ERDC TN-DOER-E31
February 2012

Fishery Resource Use of an Offshore Dredged Material Mound

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SUMMARY: In 1987, deepening of the Mobile Ship Channel necessitated the placement of nearly 11.5 m^3 (15 million yd^3) of dredged material at an approved open-water disposal site in the Gulf of Mexico 12.9 km (8 miles) south of the entrance to Mobile Bay, Alabama. This large volume of sediment produced a topographic feature almost 2.4 km (1.5 miles) long and 1.2 km (0.75 mile) wide, with a height of 6.1 m (20 ft) above the pre-existing bathymetry contours. Additional sediment has been placed at this mound since initial construction, and the mound remains a large topographic feature following the passage of multiple tropical storms. Although anecdotal evidence exists that the placement of dredged material in open-water sites can result in viable, even enhanced habitat attributes and functions for fish and shellfish, few published data either support or refute that conclusion. Preliminary studies at the offshore Alabama mound indicated strong associations between schooling fishes and mound features. Factors such as mound bathymetric relief, slide slope, sediment properties, overall footprint, and volume to some degree mimic conventional artificial reefs in attracting various fish species. In 2007-2008 fishery utilization of the Mobile offshore dredged material mound was assessed using a combination of conventional otter trawl and fisheries hydroacoustics methodologies. Seasonal conditions at both the mound and a nearby reference area were assessed in terms of water quality, fishery resource assemblage composition, and diel distribution patterns. Trawl catches were used to determine composition of the fishery assemblage at each site by season. Analysis using a Generalized Linear Model indicated that no significant differences were detected between site by date or site by time. There was a significant difference in density between seasons. The mound and reference area were characterized by typical northern Gulf of Mexico coastal fish assemblage dominated by demersal, bottom-feeding fishes as well as mid-water planktivores. The assemblage associated with the dredged material mound appears to be taking advantage of habitat functions provided by the mound, including use by juvenile red snapper.

INTRODUCTION: The U.S. Army Corps of Engineers dredges nearly 229.4 m^3 (300 million yd^3) of sediment annually to maintain navigable waterways across the United States. Large volumes of dredged material historically have been placed at a number of sites in U.S. coastal waters, although negative perceptions and concerns for detrimental impacts on habitat led to restrictions on all forms of open-water placement. Options for upland confined placement are increasingly difficult to identify, and exorbitantly expensive to create and maintain. Consequently, open-water placement is the most economically viable option for many dredging projects. Dredging of navigation channels in Mobile Bay, Alabama exemplifies the inherent conflict in finding suitable placement sites for large quantities of sediment on practically an annual basis. The deepening of the Mobile Ship Channel in 1987 from 40 ft to 45 ft required removal of nearly 11.2 m^3 (14.6 million yd^3) of material and placing it at an approved disposal area approximately 9.3 km (5 miles) south of Dauphin Island, Alabama. Dredged sediment was placed at a designated site in a predefined sequence to build the mound. The sediment was transported by split-hull hopper barges to the site and released within an approximate 305-m by 2750-m "drop zone" to construct a 6.1-m-high mound in 10.7 m to 13.7 m of water. Post-construction slide slopes of the newly formed mound were measured at 1V:24H to 1V:130H. In addition to simply accommodating the large volume of dredged material within approved site boundaries, this disposal plan enabled the construction of a mound configured to create a "structure" on an otherwise featureless bottom profile. At the time of construction, it had been hypothesized that such a structure could function as a wave attenuator during severe storms, thereby benefiting coastal shorelines by reducing erosion. The focus of the present study, however, was on documenting fishery resource habitat attributes of a large, semi-permanent topographic feature consisting of mixed sediments.

Beneficial use of dredged material refers to the broad concept that a byproduct of navigation infrastructure construction or maintenance can be used in a way that is both economically and environmentally acceptable and accrues natural resource benefits to society (Payonk 1996). Examples of viable beneficial use options span from manufactured topsoil to large-scale habitat restoration and creation projects, including expansive intertidal wetland development projects. Construction of underwater reef from hard dredged material, nearshore berm construction and beach nourishment with sandy dredged material, provision of fill for industrial and commercial development, and even capping of sanitary landfills or Brownfields qualify as viable beneficial uses. Islands and coastal uplands have been created with dredged sediment to provide nesting and refuge habitats for birds and other wildlife. Most of the original "bird islands" were built primarily as convenient placement options that rapidly developed incidental habitat for a variety of bird species. The Interior Least Tern *(Stern antillarum athalasso)* is a prime example of a species that has become highly dependent on habitat created by deposition of dredged material (Guilfoyle et al. 2004, Kerlinger 1997, Wilder 1997). Along the U.S. Atlantic and Gulf coasts there are now more than 2000 habitat islands ranging in size from 1 to 200 acres (Yozzo et al. 2004). The importance of these isolated habitats in support of bird conservation efforts is reflected in the fact that the design of islands for specific bird species is now considered to be a very desirable project outcome. Dredged material has also been used to create foundations for oyster reefs in Chesapeake Bay by depositing sediment in areas historically known to support oyster populations, and then covering or capping the dredged material mounds with a layer of oyster shell (Earhart et al. 1988, Clarke et al. 1999). Dredged material has also been successfully used in the creation of intertidal mudflats in Maine, where infaunal abundance, species composition, and diversity were shown to be similar between natural reference and constructed flats within two of years of placement (Ray 2000).

Although a source of persistent concern for regulatory agencies, large volumes of dredged material are commonly placed in open-water environments. To maintain navigable waterways, approximately 400 million yd^3 of material are dredged on an annual basis. Of this total, about 60 million yd^3 are placed in ocean waters at more than 100 Environmental Protection Agency (EPA) sites. As a result, the Corps has looked for opportunities to use dredged sediment to restore degraded fish habitat or create and enhance existing Essential Fish Habitat (EFH) as defined in the Magnuson-Stevens Act (1996) (i.e. those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity). This effort has fallen into three primary categories: borrow pit restoration, hard material reef construction, and offshore mound or berm construction.

Strategies considered for borrow pit restoration include: a complete fill to re-establish historical bathymetry contours, thereby allowing reestablishment of seagrass and/or mollusk beds, or a partial fill to maintain vertical relief and retain attraction recreational fishery resources (Reine et al. 2009). Several examples of hard material reef construction currently exist, including the Wilmington Offshore Fisheries Enhancement Structure (WOFES) and the New Jersey Shark River Reef. The WOFES structure was constructed of 764,600 m^3 (1 million yd^3) of fossiliferous limestone 5.56 km (3 nautical miles (n.m.)) offshore from the entrance to the Cape River, North Carolina. The Shark River Artificial Reef Site was constructed with granite nearly 16 n.m. offshore of the Shark River Inlet. Many completed structures fall into a third category: construction of offshore berms or mounds. Common usage of the terms "berms" or "mounds" has evolved such that the former term refers to generally low elevation deposits of dredged material placed in relatively shallow inshore areas as "feeder" berms, which are intended to migrate onto nearby beaches. In contrast, mounds generally refer to dredged material deposits placed in deeper waters, often with substantially higher vertical relief. Large, stable, permanent mounds exist in Mobile, Alabama; Tampa, Florida; and Norfolk, Virginia; for example. In Galveston, Texas, over 2000 single hopper barge loads of dredged material were used to create an offshore mini-mound complex. The present study documents fishery resource utilization of a large, stable offshore mound in northern Gulf of Mexico waters.

