4	6.6	0.3	1.9	0.8	0.7	0.6	0.9	3.8	1.8
Nematoda (*LPIL*)	NE	–	–	–	–	–	–	0.1	1.4	1.4	0.6	0.8	1.9	5.1	1.7
Elasmopus levis	A	–	–	–	–	0.2	7.5	0.4	1.5	0.1	0.5	1.7	0.4	1.0	0.8
Microdeutopus gryllotalpa	A	36.9	36.4	4.0	9.8	0.6	11.6	0.3	1.1	0.1	0.1	0.1	0.1	0.3	0.8
Prionospio heterobranchia	P	–	–	0.2	0.2	0.4	5.0	–	0.7	0.4	0.1	0.1	0.9	1.4	0.8
Notomastus (*LPIL*)	P	–	–	0.1	1.3	5.4	0.04	–	0.1	0.2	0.7	0.6	0.2	0.01	0.6
Capitella (*LPIL*)	P	10.9	–	0.5	3.5	0.02	0.3	6.4	0.7	0.1	–	2.1	–	0.1	0.5
Hesionidae (*LPIL*)	P	2.2	9.1	1.7	3.1	0.4	3.4	0.1	0.5	0.1	0.6	0.3	0.1	0.1	0.4
Streblospio benedicti	P	–	–	0.4	6.1	0.4	1.8	–	0.1	0.1	–	0.1	–	0.02	0.2
Mytilus edulis	B	–	9.1	0.1	0.7	–	–	2.9	0.1	0.03	0.2	0.4	0.02	0.03	0.2
Corophiidae (*LPIL*)	A	–	9.1	0.1	0.4	0.5	0.2	–	–	–	–	–	–	–	0.1

[a] H5 = Dredged Hole #5.
[b] H6 = Dredged Hole #6.
[c] Bt = Bottom sample.
[d] Md = Mid-depth sample.
[e] RA = Reference area.
[f] TP = Top of mound sample.
[g] BR = Before restoration.
[h] AR = After restoration.
[i] Taxon = A = amphipod, P = polychaete, B = bivalve, O = ostracod, NE = nematode.
[j] LPIL = Lowest practical identification level.

Please cite this article in press as: Reine, K., et al. Fishery resource utilization of a restored estuarine borrow pit: A beneficial use of dredged material case study. Mar. Pollut. Bull. (2013), http://dx.doi.org/10.1016/j.marpolbul.2013.05.031

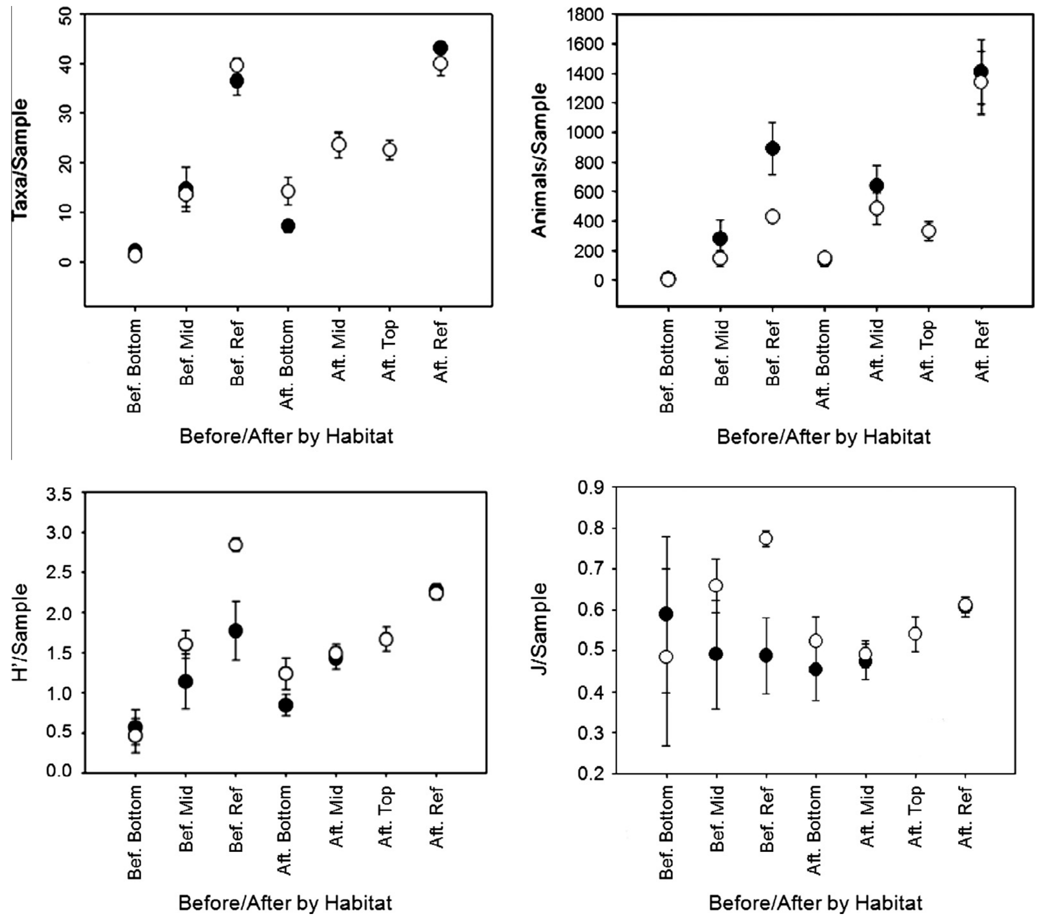

Fig. 2. Taxa/sample (mean ± SE), abundance (#animals)/sample (mean ± SE), Shannon–Weiner diversity index (H′)/sample (mean ± SE), and Pielou's evenness index (J)/sample (mean ± SE) by borrow area, habitat and time period. Clear = hole 6, black = hole 5, Bef. = before restoration, Aft. = after restoration.

the reference stations, fewer in the mid-depth stations and the least in the bottom stations. Student's *T* test results indicated that numbers of taxa per sample were higher after restoration than before. Similar results were found in the ANOVA for numerical abundance with the exception that there was also a significant ($p < 0.05$) Habitat X Before/After interaction effect. Both Habitat and Before/After factors were significant ($p < 0.05$) and Tukey's HSD and Student's *T* tests for these factors produced identical results to that of taxa/sample. The Tukey HSD test for the abundance Habitat X Before/After interaction revealed that prior to restoration Bottom station abundances were significantly lower ($p < 0.05$) than all other stations. After restoration Bottom station abundances were lower than all other stations except for before restoration mid-depth stations (Before Mid) which, in turn, while not different from post-restoration mid-depth values were lower than all remaining stations. This pattern continues with the pre-restoration Reference station values being intermediate between post-restoration mid-depth stations and post-restoration reference stations. The three-way ANOVA of Shannon–Weiner Diversity Index ($H'ln_e$) values was significant ($p < 0.05$) for sites, habitats, and the Site X Habitat X Before/After interaction effect. Diversity was higher at Dredged Hole #6 than Dredge Hole #5 (Student's *T* test, $t = 1.97$, $p < 0.05$) and decreased significantly in value with depth (reference > mid > bottom, Tukey's HSD, $Q = 3.33$, $p < 0.05$). Tukey's HSD test results for the means in the 3-way interaction factor indicated overlapping degrees of difference between reference, mid-depth, and bottom depth index values. The 3-way ANOVA of Pielou's evenness index produced no significant difference ($p > 0.05$) for the whole model or any of the effect factors.