METHODS

Study area. The Mobile Offshore Dredged Material Disposal Site stable mound is comprised of mixed sediments and located 9.3 km (5 miles) south of the eastern end of Dauphin Island, AL (Figure 1). The site can be found on NOAA chart 11376 at approximately 30^o 10' N and 88^o 7' W. The placement area is approximately 8.9 km^2 (4.8 $n.m.^2$) in size and receives new dredged material on an annual basis. The mound has an approximately rectangular footprint and the highest elevations of the original mound reached -6 m (19.7 ft) MLLW.

Water quality. A calibrated YSI (Model 6920 V2) water quality sonde was used to measure DO concentration (mg/l), temperature (^{o}C), and salinity (ppt) at surface, mid-, and bottom depths at five mound and two reference area stations.

Fishery hydroacoustics. Surveys were conducted in October 2007, and April and May 2008. 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 -3dB). Targets satisfying single target criteria with target strength (TS) above -52.6 dB (equivalent to a length of 4 cm) were accepted as valid individual fish echoes. 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 (1,500 m/sec) and τ is pulse length duration (0.3 ms). Water temperature, salinity, and depth were measured at the study site 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.

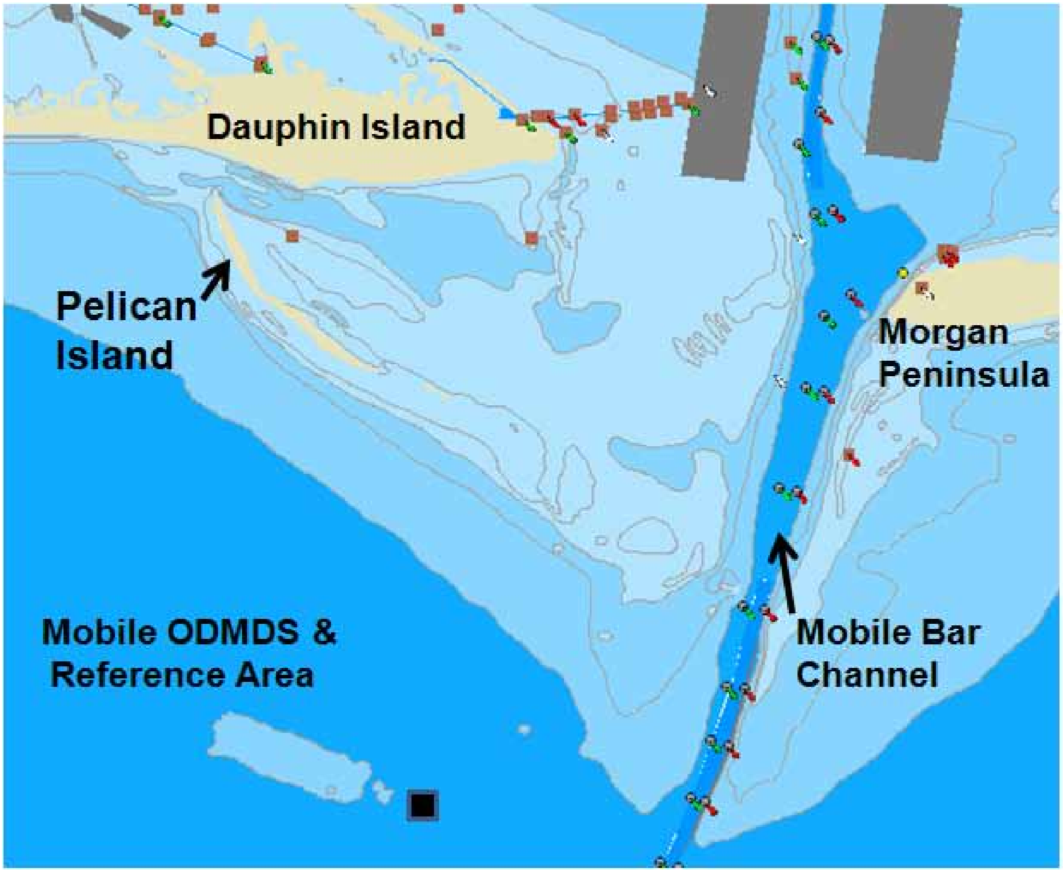

Figure 1. Location of the Mobile Offshore Dredged Material Disposal Site (ODMDS) and nearby reference area. (Reference area identified by black square.)

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 U.S. Army Engineer Research and Development Center (ERDC). Data were collected during mobile surveys with boat speed limited to 5 km/ h (3.1 mph). Each site was divided into parallel transects, spaced at 200-m (652.2-ft) intervals, covering the full north to south footprint of the disposal mound. Twelve transects (mean length = 1 km) were occupied at the disposal mound and four at a nearby reference area. Total survey distance was 12 km (mound) and 4 km (reference area), respectively. During each seasonal survey, all transects were surveyed during both day and nighttime hours. To equalize effort among sampling units, individual transects were divided into 100-m segments, referred to as elementary sampling distance units (ESDUs). Fish densities (fish/100 m^3) were calculated for each ESDU by dividing the total number of accepted fish targets detected by the volume of water sampled. This approach has been widely used in fisheries hydroacoustic studies as a basis for statistical analyses and comparisons (e.g., Gangl and Whaley 2004). 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 within each ESDU (scaled to fish per 100 m^3). Volumetric fish densities were calculated for surface, mid-, and lower portions of the water column. This was accomplished by multiplying the density returned as fish per square meter times the area of 1 ha (10,000 m^2).

Conventional fisheries gear. Otter trawls were used to examine fish assemblage taxonomic composition, and to provide ground truth data for the hydroacoustic surveys. Triplicate, 20-minute fish trawls using a 5-m otter trawl were conducted seasonally. All fish collected were identified to species, counted, and total length (TL) was measured to the nearest milimeter.

Statistical analysis. Transects were divided into ESDUs of 100-m segments. Fish densities between ESDUs were subjected to Analysis of Variance (ANOVA) using square–root transformed data with a three-way (site, sample date, and time of day) factorial design. The data failed tests for normality and homogeneity of variance prior to ANOVA. Fish density data were then pooled by sampling transects and again subjected to tests for normality and homogeneity of variance prior to ANOVA. The data failed in both cases. Data were then analyzed using a Generalized Linear Model (GLZ), which specifies the (linear) relationship between a dependent (or response) variable Y, and a set of predictor variables, the X's. The GLZ uses a general approach based upon maximum likelihood (ML) techniques, which can be used for both discrete and continuous distributions and do not require homogeneity of variances. Tests for significance were performed via the likelihood ratio (LR) test, which produces chi-square statistics (X_2) in lieu of the standard F-statistics (which assumes a linear relationship and normality of the error terms with equal but unknown variances).

RESULTS

Water quality. In October 2007, DO concentrations (range = 5.8 - 7.2 mg/l) were relatively high, at saturation throughout the water column. Salinity averaged 34 ppt during the ebbing tide with no evidence of stratification. During the flooding tide, salinity values ranged from 28.2 ppt in surface waters (< 2m) to 34.5 ppt near the bottom (6.5 m) (mean = 31.7). Water temperature averaged 20 $\pm$0.5 ^{o}C near the surface to 23$\pm$0.3 ^{o}C near the bottom. Water quality parameters were similar at both the mound and a nearby reference area.

In April 2008, DO concentration profiles were similar at both sites, increasing from 4.5 mg/l at a 9-m water depth to 8 mg/l in surface waters. Salinity values differed by no more than 2 ppt among all depth strata sampled. Salinities were lower in surface waters (23.4-25.0 ppt) and highest near the bottom (31.0-33.0 ppt). Water temperatures were relatively uniform, averaging 19.2 ^{o}C at both the mound and reference area. No evidence of a halocline or thermocline was found.