The one-way ANOVA's for post-restoration samples were also significant ($p < 0.05$) for taxa/sample, animals/sample, and Shannon–Weiner diversity index but not for Pielou's evenness index. Tukey's HSD test for taxa/sample indicated the same pattern of decreasing values (reference > middle > bottom) as found in the 3-way test. Shallow depth (Top) samples were intermediate between the middle and bottom depth values. An identical pattern of results was found in Tukey's HSD test for animals/sample. Test results for diversity (H′) were significantly different ($p < 0.05$) only between reference areas and those of the remaining stations.

Multivariate Methods: The results of both hierarchical clustering and nMDS are similar in the sense that there is a high degree of similarity among all stations and time periods (Fig. 3). The relatively high stress value (0.16) for the nMDS analysis indicates that only the largest differences among samples can be reliably interpreted (Clarke and Warwick, 2001). In this case, bottom samples, particularly those from the post-restoration time period, differed the most from the remaining samples. Bottom station samples also were the most variable in species composition as measured by MVDISP (Multivariate Dispersion). Mid- and shallow depth (Top) and reference samples from both dredged holes were relatively similar to one another. Multivariate dispersion was least among reference stations and intermediate among mid and shallow depth stations. ANOSIM of the species composition data (Habitat X Before/After) was significant ($p = 0.1\%$ or 0.001) for the global (overall) test and for all but two of the pairwise tests. The two pairwise tests where insignificant ($p < 5.0\%$) results were obtained were between the Top (shallow) station at Dredged Hole #6 following restoration and either the bottom or mid-depth stations.

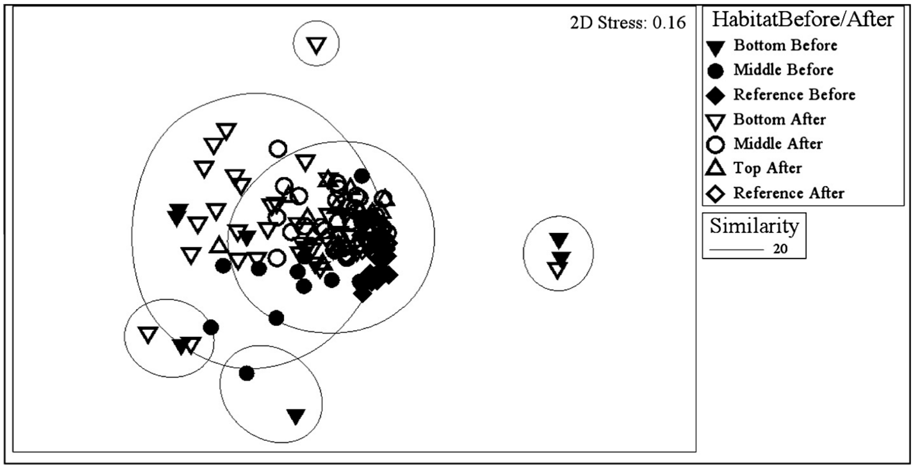

Fig. 3. Hierarchical clustering and non-metric dimensional scaling results. Inverted triangle = bottom, circle = middle, diamond = reference, upright triangle = top, filled = before, unfilled = after.

The highest R values (i.e. the strongest indication of a difference) were between combinations including either Bottom sample before restoration or reference samples after restoration. SIMPER analysis of the habitat by before and after time periods also indicated the greatest differences in species composition in pairwise comparisons involving pre-restoration bottom samples. The lowest degree of difference was encountered among comparisons involving post-restoration Reference, Middle or Top (shallow) samples. Examination of the pairwise data for those species contributing the most to dissimilarity is not so much the presence or absence of characteristic taxa within a habitat creating the differences but their relative abundances that is responsible. For instance, the amphipod *Ampelisca* (LPIL) and oligochaetes are found in nearly all habitats and time periods, but their far lower abundances in Bottom stations, particularly during the pre-restoration time period, often results in them contributing the most to dissimilarity. Much of the difference between other habitats can be traced to the relative abundances of the amphipods *Microdeutopus gryllotalpa* and *Rudilemboides naglei,* the ostracod Sarsiellidae (LPIL), and the polychaete *Mediomastus ambiseta*.

4.4. Conventional fisheries gear catch

4.4.1. Summer catch (August 2006)

Pre-restoration, site-specific data on fisheries resources were described by Versar (1999). Fish trawls and gill nets sets in August indicated that weakfish (*Cynoscion regalis*) adults and juveniles were using the habitat created by the dredged holes; however trawling in the deep portion of Dredged Hole #6 (−11 m MLW) produced much fewer juvenile weakfish than similar tows in the shallower Dredged Hole #5 (−5.5 m MLW). The deep basin of Dredged Hole #6 contained large amounts of organic detritus, which may be avoided by weakfish. Bay anchovy (*Anchoa mitchilli*) was the only other fish caught in relatively large numbers in both Dredged Holes in 1999 (Table 2). Post-restoration trawling in Dredged Hole #5 and #6 produced four species of crustacean and nine species of finfish during summer sampling (Table 2). Note that only the more numerically abundant species or those taken during two or more seasonal sampling events are listed in the summary in Table 2. Post-restoration species composition did not differ from that of pre-restoration results as weakfish and bay anchovies were still the numerically dominant species occurring in both pits. The presence of large numbers of juvenile weakfish in 2006 suggests that the holes were still being used as a nursery habitat, although absolute numbers were lower than pre-restoration results from 1999. The only macroinvertebrate species captured during pre-restoration studies was blue crab (*Callinectes sapidus*), which had higher totals in Dredged Hole #5 during both pre- and post-restoration when compared to Dredged Hole #6, although abundance did not differ greatly. Gill nets produced only a few species of fish during either pre- or post-restoration. Gill net captures tended to be adults, while trawling tended to produced larger numbers of juveniles.

4.4.2. Spring catch (May 2007)

Trawling in Dredged Holes #5 and #6 in May 2007 produced three species of crustacean and three species of fish. Bay anchovies were the numerically dominant fish species in both holes, although CPUE was somewhat lower than in summer samples. Two species of crustaceans, blue crab and black fingered mud crab (*Panopeus herbstii*), were taken in Dredged Hole #6. Neither species was collected in Dredged Hole #5. Gill net sets produced eight species of fish dominated by Atlantic menhaden (*Brevoortia tyrannus*) and blue fish (*Pomatomus saltatrix*), which were taken in approximately equal numbers between the restored and un-restored hole (Table 2). Two commercially important species, striped bass (*Morone saxatilis*), and northern kingfish (*Menticirrhus saxatilis*) were taken by gill net in Dredged Hole #5. In Hole #6, weakfish, which were present in both holes in large numbers in summer sampling, was only captured by gill net in spring sampling.