In August 2008, DO measurements were again relatively high, ranging from 6 to 6.5 mg/l at the reference area. At the mound, surface and mid-water DO concentrations were similar to those at the reference area; however, lower water column values fell to 3 mg/l at several stations. Water temperature was fairly uniform throughout the water column averaging 28 ^{o}C at both sites. Salinity ranged from 30 ppt in the upper to mid-water column to near 33 ppt in lower depth strata.

Species composition. Trawling resulted in a total catch of 4,382 fishes during three seasonal surveys. Nearly 65% of the total catch (n = 2,840) occurred during the October effort. Catch totals were similar for both April (n = 647) and August (n =895) sampling. Twenty-nine species, representing eighteen families, were captured. Catch per unit effort (CPUE) was determined for each species as the number of fish per trawl hour. Catch totals, fish lengths, and CPUE for each species are summarized in Tables 1 and 2.

Table 1. Species and standard length of fishes collected in trawl samples from an offshore dredged material mound.

Species		October 2007 Length (cm)				April 2008 Length cm)				August 2008 Length (cm)			
Common Name	Scientific Name	No.	Min	Max	CPUE	No.	Min	Max	CPUE	No.	Min	Max	CPUE
Atlantic bumper	*Chloroscombrus chrysurus*	122	10.4	17	366	72	5.1	9.6	216	10	15.4	19	30
Harvestfish	*Peprilus alepidotus*	-	-	-	-	-	-	-	-	204	5	10	612
Butterfish	*Peprilus burti*	-	-	-	-	20	4.1	5	60	-	-	-	-
Striped anchovy	*Anchoa hepsetus*	-	-	-	-	-	-	-	-	-	-	-	-
Bay anchovy	*Anchoa mitchilli*	161	3.5	14.5	483	131	5	9.9	393	-	-	-	-
Dusky anchovy	*Anchoa lyolepis*	-	-	-	-	73	10.1	15	219	-	-	-	-
Spadefish	*Chaetodipterus faber*	5	9.4	11.9	15	-	-	-	-	-	-	-	-
Scaled sardine	*Harengula jaguana*	7	9.8	12	21	52	8.1	9.5	156	38	9.1	18	114
Longspine porgy	*Stenotomus caprinus*	6	9.4	10.5	18	-	-	-	-	-	-	-	-
Atlantic croaker	*Micropogonias undulatus*	-	-	-	-	-	-	-	-	5	16.2	18.4	15
Atlantic threadfin	*Polydactylus octonemus*					1	12.5	12.5	3	-	-	-	-
Spotfin majarra	*Eucinostomus argenteus*	16	8.2	13.4	48	-	-	-	-	-	-	-	-
Sand seatrout	*Cynoscion arenarius*	-	-	-	-	-	-	-	-	7	9.1	12	21
Red snapper	*Lutjanus campechanus*	106	6.8	31	318	-	-	-	-	-	-	-	-
Lane snapper	*Lutjanus synagris*	1	12.2	12.2	3	-	-	-	-	-	-	-	-
Mutton snapper	*Lutjanus analis*	1	24.4	24.4	3	-	-	-	-	-	-	-	-
Hardhead catfish	*Arius felis*	2	29.3	32.1	6	-	-	-	-	-	-	-	-
Sand perches	*Diplectrum spp.*	4	8.7	24.6	12	-	-	-	-	-	-	-	-
Pigfish	*Orthopristis chrysoptera*	9	13.7	18.8	27	1	13	13	3	-	-	-	-
Northern searobin	*Prionotus carolinus*	-	-	-	-	-	-	-	-	1	10.5	10.5	3
Tomtate	*Haemulon aurolineatum*	15	15	23	45	-	-	-	-	-	-	-	-
Inshore lizardfish	*Synodus foetens*	7	19	28.2	21	-	-	-	-				
Bay whiff	*Citharichthys spilopterus*	3	5	13.5	9	-	-	-	-	-	-	-	-

Table 2. Species and standard lengths of fishes collected in trawl samples from a nearby reference area.

Species		October 2007 Length (cm)				April 2008 Length cm)				August 2008 Length (cm)			
Common Name	**Scientific Name**	**No.**	**Min**	**Max**	**CPUE**	**No.**	**Min**	**Max**	**CPUE**	**No.**	**Min**	**Max**	**CPUE**
Atlantic bumper	*Chloroscombrus chrysurus*	2050	5	15	6150	36	4.5	9.6	108	15	15	25	45
Harvestfish	*Peprilus alepidotus*	-	-	-	-	-	-	-	-	525	5	10	1575
Butterfish	*Peprilus burti*	-	-	-	-	2	10	12	6	-	-	-	-
Striped anchovy	*Anchoa hepsetus*	-	-	-	-	-	-	-	-	55	5.1	12.7	165
Bay anchovy	*Anchoa mitchilli*	137	5	9.8	411	54	5	10	393	-	-	-	-
Dusky anchovy	*Anchoa lyolepis*	-	-	-	-	188	5.1	15	564	-	-	-	-
Scaled sardine	*Harengula jaguana*	5	9.5	12.4	15	12	10.1	13	36	8	8.8	14.9	24
Longspine porgy	*Stenotomus caprinus*	1	8.6	8.6	3	-	-	-	-	-	-	-	-
Spot	*Leiostomus xanthurus*	1	7.4	7.4	3	-	-	-	-	-	-	-	-
Atlantic croaker	*Micropogonias undulatus*	6	15.7	19	18	-	-	-	-	11	8.2	20	33
Spotfin mojarra	*Eucinostomus argenteus*	10	8	10.2	30	-	-	-	-	-	-	-	-
Red snapper	*Lutjanus campechanus*	16	9.5	12.5	48	-	-	-	-	4	7.1	8.4	12
Hardhead catfish	*Arius felis*	2	36	36.5	6	1	29	29	3	1	28	28	3
Sand perches	*Diplectrum spp.*	-	-	-	-	-	-	-	-				
Pigfish	*Orthopristis chrysoptera*	3	14.5	14.7	9	1	16	16	3	-	-	-	-
Bank sea bass	*Centropristis ocyurus*	-	-	-	-	2	12	14	6	-	-	-	-
Northern searobin	*Prionotus carolinus*	-	-	-	-	-	-	-	-	5	6.4	11.2	15
Inshore lizardfish	*Synodus foetens*	-	-	-	-	-	-	-	-	5	14.2	19.1	15
Bay whiff	*Citharichthys spilopterus*	4	10	27.6	12	-	-	-	-	-	-	-	-
Gulf flounder	*Paralichthys albigutta*	1	8.5	8.5	3	-	-	-	-	-	-	-	-
Blue runner	*Caranx crysos*	2	17.2	18.5	6	-	-	-	-	-	-	-	-
Clearnose skate	*Raja eglanteria*	1	35	35	3	-	-	-	-	-	-	-	-
Sharpnose shark	*Rhizoprionodon terraenovae*	-	-	-	-	1	88.8	88.8	3	-	-	-	-

Fall assemblage (October 2007). A total of 19 species of fish were collected during the fall sampling effort. Of these, six species were found only at the dredged material mound and four species were exclusive to the reference area. Two pelagic species (bay anchovy, *Anchoa* mitchilli, and Atlantic bumper, *Chloroscombrus chrysurus*) and one benthic species (red snapper, *Lutjanus campechanus*) were numerically dominant at the mound site. Bay anchovy (n = 161, CPUE = 483 fish/trawl hr) and Atlantic bumper (n = 122, CPUE = 366 fish/trawl hr) are relatively small planktivores that represent forage for larger predatory fishes. Red snapper (n = 106, CPUE = 318 fish/trawl hr) are the basis for important recreational and commercial fisheries in the northern Gulf of Mexico. Combined, these three species accounted for nearly 84% of the total catch at the mound. These three species were also dominant at the reference area, accounting for 98% of the total catch. CPUE for bay anchovy (n = 137, CPUE 411 fish/trawl hr) in the reference area was comparable to that at the mound. However CPUE for red snapper (n= 16, CPUE = 48 fish/trawl hr), a fish known to inhabit natural or artificial reefs, was considerably lower at the reference area. Large schools of Atlantic bumper (n = 2,050, CPUE = 6,150 fish/trawl hr) were present at the reference area, which reflected a significantly higher CPUE when compared to the mound. Other species present at both sites included spotfin mojarra (*Eucinostomus argenteus*), longspine porgy (*Stenotomus caprinus*), pigfish (*Orthopristis chrysoptera*), scaled sardines (*Harengula jaguana)*, hardhead catfish (*Arius felis*), and bay whiff (*Citharichthys spilopterus*). Of these, the spotfin mojarra was the most numerous, ranging from 30 (reference area) to 48 (mound) fish/trawl hr. With the exception of the bay whiff, higher CPUE values were obtained at the mound site for these species when compared to the reference area (Tables 1 and 2). Four fish species were caught only at the reference area. Most notable were the Atlantic croaker (*Micropogonias undulatus*) and spot (*Leiostomus xanthurus),* with CPUEs ranging from 3 to 18 fish/trawl hr. Both species are fished recreationally. The Atlantic croaker is considered one of the most commercially important fisheries in the Gulf. Six species of fish were caught at the mound that were not present at the reference area. These included two species of snapper (CPUE = 3 fish/trawl hour), lane snapper (*Lutjanus synagris*), and mutton snapper (*Lutjanus analis*), which are typically caught incidentally with red snapper and are species that prefer low relief structures. Also present were spadefish (*Chaetodipterus faber,* CPUE=15 fish/trawl hr), a species known to frequent both natural and artificial reefs, the inshore lizardfish (*Synodus foetens*, CPUE = 21 fish/hr), sand perch (*Diplectrum formosum*, CPUE 12 fish/trawl hr) and tomtate (*Haemulon aurolineatum*, CPUE = 45 fish/trawl hr).

Spring assemblage (April 2008). Eight species were caught in otter trawls at both the mound and reference area during the spring survey. At both sites, greater than 90% of the total catch was comprised of four pelagic species including bay and dusky (*Anchoa lyolepis*) anchovies, Atlantic bumper and scaled sardines. At the reference area, dusky anchovy was the dominant species accounting for 63% of the total catch (n = 188, CPUE 564 fish/trawl hr). This species was also relatively abundant at the mound (n = 73, CPUE 219 fish/trawl hr), although the bay anchovy was the dominant species (n = 131, CPUE 393 fish/trawl hr), accounting for nearly 40% of the total catch. A species common to soft bottom habitat, the Atlantic bumper was found both at the mound (n = 72, CPUE 216 fish/trawl hr) and reference area (n = 36, CPUE 108 fish/trawl hr). Scaled sardines were present at both sites, but more numerous at the mound (n = 52, CPUE 156 fish/trawl hr) than at the reference area (n = 12, CPUE 36 fish/trawl hr). Fishes exclusive to the mound during the spring survey included the Atlantic threadfin (*Polydactylus octonemus*) and the sharpnose shark (*Rhizoprionodon terraenovae*), both caught in low numbers (CPUE = 3 fish/trawl hr). Two species, the bank sea bass (*Centropristis ocyurus,* CPUE = 6 fish/trawl hr) and the hardhead catfish (CPUE = 3 fish/trawl hr) were found exclusively at the reference area.

Summer assemblage (August 2008). The summer catch was dominated by harvestfish (*Peprilus alepidotus*), which accounted for 75 to 80% of the total catch at both the mound and the reference area. CPUE ranged from 612 fish/trawl hr (mound) to 1,575 fish/trawl hr (reference area). Present in much lower numbers (n = 38, CPUE 114 fish/trawl hr), scaled sardines were the second-most-abundant fish captured at the mound. This species was also present at the reference area, but as observed in the spring catch data, in considerably lower numbers (n = 8, CPUE 24 fish/trawl hr). Although accounting for less than 10% of the total catch, the striped anchovy (*Anchoa hepsetus*) was the second-most-abundant fish captured at the reference area. Species present at both sites in small numbers included Atlantic croaker, Atlantic bumper, and the northern searobin (*Prionotus carolinus*) with CPUEs ranging from 3 to 45 fish/trawl hr. Sand seatrout (*Cynoscion arenarius*) was the only species captured exclusively at the mound. In addition to the striped anchovy previously mentioned, four additional species (red snapper, Gulf flounder, Hardhead catfish, and inshore lizard fish) were captured exclusively at the reference area with CPUE ranging from 3 to 15 fish/trawl hr.

FISH SIZE DISTRIBUTION

Conventional gear catch. Size frequency distributions for fishes by season can be found in Figures 2 and 3. Total lengths (TL) ranged from 4.5 to 88.8 cm. Of the three numerically dominant species, Atlantic bumper were largest in terms of mean total length at 12.6 cm (range = 4.5 to 25 cm). Harvestfish, captured only during the summer sampling event, fell entirely within one size class (5-10 cm, mean = 7.2 cm). Along with harvestfish, Atlantic bumper and bay anchovies also were most commonly captured in the 5- to 10-cm size class. This size class accounted for slightly more than 40% of all fishes captured at the dredged material mound and greater than 66% of all fishes captured at the reference area. Dusky anchovies, third in abundance, also fell within the10- to 15-cm TL size class. This size class represented 44.2% of all fishes caught at the dredged material mound, but only 15.3% of those captured at the reference area. Dusky anchovies, scaled sardines, spotfin mojarra and Atlantic croaker were frequently captured in the 10- to 15-cm TL size class. At the mound, slightly more than 5% of the total catch (consisting primarily of tomtate, Atlantic bumper, and scaled sardines) fell within the 15- to 20-cm TL size class. This size class accounted for only 0.6% of the total catch at the reference area. Fishes with TL greater than 20 cm represented only 2.4% of the total catch at the mound and only 0.3% at the reference area. Fish species that fell into the larger size categories included hardhead catfish, mutton, and red snapper. Red snapper occurred in six 5-cm-increment size classes, ranging from 5-10 cm to 30-35 cm TL, although the majority were in the 10- to 15-cm TL size class and were associated with the mound. A comparison of Figures 2 and 3 indicates that fishes > 20 cm TL were almost exclusively found at the mound during the fall sampling season.

Fisheries hydroacoustics. Target strength data were used to estimate fish lengths for all acoustically detected and accepted targets. Mean fish length was determined by site, time of day, season, and overall distribution. Estimated lengths of all single target fishes ranged from 4.0 to 110.9 cm. Results indicated that mean fish length was slightly greater for daytime than nighttime surveys at both the mound (day = 16.6 cm, night = 15.6 cm) and reference area (day = 13 cm, night = 10.4 cm). Average fish length by season was greatest during the fall daytime survey (mean = 19.6, SD± 0.8cm), followed by the summer (mean = 15.5 cm, SD±1.9 cm) and spring (mean = 13.2 cm, SD±3.2 cm) events. Lowest overall fish length (mean = 10.2 cm) occurred for the fall nighttime survey completed at the reference area.