4.4.3. Fall catch (November 2007)

Trawling in Dredged Holes #5 and #6 produced eight species of fish. Forage fishes (e.g. Atlantic silversides, *Menidia menidia*) were numerically dominant in Dredged Hole #6, followed by juvenile croaker (Table 2). Both species were present in Dredged Hole #5, but caught in much smaller numbers. In Dredged Hole #5, naked gobies (*Gobiosoma bosc*) were numerically dominant. Numerous small grass shrimp were present in Dredged Hole #6 trawls, but absent in Dredged Hole #5. Gill net sets produced three specimens of relatively large scup (*Stenotomus chrysops*). Post-restoration species composition was similar to that reported by Versar (1999). The data suggests that Dredged Hole #6 may be favored by croaker and sand shrimp as refuge habitat in fall.

4.4.4. Winter catch (February 2000)

Winter sampling was conducted in February 2000 by Versar as part of the pre-restoration planning assessment. Based on these unpublished data, the only species captured during otter trawling was the four-spined stickleback (*Apeltes quadracus*). This species

Table 2
Summary of trawl and gill net species collected in Dredged Hole #5 and #6 (*Note*: Summary is not all inclusive. Species with very low abundance or those taken in only one season with low abundance were not included.).

Species	H5-A BR #	H5-A BR C	H5-A BR L	H5-A PR #	H5-A PR C	H5-A PR L	H5-M PR #	H5-M PR C	H5-M PR L	H5-N BR #	H5-N BR C	H5-N BR L	H5-N PR #	H5-N PR C	H5-N PR L
Cynoscion regalis	161	966	9.8	12	48	12.2	–	–	–	–	–	–	–	–	–
	8*	<1	47.6	3*	<1	27.7						–	–	–	–
Callinectes sapidus	25	138	9	80	320	9.2	–	–	–	8	48	4.9	–	–	–
Anchoa mitchilli	22	132	7.1	37	148	4.9	5	20	8.4	2	12	4.4		–	–
L. xanthurus	6*	<1	17.9	1*	<1	14.3		–	–	–	–	–	–	–	–
Brevoortia tyrannus	1*	<1	17	–	–		6*	1	34.8	–	–	–	–	–	–
Menidia menidia	–	–	–	–	–	–	1	4	–	1	6	10.6	1	4	4.1
M. undulatus		–	–	1*	4	20.9		–	–	2	12	3.2	1	4	4.2
Opsanus tau		–	–	1	4	8.1		–	–	–	–	–	–	–	–
Pomatomus saltatrix	1	<1	39	1*	<1	39.5	2*	<1	49	–	–	–	–	–	–

Species	H6-A BR #	H6-A BR C	H6-A BR L	H6-A PR #	H6-A PR C	H6-A PR L	H6-M PR #	H6-M PR C	H6-M PR L	H6-N BR #	H6-N BR C	H6-N BR L	H6-N PR #	H6-N PR C	H6-N PR L
Cynoscion regalis	14	84	8.8	20	80	14.2	–	–	–	1	4	16.2	–	–	–
	5*		<1		42.8	–	4*	<1	33.4				–	–	–
Callinectes sapidus	12	72	9.8	49	196	9.4	5	20	6.7	2	12	4.1	–	–	–
Anchoa mitchilli	12	72	7.6	19	76	4	2	8	8.3		–	–	–	–	–
L. xanthurus	3*	<1	17.8		1*	<1	16.5	–	–	–	–	–	–	–	–
Brevoortia tyrannus	1*	<1	38.3	–	–		7*	1.2	34.7	*	1.1	13.6	–	–	–
Menidia menidia	–	–	–	–	–		–	–	–	–	–	–	24	100	9.9
M. undulates		–	–	–	–	–		–	–	17	102	2.5	16	64	7.3
Opsanus tau		–	–	6	24	10.7		–	–	–	–	–	–	–	–
Pomatomus saltatrix	–	–	–	1*	<1	43.5	3 *	<1	44.2	–	–	–	–	–	

∗ = Gill net capture, A = August, M = May, N = November, BR = before restoration, PR = post-restoration, # = number, C = CPUE.
L = Average fish length (cm).

is a year-round resident in Barnegat Bay. Although the available winter sampling data are sparse, sampling produced no evidence that either dredged hole was used as an over-wintering thermal refuge for fishes or shellfish.

4.5. Multivariate analysis of trawl data

Hierarchical clustering of the Barnegat Bay trawl data indicated that species composition varied more among sampling periods and time of year than between sites. For example, all August samples (1999 and 2006) grouped together regardless of site. All but one of the November (1999 and 2007) samples (Dredged Hole #6 November 1999) also occurred in a single cluster group. Samples from May 2007 did not cluster together. nMDS plots were significant (Stress = 0.12) and the results mirrored those of hierarchical clustering (Fig. 4) with August and November samples forming relatively compact groups. May samples were found to be intermediate between the August and November groupings. ANOSIM tests failed to produce significant results ($p > 0.05$) for either sites or sampling periods, nor were there significant results when the data were reanalyzed using a BACI (Before/After-Control/Impact) design. However, when tests were performed with the data categorized by month (August, May, and November) a significant ($p < 0.05$) difference was obtained. Pair-wise tests by month indicated that August samples differed from those in both May and November, but May and November did not differ between themselves. Similarity Percentage (SIMPER) analysis of the month data indicated that August samples were characterized by high abundances of blue crabs, anchovies, and spot, whereas May samples were characterized by anchovies and bluefish. High numbers of Atlantic silversides and Atlantic croakers characterized November samples. Pair-wise comparisons of months using SIMPER indicated that relatively high abundances of blue crabs, weakfish and spot contributed the observed differences between August and May samples, while these three species plus anchovies differentiated August from November samples. There was no significant difference ($p > 0.05$) found between May and November samples.

5. Fish size distribution and density

5.1. Conventional gear catch

Total lengths (TL) of collected fishes ranged from 2 to 53 cm (Table 2). Of the three numerically dominant species weakfish were largest in terms of mean total length at 17.8 cm. Atlantic silversides ranged from 4.1 to 10.8 cm TL, and bay anchovy from 2.1 to 9.3 cm TL. Both bay anchovies and Atlantic silversides exhibited two size classes of 0–5 and 5–10 cm TL. Although not numerically dominant, bluefish (mean = 46 cm TL), menhaden (mean = 35.6 cm TL) and scup (mean = 24 cm TL) was three of the largest species in the overall catch.

5.2. Fisheries hydroacoustics

Estimated lengths of all accepted single targets ranged from 4 to 60 cm, which corresponds relatively well with the conventional catch data. For every sampling event, regardless of tidal cycle, time of day, or season the majority of acoustically detected fishes (75–90% per survey) were less than 10 cm in length. Results from the conventional gear catch indicated that these targets were predominantly bay anchovies, Atlantic silversides, and juvenile Atlantic croaker. Patterns were similar for both dredged holes, with targets in the 10–15 cm category representing 7–13% of the total detections. Weakfish was the numerically dominant species captured in this size class. Numbers of targets in the 15–20 cm size class were also similar in both dredged holes at 1.5–4% of the total detections. The only exception occurred in the November survey in Dredged Hole #5, where no detections in this size class were

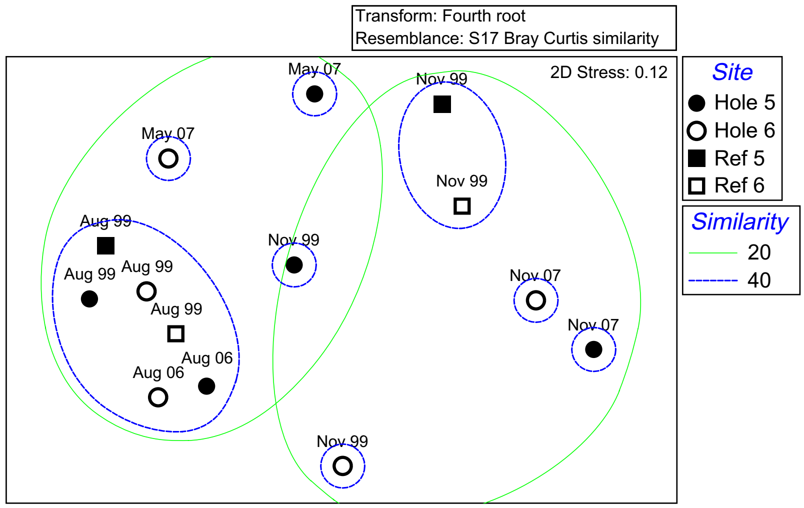

Fig. 4. Biplot of nMDS and clustering results. All data fourth-root transformed and compared using Bray–Curtis similarity index.