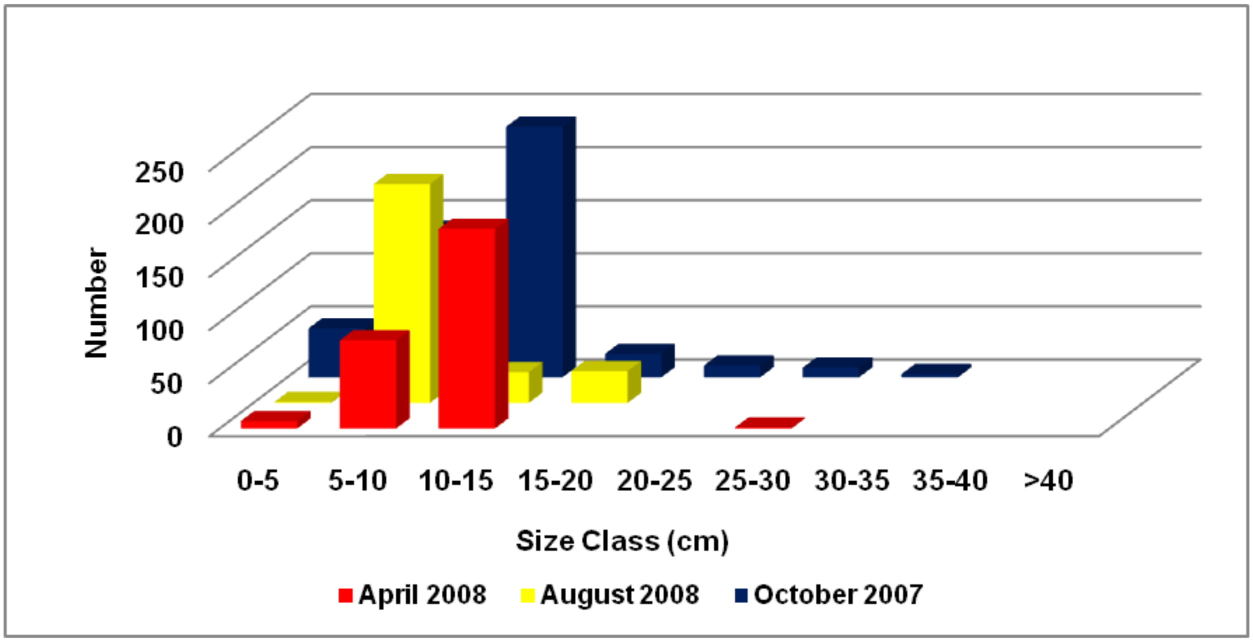

Figure 2. Length frequencies of fishes in seasonal trawl catches at the Mobile dredged material mound.

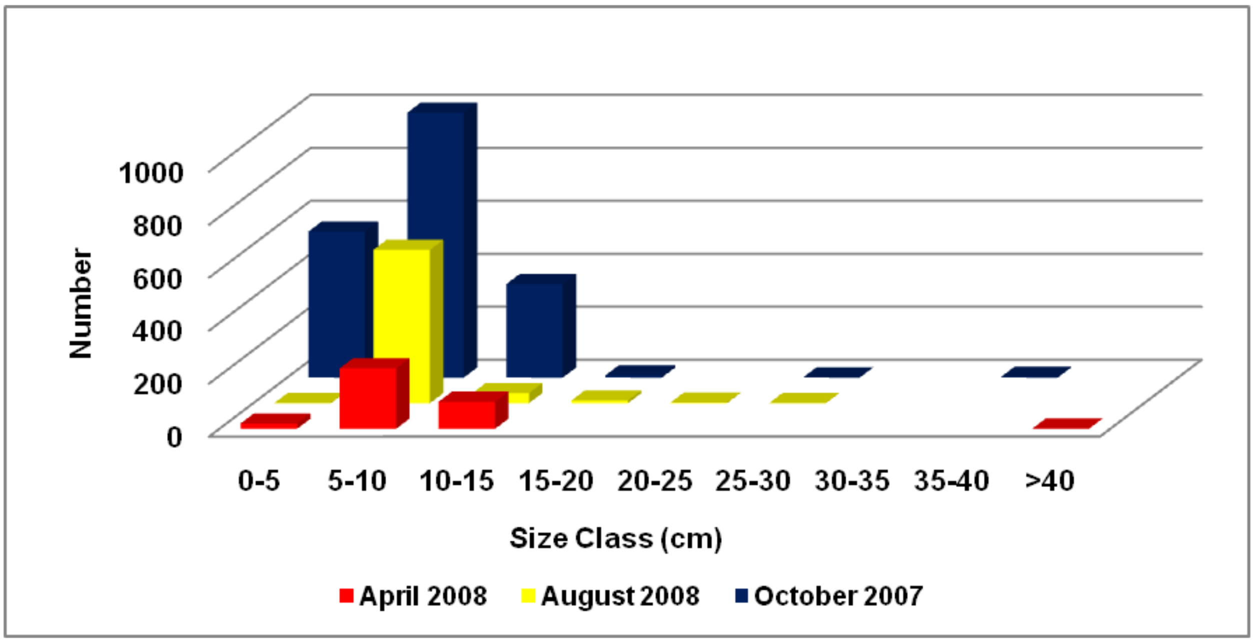

Figure 3. Length frequencies of fishes in seasonal trawl catches at the reference area.

The size class distributions of acoustically detected single-target, non-schooling fishes during seasonal day- and nighttime surveys of the mound and reference area are found in Figures 4 and 5. Due to the relatively low numbers of targets detected in the upper size classes, the results are reported in a logarithmic scale. A total of 4,194 fishes were acoustically detected at the mound, whereas 2,780 were detected at the reference area. For every sampling event, regardless of time of day, season, or location, one-third of all single-target fishes fell within the 5- to 10-cm TL class. Results from the conventional gear catch indicated that these targets were predominantly bay

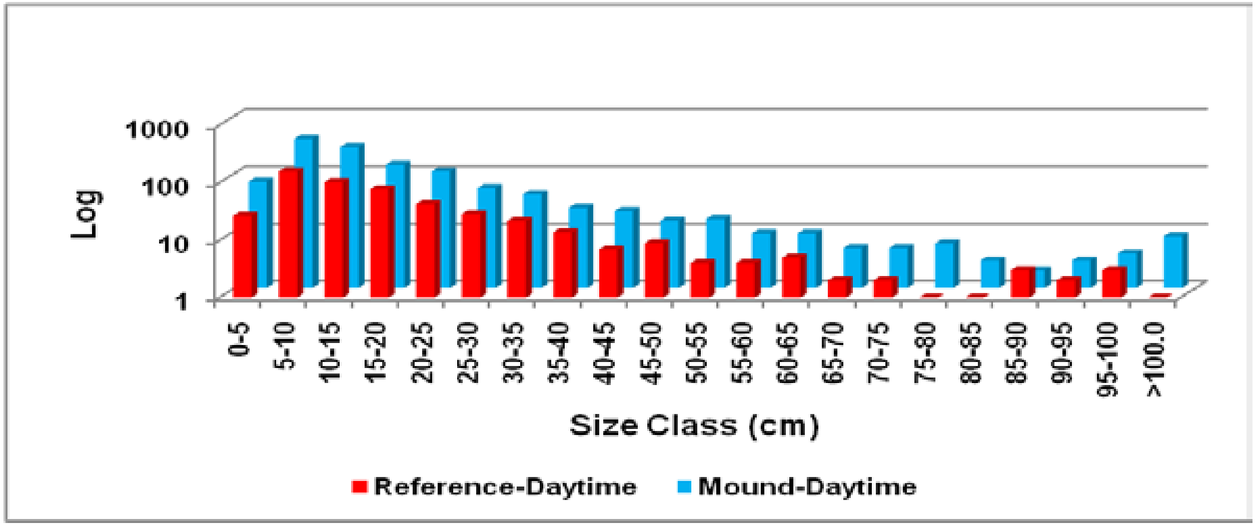

Figure 4. Length frequencies of acoustically detected single-target fishes for daytime seasonal surveys.

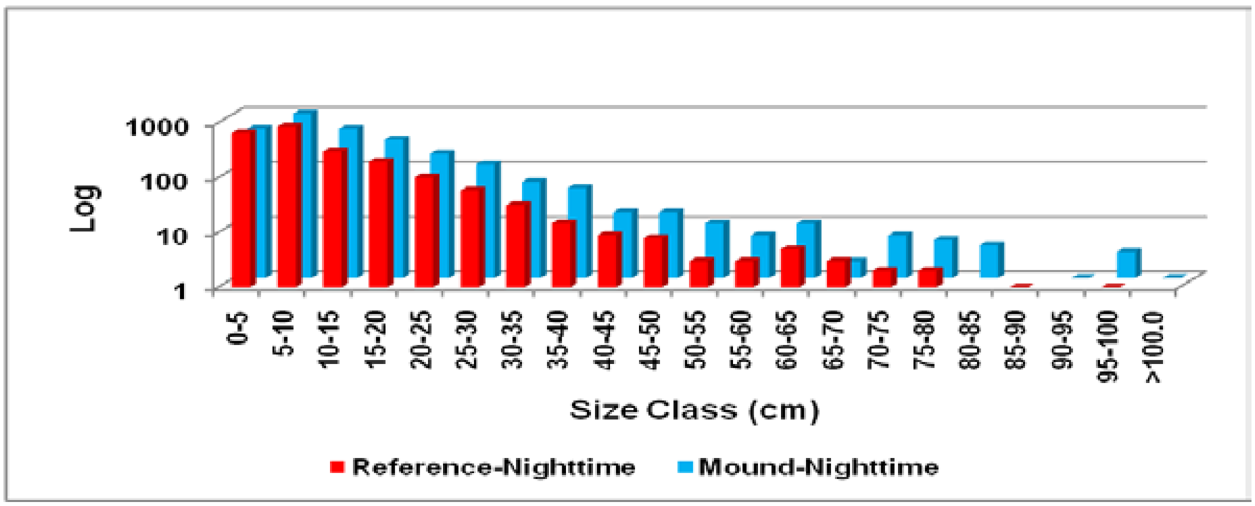

Figure 5. Length frequencies of acoustically detected single-target fishes for nighttime seasonal surveys.

anchovies, Atlantic bumper, and harvestfish, pelagic fishes known to occur in loose to dense schools. Fishes in the second-most-abundant size class accounted for between 20% (mound, size class 10-15 cm) and 25% (reference area, size class <5 cm) of the total detections. Trawl results indicated that fishes less than 5 cm TL (n = 624) consisted almost exclusively of Atlantic bumper, in addition to bay anchovies (approximately 10%) and butterfish (3%). At the mound, 10- to 15-cm TL Atlantic bumper and red snapper accounted for 90% of the fall total catch. This size class was the third-most-abundant at the reference area and consisted primarily of Atlantic bumper (93% of the total catch) in fall and dusky anchovy (85% of the total catch) in spring. At both the mound and reference areas, slightly more than 10% (n = 753) of fishes fell within the 15- to 20-cm TL size class. The most commonly captured species in this size class included bottom-feeding benthic fishes such as tomtate and Atlantic croaker. The next three size classes (20-25 cm, n = 439; 25-30 cm, n = 262; and 30-35 cm, n = 154) decreased from 7% to 2% of the total acoustic detections. These size classes were comprised mostly of red and mutton snapper, hardhead catfish, tomtate, and lizard fish at the mound and hardhead catfish and bay whiff at the reference area, most of which were caught during fall sampling. With the exception of one sharpnose shark (88.8 cm TL), none of the fishes captured in otter trawls exceeded 45 cm TL. Acoustic detections in the upper size classes (45 to > 100 cm) accounted for 3.6% (n = 149) and 2.3% (n = 65) of the total acoustic detections at the mound and reference area, respectively.

Fish vertical distribution patterns. Of the 4,194 non-schooling fishes detected, 2,887 occurred in October, 939 in April, and 368 in August. Note that the August total only includes daytime surveys. Because all single targets are recorded with reference to their depth in the water column, data post-processing allowed discrimination of fishes based on pre-determined depth intervals. To display changes in vertical distribution of fishes, the water column was divided into 1-m increments from surface to bottom (Figure 6). In October, fishes were concentrated in three lower depth strata; the 7- to 8-m depth stratum, which contained 15.2% of non-schooling fishes; 8- to 9-m, which contained 20.2%; and 9- to 10-m, which contained 20.6%. These three depth strata combined accounted for over half of all fishes acoustically detected during the fall sampling (n = 1,620, 56.1%). All other depth strata averaged between 5% and 8% of the total distribution, with the exception of the uppermost depth stratum (1-2 m), which had the fewest single target fishes (n = 44, 1.5%). April's survey results were similar to October in that the 7- to 8-m, 8- to 9-m, and 9- to 10-m depth strata had the highest fish counts, cumulatively accounting for over half (n = 506, 53.9%) of the non-schooling fishes. Two mid-water depth strata produced the second-highest fish counts in April. These two depth strata accounted for 11.2% (n = 105) and 13.3% (n = 125) of fish targets. The 1- to 2-m (n = 13, 1.4%) and 2- to 3-m (n = 24, 2.6%) depth strata had the fewest fishes in spring. These two upper depth strata accounted for only 4% of the total distribution. A nearly equivalent number of fishes (n = 36, 3.8%) was found in the lowest depth stratum (10-11 m). As observed in both the spring and fall surveys, fishes were concentrated in the deeper water strata during the summer. Highest fish counts occurred in the 9- to 10-m depth stratum (n= 97, 26.4%). Numbers of fishes decreased with decreasing water depth from 82 (8-9 m), to 62 (7-8 m), to 41 (6-7 m). These four depth strata accounted for slightly more than 75% of the total detections. Fewest fishes (n = 16) were found in the uppermost three depth strata (1-2 m, 2-3 m, and 3-4 m), totaling only 4% of all acoustically detected fishes.