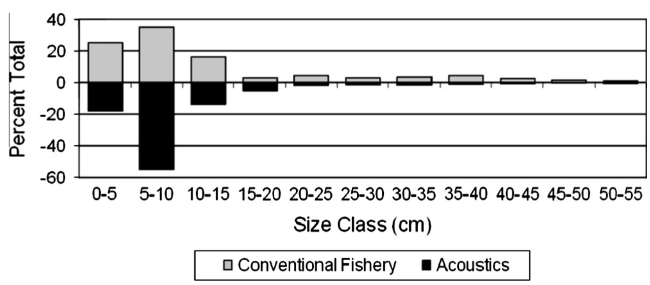

Fig. 5. Length frequency distributions of fishes in Dredged Holes #5 and #6 based on conventional fishery gears and hydroacoustic measurements.

made. Additional 5 cm length increment size classes accounted for less than 1% each of the total detections.

5.3. Length–frequency comparison

The length frequency distributions of fishes in the combined trawl and gill net catches is compared with that of acoustically estimated target lengths derived from the target strength data (Fig. 5). Because much larger numbers of fish were acoustically detected when compared to totals from conventional gears, results were converted to a relative frequency percentage by size class. Data were combined for all seasonal surveys and results presented for daytime data collection efforts because all conventional gear surveys were conducted during daylight hours. A close correspondence is seen between size frequencies of fishes caught by the conventional and hydroacoustics gears. Seasonal partitioning of the data indicated strong correspondences among size distributions of fishes collected in August and November. In May, however, acoustic detections were considerably lower than expected in four size classes (30–35, 35–40, 40–45 and 45–50 cm), represented primarily by bluefish and Atlantic menhaden.

5.4. Fish vertical distribution patterns

A total of 1169 single target (non-schooling) fishes were detected during seasonal hydroacoustic surveys of Dredged Hole #5 (581 in August, 355 in May, and 233 in November). To display changes in vertical distribution of fishes, the water column was divided into 1-m increments from surface to bottom (Fig. 6). In August fishes were concentrated in the 3–4 m depth stratum, which

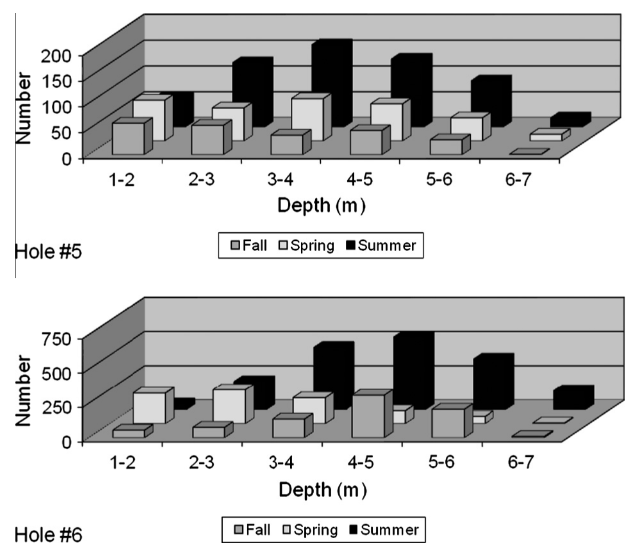

Fig. 6. Vertical distribution of fish targets in Dredged Holes # 5 (top) and #6 (bottom).

had the highest number of individual fish targets ($n = 160$, 28% of detections). Both adjacent depth strata (2–3 m and 4–5 m) contained slightly more than 20% ($n = 252$) each of accepted fish targets. In May 2007 fish targets ($n = 297$) in Dredged Hole #5 were generally evenly distributed throughout the first 5 m of the water column. The deepest two depth strata (5–6 m and 6–7 m) combined had the fewest fish targets ($n = 58$) during May sampling. In November slightly more than 50% of fish targets were found in the upper two depth strata ($n = 118$). Fewest fish targets ($n = 30$) were detected in the lower two depth stratum.

In Dredged Hole #6, 3112 fishes were detected during seasonal surveys. Number of single fishes were higher in August ($n = 1742$) than in May ($n = 810$) or November ($n = 789$). Fishes were found in highest numbers in the 3–4 m ($n = 455$) and 4–5 m ($n = 530$) depth strata during the summer surveys (Fig. 6). Fishes in the adjacent upper and lower depth strata accounted for 14.9% ($n = 206$, 2–3 m) and 21.3% ($n = 371$, 5–6 m) of the total number of targets. Fewer fishes were detected ($n = 42$) in the uppermost ($n = 42$) and deepest depth stratum ($n = 138$). During spring sampling, high numbers of fishes ($n = 669$, 82% of the total detections) occurred in the upper 3 m of the water column. Fewest fish targets ($n = 57$) were found in the lower two depth stratum. In November the

pattern reversed from that observed in spring, with the majority of fish detections in the 4–5 m ($n = 309$) and 5–6 m ($n = 206$) depth strata. The upper third of the water column accounted for approximately one-third of all fish detections ($n = 265$).

5.5. Fish densities

Fish densities were not uniformly distributed among ESDUs. Highest estimated density approached 850 fish/100 m^3 for a single ESDU in which schooling fishes were present, whereas no fishes were detected in nearby ESDUs along the same transect. Fish density estimates are given for site, season and time of day in Table 3.

5.6. Fish density by site and season

Average fish densities by site were compared between seasons. Fish densities during the summer survey averaged 14.8 fish/100 m^3 in Dredged Hole #5, compared to 9.5 fish/100 m^3 in Dredged Hole #6. Spring results resembled those of summer surveys in that fish density in Dredged Hole #5 was slightly higher (mean = 3.8 fish/100 m^3) than in Dredged Hole #6 (2.1 fish/100 m^3). The pattern reversed in fall with higher fish densities in Dredged Hole #6 (1.6 fish/100 m^3) than in Dredged Hole #5 (0.6 fish/100 m^3). Total densities were found to be significantly different ($p < 0.05$) by sampling date (Fig. 7).