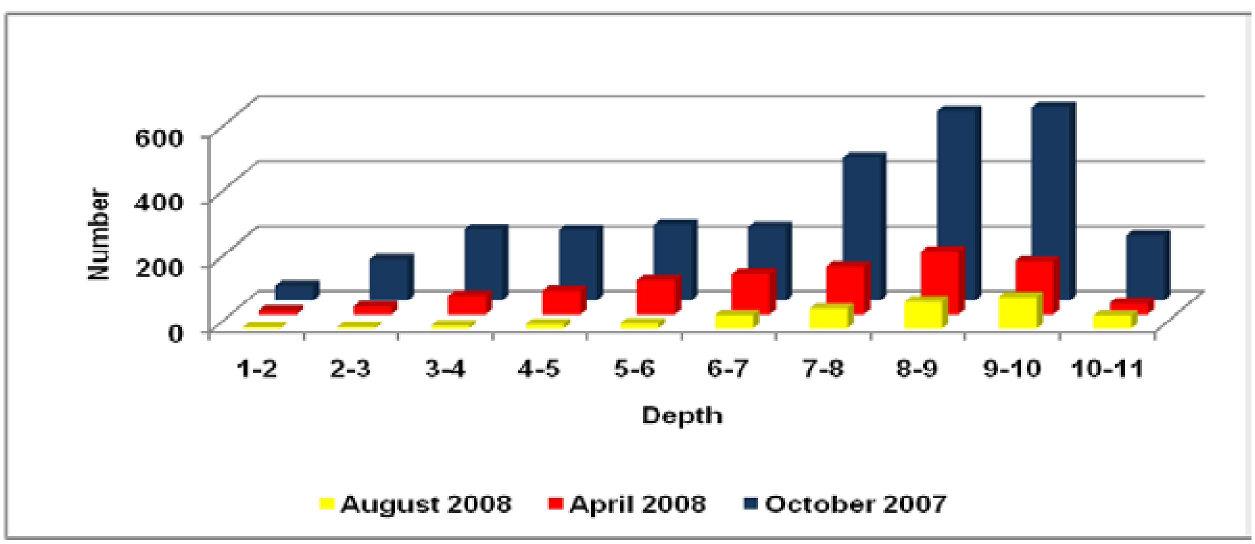

Figure 6. Vertical distribution of non-schooling fishes at the dredged material mound.

A total of 2,780 (2,379 in October, 341 in April and 60 in August) non-schooling fishes were detected at the reference area. Nearly 18% (n = 422) occurred in the lowest depth stratum during fall, increasing to over 20% (n = 70) in spring and to greater than 50% (n= 32) during summer. At the mound the lowest depth stratum (10-11 m) accounted for 3.8% (spring) to 10.9% (summer) of all fish targets. With the exception of the lowest depth stratum, Figure 7 shows a somewhat more uniform distribution of fishes across the mid- to lower depth strata when compared to that at the mound, which had slightly more fishes congregated in three lower depth strata. In spring, 75% of all fishes were found in the lower four depth strata, whereas at the mound they were more evenly distributed from the mid- to lower depth strata. Although overall numbers of fishes were low in summer, over half of these were found in the lowest depth stratum (n = 32, 53.3%). Note that fish totals for summer only included those detected during daytime surveys. As observed at the mound, fewest fishes were found in the upper portion of the water column. Less than 1% of all fishes occurred in the 1- to 2-m depth stratum during seasonal surveys at the reference area.

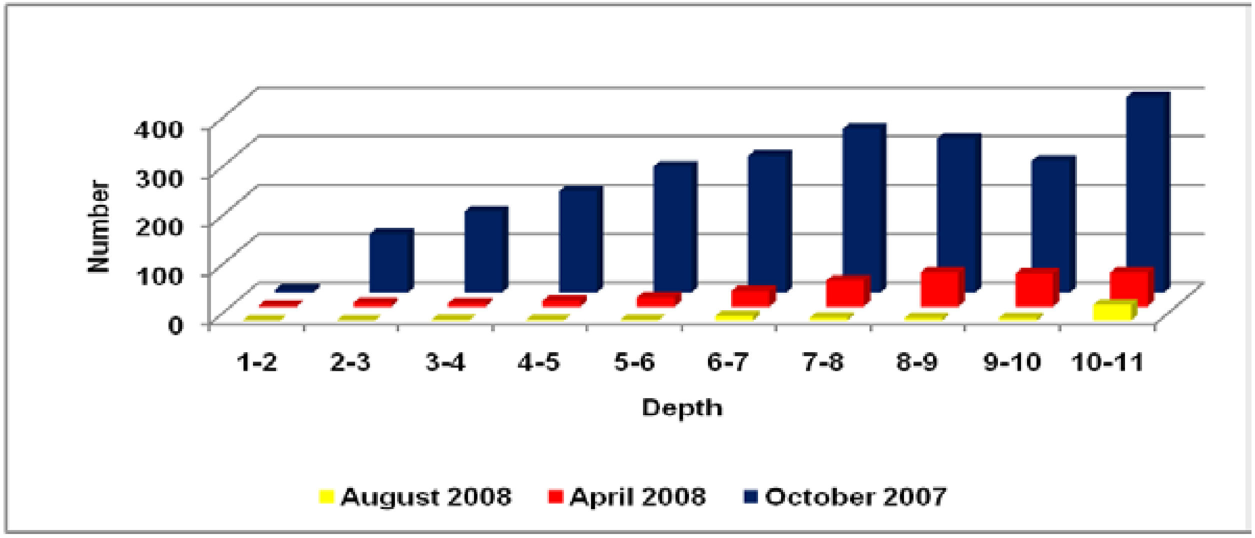

Figure 7. Vertical distribution of non-schooling fish targets at the reference area.

Fish densities. Average fish densities were compared by site between seasons. Fish density was lowest during the spring survey. Peak density was only 1 fish/100 m^3 (726 fish/ha) during the nighttime sampling event at the mound. The remaining three spring sampling events (day-mound and day- and night-reference) exhibited low fish densities ranging from 0.04 fish/100 m^3 (34 fish/ha) to 0.31 fish/100 m^3 (279 fish/ha). Highest individual ESDU density was 6.2 fish/100 m^3. Higher ESDU densities were associated with the northern perimeter side slope and the northeastern quadrant of the mound footprint during the spring survey. Otter trawls taken along the northern perimeter of the mound indicated that bay and dusky anchovies along with scaled sardines were the dominant species captured and thus contributed to the higher densities in this area of the mound during spring sampling.

Fish density increased during the summer survey. Of the four sampling events, lowest density (0.29 fish/100 m^3) occurred at the reference area during the daytime survey. Fish density estimated for the corresponding survey completed at the mound was slightly higher (0.50 fish/100 m^3). Both the mound and reference sites averaged less than 400 fish/ha during daytime summer sampling.

Much of the overall increase in fish density during the summer survey is attributed to the nighttime density estimates. Fish density averaged 2.64 fish/100 m^3 (1,950 fish/ha) at the mound and nearly 5 fish/100 m^3 (4,468 fish/ha) at the reference area. Clarke and Kasul (1994) reported echo-integrated bottom fish density estimates of slightly less than 1,000 fish/ha at the mound during summer sampling. They reported much lower mid-water fish densities at only 173 fish/ha during summer sampling. Highest individual ESDU density was nearly 4 fish/100 m^3 at the mound and slightly more than 9 fish/100 m^3 at the reference area. An examination of acoustic echograms did not reveal evidence of large schools of fishes located in the mid- to deep portions of the water column as were observed during the fall. A few small schools were detected, primarily within the deepest 2 m of the water column. Conventional fisheries data indicated that these targets were primarily harvestfish, small pelagic fishes that are known to occur in schools. Harvestfish accounted for nearly 80% of the summer catches at both the mound and reference area. Density plots showed a nearly uniform spatial distribution of fishes across the area. The majority of ESDU cells had density estimates ranging from 2 to 3 fish/100 m^3.