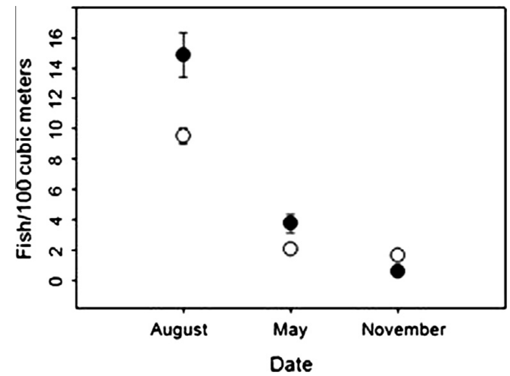

Fig. 7. Total numbers of fish/100 m^3 ± SE by sampling date in Dredged Holes #5 (solid circles) and #6 (open circles). All values are significantly different ($p < 0.05$) within sampling date.

5.7. Influence of tide on fish distribution

Normal tidal amplitude in Barnegat Bay is 0.95 m (3 ft). However, near the study area dampening effects reduce the amplitude to approximately 0.15 m. Mean tidal current velocities at the nearby inlet are 1.1 m/s during flood and 1.3 m/s during ebb tidal stages. Although there was minimal evidence of strong tidal flows, fishes were consistently observed to move into and out of the dredged holes on a tidally-based cycle. At Dredged Hole #6, fish densities were highest during the ebb tidal cycle in all three seasonal surveys when combining day and nighttime results (Table 3). Across all seasons, fish density averaged 4.7 fish/100 m^3 for surveys completed during an ebbing tide and 3.9 fish/100 m^3 during a flooding tide.

The pattern of greater fish density during ebb tidal cycles observed at Dredged Hole #6 was not seen as consistently at Dredged Hole #5. Summer survey densities were slightly higher during the flood tide (15.4 fish/100 m^3) than during the ebb tide (14.2 fish/100 m^3). The reverse was true for the spring sampling event (ebb = 4.7 fish/100 m^3, flood = 2.8 fish/100 m^3). In fall surveys nearly equal densities (0.6 fish/100 m^3) occurred during both ebb and flood tides in Hole #5. Across all seasonal surveys, fish density averaged 6.5 fish/100 m^3 during an ebbing tide and 6.3 fish/100 m^3 during a flooding tide.

Fish densities were higher in Dredged Hole #5 (control) during ebb and flood tides for both spring and summer surveys. During fall surveys higher densities were found in the restored borrow pit (Dredged Hole #6) during both ebb and flood tidal cycles. Across all surveys approximately 12% fewer fish were detected in

Table 3
Fish density per 100 m^3 (mean ± SE) for all surveys in Dredged Holes #5 and #6. (D = day, N = night, E = ebb, F = flood).

Month	Period	Tide	Dredged Hole #5		Dredged Hole #6	
			Density	SE	Density	SE
August	D	E	13.2	5.1	8.2	0.95
August	D	F	12.1	1.8	4.5	0.66
August	N	E	15.2	0.61	11.9	1.5
August	N	F	19.0	2.3	13.4	0.46
August	D	E, F	13.6	2.6	6.3	0.6
August	N	E, F	16.1	1.2	12.6	0.8
August	D, N	E	14.2	2.6	10.1	0.9
August	D, N	F	15.4	1.5	9.0	0.4
Total August density			14.8	1.5	9.5	0.5
May	D	E	6.4	2.1	1.9	0.46
May	D	F	1.8	0.46	1.1	0.28
May	N	E	3.0	0.29	2.5	0.68
May	N	F	3.9	0.84	2.6	0.54
May	D	E, F	4.1	1.1	1.5	0.27
May	N	E, F	3.4	0.4	2.6	0.43
May	D, N	E	4.7	1.1	2.2	0.41
May	D, N	F	2.8	0.47	1.9	0.3
Total May density			3.8	0.6	2.1	0.3
November	D	E	0.6	0.33	1.7	0.77
November	D	F	0.5	0.13	1.1	0.31
November	N	E	0.6	0.08	1.2	0.26
November	N	F	0.8	0.24	1.9	0.13
November	D	E, F	0.5	0.18	1.7	0.43
November	N	E, F	0.7	0.13	1.6	0.13
November	D, N	E	0.6	0.18	1.8	0.41
November	D, N	F	0.6	0.13	0.8	0.17
Total November density			0.6	0.11	1.6	0.22

Dredged Hole #6 than in Dredged Hole #5 during ebb tide surveys, and nearly 24% fewer fish during flood tide surveys. Despite these differences, tidal effects on fish density examined by ANOVA were not found to be significant ($p > 0.05$).

5.8. Influence of time of day on fish distribution

During summer surveys nighttime fish densities were higher in both Dredged Holes #5 and #6 than during daytime surveys (Table 3). Nighttime estimates of fish density (mean = 12.7 fish/100 m^3) were approximately double the daytime estimates (mean = 6.4 fish/100 m^3) in Dredged Hole #6 (Table 3). Day-night averages at Dredged Hole #5 were not as large. During spring surveys, nighttime estimates of fish density were higher than daytime estimates in Dredged Hole #6 and for one survey in Dredged Hole #5 (Table 3). In this survey daytime fish density estimates were 6.4 fish/100 m^3. This result was strongly affected by the presence of four large schools of fishes detected during the daytime survey. The highest fish density estimate during any spring nighttime survey was only 3.9 fish/100 m^3. Combined (across tidal cycles) day-night fish density averages were higher during nighttime sampling in Hole #6 (mean = 2.6 fish/100 m^3), when compared to daytime density estimates (mean = 1.5 fish/100 m^3). The reverse was true for Hole #5, where daytime fish density estimates (mean = 4.1 fish/100 m^3) exceeded nighttime estimates, although by less than 1 fish/100 m^3. Little difference was observed between day/night fish densities during fall surveys. At both the restored and control borrow pits, day-night densities (across tidal cycles) averaged less than 0.2 fish/100 m^3. The highest single day-night difference was only 0.8 fish/100 m^3 in Dredged Hole #6. During all seasons, higher nighttime densities resulted from an influx of small fishes (<10 cm), consisting primarily of bay anchovies. Results from two-way ANOVA (Site X Day/Night) for each of the three sampling events were identical in the sense that there were statistically significant differences ($p < 0.05$) for Site and Day/Night, but not for the Site X Day/Night interaction (Fig. 8). This indicates that differences detected between sites or day/night surveys were a consistent pattern.

6. Discussion

Impacts resulting from changes in bathymetry are often the result of alterations in current flows. Wong and Wilson (1979) have modeled current flow/borrow pit interactions in the Lower Bay of New York Harbor and shown that currents decelerate as they pass over and into borrow pits and accelerate around the periphery of the pit. Large pits are capable of changing both the velocity and current direction. Polis (1974) indicated that pit morphology has strong influences upon current flows. Depressions with large aspect (width to depth) ratios, i.e. wide and shallow pits, are more likely to be well flushed than one with low aspect rations, i.e. narrow and deep pits. Polis credits Koo (1973) with the observation that pits with relatively gentle side slopes are also more likely to be well flushed than pits with steep banks like those of the current study. In addition, local conditions can have profound effects on the character of a borrow pit. Borrow pits with connections to nearby channels tend to be better flushed that isolated pits (Murawski, 1969). This condition is somewhat analogous to that of dead-end dredged channels were low flushing rates can lead to water mass stagnation and low DO concentrations (Lindall et al., 1973; Ray, 1982). Another key factor for many estuarine borrow pits is that they are located in close proximity to shore and do not benefit from water column mixing from wind-driven waves. Borrow pits in the current study were as close at 30 m from shore. Current velocities (>1 m/s) at the Barnegat Bay Inlet were significantly reduced (0.15 m/s) near the study site due to dampening effects.

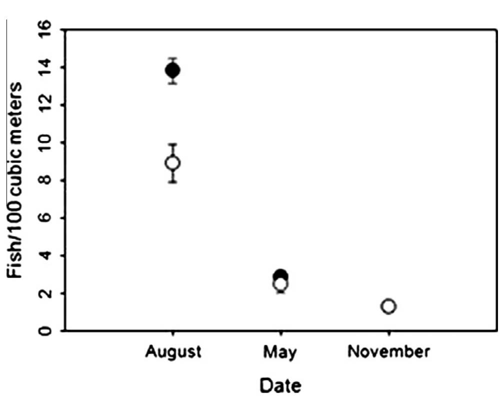

Fig. 8. Total numbers of fish/100 m^3 ± SE collected in day (open circles) versus night (filled circles) by sampling date. All night values are significantly greater ($p < 0.05$) than day values within all sampling dates.

Low DO concentration results when flow decelerates sufficiently to allow microbes to deplete oxygen from the water. This condition is exacerbated by the development of thermoclines, which act to reduce interchange between surface and bottom water masses. Chronic or persistent stratification of the water column can result in hypoxia (low DO concentration, generally <3 mg/l) or anoxia (no DO). In a study of borrow pit oxygen demand in New York Harbor, Swartz and Brinkhuis (1978) found that reduced DO levels were seasonal in nature and highly variable from site to site. A borrow pit (West Bank) with poor mixing became hypoxic during the spring – summer period, while a second more exposed site (East Bank) did not. Murawski (1969) examined 38 dredged holes along the Intra-Coastal Waterway in New Jersey and observed that DO concentration of <5 mg/l were common in holes that exceeded a depth of 6 m. Biological consequences of low DO vary from physiological stress on individual organisms to the death of entire assemblages (Diaz and Rosenberg, 1995). Pits experiencing recurrent hypoxia or anoxia may develop depauperate assemblages or be devoid of macroscopic life. In a study of a Danish fjord with seasonal oxygen depletion, Jørgensen (1980) found that in some areas, the benthos experienced periodic mass mortality and were unable to completely recover between anoxic episodes. Reine et al. (2012a, In prep.) studied two borrow sites (Brookley and Airport Holes) located in upper Mobile Bay, Alabama. Water quality data indicated hypoxic/anoxic conditions were present during spring and summer with dissolved oxygen (DO) concentrations less than 2.5 mg/L (<30% saturation) at depths of 4 m, falling to near 0.0 mg/L at depths greater than 5 m. Haloclines were present during both spring and fall sampling events. Number of benthic taxa averaged 13 in samples collected from the natural bay bottom, 6.7 in the shallower Airport Hole to only 2.9 in the deeper Brookley Hole. Animals per square meter ranged from 3300 to 3500 in the natural bottom, 1800 in Airport Hole to only 141 in Brookley Hole. In June 2012, 1.2 million cubic yards of dredged sediment was used to restore Brookley Hole. Post-restoration sampling is currently underway. In 2000 and 2003 the New York District US Army Corps of Engineers and the New York State Department of Environmental Conservation (NYDEC) conducted a series of ecological investigations of borrow pit in Norton Basin and Little Bay. These are relatively steep-sided deep (60 ft) pits that are sheltered by surrounding land features from wind-generated currents with shallow entrance channels affecting tidal exchange. The majority of samples retrieved from the deep portions of Little Bay yielded no benthic organisms. The deep areas of Norton Basin (6500 animals/m^2) outperformed similar strata in Little Bay (<4500 animals/m^2), but fell well short of the values (25,000 animals/m^2) in the natural bottom. Low DO was determined to be a key factor of

the ecological conditions of the pits. The highest number of occurrences of hypoxia recorded during the study at the reference stations was four. The southern Norton Basin pit had 20 occurrences, while Little Bay failed this standard 100% of the time (44 occurrences) and was almost always anoxic (<1 mg/l) at depth. Another key finding was a persistent cold water layer, or thermocline, below 25 ft, indicating that there is essentially no exchange with surface or other surrounding waters. An ecological and physical characterization of eleven dredged holes was conducted in the Tampa Bay Estuary to assess habitat value during a two year study conducted as part of the Tampa Bay Dredged Hole Habitat Assessment Project (TBDHAP, 2005). Conclusions from the study were that seven of the eleven studied holes provided suitable habitat for aquatic organisms and should remain in their current conditions. However, restoration of the bay bottom to more natural conditions, through complete or partial filling, could enhance the habitat value at four holes.

Specific to New Jersey borrow pits, Murawski (1969) recorded both hypoxic (1.8 mg/l at 8.8 m) and anoxic levels (0.00 mg/l at 10.3 m) in the lower portion of the pit basin of Dredged Hole #6, located in Barnegat Bay, during the month of August. Murawski (1969) noted that even though a relatively small portion of the New Jersey pits he examined were completely anoxic, 20 of 33 had no benthic communities at all. In 1992, New Jersey Department of Environmental Protection (NJDEP), as reported in Versar (1999), resurveyed Dredged Holes #5 and #6 and found values not substantially different from those reported by Murawski (1969). Versar (1999) recorded DO on an hourly basis for 4 consecutive days at an instrument moored 1-m off the bottom of Dredged Holes #5 and #6. Hourly averages were 5 mg/l in Dredged Hole #5 and 4 mg/l in Dredge Hole #6. DO concentrations fell sporadically below 3 mg/l in Dredge Hole #6, but never below hypoxic levels (2 mg/l). During the present study DO concentration measurements in Dredged Holes #5 and #6 fell into ranges of "typical" values (7–9 mg/l) for shallow, open-water, estuarine sites. Given the lack of water column stratification and high DO concentrations, it is not surprising that there is little difference in the distribution or structure of the benthic community between Dredged Hole #5 and #6, among depths, or over time. The same pattern of decreasing taxa richness (taxa/sample), abundance, and diversity with increasing depth are found in both borrow areas and both time periods (pre- and post-restoration). Likewise the species composition of reference areas and middle and shallow (Top) depth samples are quite similar to one another in both borrow areas and both time periods. Only bottom depth samples appear to be different as evidenced by the lowest values for taxa richness, abundance, diversity, and the highest degree of variation in species composition. The results from bottom depth samples are mostly likely due to differential survival as a result of periodic exposure to low oxygen conditions.

Hypoxia (DO < 2 mg/l) remains a central issue related to the habitat quality of dredged holes. Although anoxic conditions did not occur during any of the sampling events of the present study, it is possible and even probable that such conditions do occasionally occur in these dredged holes. Hypoxic conditions are probably a sporadic phenomenon that occurs primarily during extended periods of calm weather that could induce either density or thermal stratification of the water column.

The properties of sediments accumulating in a borrow pit have consequences for benthic organisms which colonize the pit basin. Benthic community composition and structure are largely determined by the type of sediment present (Lenihan and Micheli, 2001). Sandy sediment assemblages can be quite different from those of muddy substrates, both in species composition and trophic structure. Muddy substrates are generally dominated by burrowing and surface-feeding detritivores, whereas sandy substrates tend to be dominated by filter-feeders (Gray, 1974; Diaz and Schaffner, 1990; Snelgrove and Butman, 1994). Differences in assemblage structure can represent relatively different qualities as forage for consumer organisms such as demersal fishes and invertebrates. Thus when a pit in a sandy area (Dredge Hole #6) fills with muddy sediments, the shifted benthic assemblage may not provide sufficient or appropriate food for predator species. In addition, muddy sediments have the capacity to retain far greater levels of contaminants than sand and therefore increase the possibility that benthos inhabiting the pit represent a pathway for bioaccumulation and trophic transfer of contaminants.

Another consequence of decelerate current flow is an increase in sedimentation. As flow decreases, there is an increased likelihood that particles in the water column will settle out of suspension. If the current flows are sufficiently slow, as is the case in the current study, particles finer than the original substrate settle out, gradually changing the nature of sediment present in the pit basin. Gradual infilling of sandy dredged sites by fine materials has been reported by Jones and Candy (1981). The nature of the sediment that settles into borrow pits varies as a function of location and prevalent sediment transport processes. McGrorty and Reading (1984) found that a shallow muddy dredge pit near a salt marsh in southeast England filled with sediments coarser than the surrounding area, while a deeper sandy site filled with relatively fine sediments. The latter best describes Dredge Hole #6. Pre-restoration sediment samples (Versar, 1999) indicated that the natural estuarine bottom was comprised of coarse sand fraction (mean grain size 241 μm) with only a 22.7% silt/clay fraction. The deep pit basin of Dredged Hole #6 however was comprised of sandy silt with a very fine sand fraction (mean grain size 24 μm) with a silt/clay fraction of 94%. Sediment samples taken from Dredged Hole #6 after restoration consisted of sandy silt to silty sand with a medium to very fine sand fraction (mean grain size 50 μm) and a percent clay/silt fraction of 59% indicating finer sediments were again settling into the pit basin.

Fishes and large invertebrates also utilize borrow pits however there is considerable confusion and disagreement about the nature and extent of utilization. One study in the Chesapeake Bay region has shown that some large benthic invertebrates such as blue crabs can be found in large numbers in shallow borrow areas (Schaffner and Diaz, 1988). Blue crab and pink shrimp (*Pandalus jordani*) were also more abundant within dredged holes when compared to the adjacent shallower areas of the Tampa Bay Estuary (TBDHAP, 2005). In the current study, blue crab was the most abundant macroinvetebrate capture in otter trawls. Numerous anecdotal accounts exists that fishes are found in association with borrow pits. Attempts to verify and quantify this observation by scientific sampling have led to mixed results. Bokuniewicz et al. (1986) reviewed a number of studies from New York Harbor (including Conover et al., 1985, and Pacheco, 1983) and concluded that abundance (CPUE) and diversity of pit fish assemblages were higher than those of surrounding shallow water habitat. Woodhead and McCafferty (1986) and Clarke et al. (unpublished data, 1998) also examined pits in lower New York Harbor, but did not detect differences between borrow pit and control area assemblages. Reine et al. (2012a, In prep.) found that while fishes were abundant in the upper half of the water column in Brookley Hole, Mobile Bay, Alabama, they avoided the lower half of the pit, presumably from low DO concentrations, which lead to hypoxic conditions just below mid-water depths to anoxia within 1–2 m of the pit basin bottom. Likewise the borrow pit identified as Little Bay, New York Harbor clearly demonstrated that fishes avoided the lower half of the pit from both the presence of hypoxic/anoxic conditions as well as a persistent thermocline, discussed in the above text.

The difficulty in detecting a pattern in fish utilization of borrow pits may be due to the ephemeral nature of the association. In the

current study, some broad characterizations however can be made. Both sites had similar patterns with regards to the influx of small fishes (Bay anchovies and Silversides) into the borrow pits during the nighttime period. Likewise both borrow sites followed a similar pattern of fish utilization based on changes in tidal direction. During summer, fish densities during the flooding tide exceeded densities during an ebbing tide at both borrow sites. In spring, fish densities were higher in both borrow pits during the ebb tidal cycle, whereas fish occupation did not appear to be influenced by changes in tide during fall.

During both spring and summer, fish densities were greater in Dredge Hole #5, when compared to Dredged Hole #6 however the reverse was true during fall sampling. During summer, juvenile weakfish may find Dredged Hole #5 to be a more suitable nursery area. Likewise, in fall, juvenile Atlantic croaker and grass shrimp, of which both species were absent in Dredged Hole #5, contributed to higher echo-integrated fish densities in Dredged Hole #6. The reasons why these species preferred one borrow pit over the other are unclear given that both borrow sites had similar post-restoration water depth and high DO concentrations. One possibility may be differences in current velocities and flow patterns at each site.

Murawski (1969) noted that fishes were present in some dredged holes in New Jersey during the winter and hypothesized that the fishes were seeking refuge in the slightly warmer water present in the thermally stratified pits. The concept that fishes would occupy borrow sites as thermal refuges has not be confirmed by published studies. Borrow pits where water exchange is sufficiently limited to permit formation of a thermocline in winter are also likely to experience hypoxia and anoxia in the summer. Forage for over-wintering, bottom-feeding fishes within the confines of a pit could conceivably become limiting as benthic recolonization rates are generally low prior to the spring recruitment period. Winter sampling by Versar (1999) did not indicate the presence of over-wintering fishes in either Dredge Hole #5 or Dredged Hole #6. Fish assemblages as determined by otter trawls were limited to only four-spined stickleback, a year round resident in Barnegat Bay.

Affinities of many fishes for habitats with surface relief are well-established, and it is feasible that fishes are similarly attracted to pits because of relatively sharp changes in bathymetry. Fishes have been shown to respond to altered current flows around and over bottom structures, but this response is usually seen when the structure projects above the surface of the bottom (e.g. artificial reefs, mound structures, and submerged aquatic vegetation). In the current study, fishery acoustic echograms from post-restoration surveys did shown evidence of fish attracted to the mounds created in Dredged Hole #6 and to the steep side-slopes of the borrow pits. This attraction was well documented for a dredged material mound created five miles offshore of Dauphin Island, Alabama (Reine et al., 2012b). This large volume of sediment obtained from the widening and deepening of the Mobile Bay Ship Channel produced a topographic feature almost 2.4 km (1.5 miles) long and 1.2 km (0.75 miles) wide. Inspection of fishery echograms of transects across the mound yielded evidence of associations between mid-water fishes and the mound crests. This attraction may result from shed eddies, as a result of the Lee wave phenomenon, which are thought to occur both up and downstream of a structure that obstructs the current field (Lindquist and Pietrafesa, 1989; Grove et al., 1991). Shed eddies (vortex currents) resulting from the interruption of bottom currents by artificial reefs are highly attractive to migrating pelagic fishes (e.g. mackerel, sardines, jacks). Mid-water planktivores are thought to use shed eddies for orientation into flows for energy efficient access to planktonic food source drifting with the currents. Clarke and Kasul (1994) also reported attraction of mid-water fishes to the dredged material mound crests in the mid-1990's. Grove et al. (1991) reported that artificial reefs produced a current "shadow" a phenomenon whereby an area of low current flow on the leeward side of the structure at or near the ocean bottom is created when high current velocities dissipate the shed eddies. The area of low current flow is believed to attract some demersal fishes to reef structures. Several fishery echograms show the presence of schooling fishes on the leeward side of the mound in the lower depth strata. Conventional fishery sampling indicated that these were benthic feeding fishes such as Atlantic croaker, which typically are found in scattered to dense schools. Although dredged material mounds and artificial reefs seem to have little in common when compared to borrow pits, in theory, fishes within pits may orient to current flows or take advantage of energetic savings in protected area with low current velocities. However, there is presently no conclusive evidence that alteration of current flows around and in borrow pits has any effect on fish behavior.

7. Conclusion

Borrow pits have been speculated to be either degraded or critical fish habitat. The existing knowledge base is insufficient upon which to base broad generalizations; however, with knowledge of site-specific conditions predications can be made with some certainty regarding the habitat quality of existing pits. Clearly pits in open-water settings are less likely to experience degraded water quality than those in confined embayments. Even in open-water settings, a stratified water column can lead to periodic hypoxic or anoxic events. Likewise, basic questions regarding fish seasonally and use of pits as habitat must be considered in light of site-specific conditions. Fishes and many motile invertebrates are tolerant of wide ranges of environmental conditions, and may not completely avoid pits even during marginal water quality conditions. Certain species may take advantage of hypoxic episodes, when benthos evacuate their burrows or migrate to the sediment/water interface, to forage by making short trips into the oxygen depleted waters. Persistent low water quality conditions will inevitably reduce fishery resource occupation. In areas characterized by recurrent water quality conditions such as Tampa Bay, Florida (Grabe, 1997), Norton Basin and Little Bay, New York Harbor (NYDEC, 2004), Brookley and Airport Holes, Mobile Bay, and multiple pits in Barnegat Bay, New Jersey (e.g. pre-restored Dredged Hole #6) filling dredged holes may improve these conditions. In most estuarine sites, re-contouring pits should result in no net habitat loss, and provide an opportunity for restoration to historical conditions. Given careful consideration of fill materials, particularly for uppermost layers, and consequences of in-filling on circulation patterns, re-contouring projects should represent an overall benefit.

Although several restoration options were considered for Dredge Hole #6, returning the pit to its historical bathymetry was not selected in order to optimize both benthic and fish habitat functions. This option would satisfy several criteria based on filling only the lower half of the pit in that it would eliminate the hypoxic/anoxic zone that had been previously documented in several studies, it would result in an overall improvement of the benthic assemblage, although it was recognized that number of taxa or abundance would most likely not reach the level of the natural bay bottom, while preserving the upper depth strata for fish utilization.

Some limitations in assessing the fishery habitat functions of the borrow pits are inherent in the study design, which are acknowledged herein. For example, fish densities were not simultaneously surveyed in other open-water habitats in Barnegat Bay, so comparisons to shallow barren or vegetated bottoms are not possible. Likewise, because the final selected alternative resulted in a partial rather than complete filling of Dredged Hole #6, a direct comparison of an un-restored borrow pit with a pit returned to

Please cite this article in press as: Reine, K., et al. Fishery resource utilization of a restored estuarine borrow pit: A beneficial use of dredged material case study. Mar. Pollut. Bull. (2013), http://dx.doi.org/10.1016/j.marpolbul.2013.05.031

historical contours cannot be made. Indeed, the "restored" condition of Dredged Hole #6 created a borrow pit of similar depth profiles to Dredged Hole #5. Thus the restoration as conducted effectively reproduced an existing borrow pit configuration, and not a distinctly different fishery habitat. Therefore it is not surprising that in terms of absolute numbers and densities of fishes, the differences between the borrow pits appear to be relatively minor. Partial filling of Dredged Hole #6 does not appear to have detrimentally affected fishery resource occupation. To that end, the project has satisfied the objectives of creating habitat less susceptible to degraded water quality conditions, while retaining sufficient vertical relief to maintain associations with juvenile weakfish and other potential forage fishes. Density or thermal stratification was not pronounced in either dredged hole during any seasonal survey. DO concentrations were relatively high, even during summer, and well above pre-restoration surveys dating back to 1969. Although not seen in this study, periodic hypoxic conditions may still occur within the borrow pits under certain conditions. To verify the outcome of improved water quality, further monitoring will be necessary during appropriate seasons and time periods. Likewise, neither borrow site was found to be a thermal refuge during winter, although more extensive monitoring would be required to verify this finding.

Fishes were observed to move freely within and outside of both borrow pits. Given the location of both dredged holes in close proximity to shorelines, the lack of strong tidal flows may affect "flux" of fishes between pits and adjacent shallow habitats. Inspection of individual echograms of transects across the dredged holes yielded some evidence of associations between fish targets and bathymetric features such as the sand mounds formed in the basin of Dredged Hole #6 and the toes or upper rims of the side slopes of the borrow pits, further analyses of the fine spatial scale interactions between fishes and borrow pits are recommended. The efficacy of created mounds in providing long-term habitat benefits can only be evaluated by longer-term monitoring. They may or may not be attractive to certain fish species. It should be noted that fisheries hydroacoustics techniques provide data on fishes in the water column only and not in contact with the substrate. Therefore, fish densities recorded herein do not include flatfishes, gobies, and other bottom-oriented species.

There was no evidence of fish avoiding any portion of the water column within the borrow pits, although depth distributions of fishes were shown to change subtly between seasons and between dredged holes. The latter observation may simply reflect differences in geometries of the dredged holes and orientation to prevailing water currents. Some variation in depth preferences of fishes on given dates was observed between sites. For example, during the fall sampling some affinity for the upper depth strata was observed in Dredged Hole #5, whereas deeper depths were occupied in Dredged Hole #6. Fishes were more evenly distributed throughout the water column in both borrow pits in the spring surveys, but congregated at mid-water depths during summer surveys at both sites.

In conclusion, there appears to be little to lose and much knowledge to be gained by additional projects demonstrating different borrow pit restoration alternatives. Surprisingly few borrow pit restoration projects have been conducted. In certain open-water situations it is likely that complete filling to historical contours would be very beneficial, particularly if the restored bottom results in establishment of submerged aquatic vegetation, oyster reef, or benthic habitats that support fishery resources.

Role of the funding source

The study was funded by the Environmental Focus Area of the Dredging Operations and Environmental Research (DOER) Program. The Program Manager is Dr. Todd Bridges. The sponsor had no involvement in the study design, in the collection, analysis and interpretation of the data or in the writing of the report. The sponsor (Program Manager) has encouraged peer-reviewed publication of studies conducted under the DOER Program, but did choose or influence the journal selected for publication.

Acknowledgments

Funding for this project was provided by the Dredging Operation and Environmental Research (DOER) Program. We thank Joan Clarke of the US Army Engineer Research and Development Center for providing guidance in statistical analysis of the fisheries hydroacoustics data. We also thank Willy Burton and staff at Versar, Inc. who ably served as captain and crew of the survey vessel. Sincere appreciation is also extended to Terry Farmer, Mark Eberle, and Beth Brandreth of the USACE Engineer District: Philadelphia for technical and logistical support.

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Please cite this article in press as: Reine, K., et al. Fishery resource utilization of a restored estuarine borrow pit: A beneficial use of dredged material case study. Mar. Pollut. Bull. (2013), http://dx.doi.org/10.1016/j.marpolbul.2013.05.031