Highest fish density estimates occurred during the fall. Daytime fish density was estimated to be 11.4 fish/100 m^3 (7,843 fish/ha) at the reference area and 14.2 fish/100 m^3 (10,415 fish/ha) at the mound. Clarke and Kasul (1994) reported fall echo-integrated fish density estimates at nearly 1,000 fish/ha (bottom) and 5,807 fish/ha (mid-water). Higher daytime densities in the current study were influenced greatly by the presence of multiple schools of mid-water fishes associated with the mound crest. The highest overall individual ESDU density occurred during fall daytime sampling (275 fish/100 m^3). Conventional fisheries data suggested that these schools were comprised of Atlantic bumper and bay anchovies. Atlantic bumper is one of the most abundant inshore fishes in the northern Gulf of Mexico and in one otter trawl alone, over 2,000 (CPUE = 6150 fish/trawl hour) Atlantic bumper were captured at the reference area site. The corresponding nighttime surveys had significantly lower ($p<0.05$) overall density of 0.95 fish/100 m^3 (741 fish/ha) at the mound and 1.85 fish/100 m^3 (1,778 fish/ha) at the reference area. Fall was the only season in which daytime fish densities exceeded nighttime densities. The reverse pattern was true during both the spring and summer surveys at both the mound and reference area. Acoustic echograms indicated that fishes tended to be more evenly dispersed during nighttime hours, although a few schools were detected in association with the mound crest. The majority of individual fish targets were located in the lower 2 m of the water column. Likely candidate species include Atlantic croaker and spot as well as red snapper.

At the mound, density estimates for combined sampling events (day and night surveys) produced seasonal density estimates that were lowest in spring (0.56 fish/100m^3), increased in summer (1.82 fish/100m^3), and peaked during fall (7.6 fish/100 m^3). Seasonal density estimates followed the same trend at the reference area, in that lowest density occurred in spring (0.2 fish/100 m^3), followed by summer (2.5 fish/100 m^3), and peaked in fall (6.6 fish/100 m^3). Of the three seasons surveyed, only summer fish densities were higher at the reference area than at the dredged material mound.

Vertical distribution of overall fish density. Vertical distribution patterns were examined by partitioning the water column into three strata: shallow (1-4 m), mid- (4-7 m), and deep (> 7 m) water depths (Table 3). Vertical distribution of fish density was similar in both spring and fall. In three of four sampling events during each season, fish density was highest in the lower depth strata (> 7 m) and decreased with decreasing water depth. A reverse pattern occurred for one sampling event during each season. During the fall, (nighttime survey, reference area) fish density was highest in the shallow water strata (2.44 fish/100 m^3) and decreased with increasing water depth, although mid- (1.93 fish/100 m^3) and deep-water densities (1.61 fish/100 m^3) did not differ greatly. During the spring, the daytime survey of the reference area had highest densities in the shallow strata (0.1 fish/100 m^3) and lowest densities in the mid-water strata (0.002 fish/100 m^3). Fish densities for this sampling event were very low throughout the water column. Vertical distributions of fishes in summer were generally opposite those observed in spring and fall. Density in the shallow strata was higher for three of the four sampling events. The only exception was the nighttime survey of the mound, when fish density (4.06 fish/100 m^3) in the deep-water strata was considerably higher than at both the mid- (1.76 fish/100 m^3) and shallow (1.09 fish/100 m^3) water depths. Location seemed to be a more important factor than time of day (day-night) for sampling events in which shallow-water fish density exceeded deep-water density. Four of five sampling events in which this vertical distribution pattern occurred were at the reference area. Three of the five events occurred during daytime surveys, while the remaining two events occurred at night.

Table 3. Echo-integrated fish density (fish/100 m^3), fish per hectare, and acoustic fish length for all seasonal surveys completed at the dredged material mound and nearby reference area (D = day, N = night, M = mound, R = reference area).

Month	Period	Area	Acoustic Length		Fish Density (Fish/100 m^3)					
			Range (cm)	Average (cm)	Overall (1- 11 m)	SE	Fish/ Hectare	Shallow (1-4 m)	Mid-water (4-7 m)	Deep (> 7 m)
Apr	D	M	5.3-28.7	15.5	0.08	0.01	50	0.002	0.0004	0.17
Apr	D	R	4.8-18.74	10.9	0.04	0.02	34	0.10	0.002	0.03
Apr	N	M	4-102.6	13.7	1.03	0.44	726	0.72	0.96	1.26
Apr	N	R	4.0-30.6	10.6	0.31	0.02	279	0.08	0.13	0.47
Aug	D	M	4.1-78.4	14.1	0.50	0.06	377	0.91	0.07	0.49
Aug	D	R	4.4-96.5	16.8	0.29	0.10	282	0.58	0.04	0.28
Aug	N	M	-	-	2.64	0.22	1950	1.09	1.78	4.06
Aug	N	R	-	-	4.72	1.67	4468	4.87	4.43	4.75
Oct	D	M	4.1-110.9	20.1	14.2	3.73	10415	7.56	14.2	17.8
Oct	D	R	4.1-100.1	19.0	11.4	7.00	7843	3.82	5.18	16.7
Oct	N	M	4.0-79.7	12.3	0.95	0.15	741	0.67	0.87	1.14
Oct	N	R	4.0-95.6	10.2	1.85	0.42	1778	2.44	1.93	1.61

Statistical analysis. Using GLZ techniques (Table 4), the analysis indicates that the interaction terms of site by date (X^2 = 5.911, p-value = 0.0521) and site by time (X^2 = 2.150, p-value = 0.1326) are not significant. Therefore inferences about the main effect of site can be directly interpreted. The data indicate that the CPUE characteristics were similar between the two sites (X^2 = 1.373, p-value 0.2413). The expected CPUE means were 2.991 and 3.107 fish per 100 m^3, respectively, for the sites. Time of sampling (season) did result in a significant change in CPUE characteristics (X^2 = 39.030, p-value < 0.0001). However, the interaction of time and date confounded the interpretation of this main effect.

A significant interaction between date and time (X^2=1414.880, p-value < 0.001) indicated that the magnitude of the differences between the levels of one factor changed with the second factor. Hence, further analysis of the cell means (Table 5) was warranted. This analysis indicated that fish densities during night sampling during the months of April and August were significantly higher than fish densities during daytime sampling (X^2 = 28.110, p-value < 0.0001 and X^2 =184.962, p-value < 0.0001, respectively). During October, the fish density estimates for nighttime surveys were significantly smaller than daytime fish density estimates (X^2 = 863.652, p-value<0.0001). Expected means are summarized in Table 6.

Table 4. Summary of statistical effects tests.

Source	DF	L-R ChiSquare	Prob>ChiSq
Site	1	1.373	0.2413
Date	2	842.086	<.0001
Site*Date	2	5.911	0.0521
Time	1	39.030	<.0001
Site*Time	1	2.150	0.1426
Date*Time	2	1414.880	<.0001
Site*Date*Time of Day	2	2.415	0.2990

Table 5. Summary of contrast effects.

Level	Contrast-1	Contrast-2	Contrast-3
Date*Time of Day[Apr 08,Day]	1	0	0
Date*Time of Day[Apr 08,Night]	-1	0	0
Date*Time of Day[Aug 08,Day]	0	1	0
Date*Time of Day[Aug 08,Night]	0	-1	0
Date*Time of Day[Oct 07,Day]	0	0	1
Date*Time of Day[Oct 07,Night]	0	0	-1
Value	-2.441	-2.255	2.274
Std Error	0.460	0.166	0.0774
ChiSquare	28.110	184.962	863.652
Prob>ChiSq	<0.0001	<0.0001	<0.0001

Table 6. Summary of three factor cell means.

Site	Date	Time of Day	Expected CPUE Mean
Mound	Apr 08	Day	0.0575
Mound	Apr 08	Night	0.9244
Mound	Aug 08	Day	0.4769
Mound	Aug 08	Night	2.6522
Mound	Oct 07	Day	14.7620
Mound	Oct 07	Night	0.9513
Ref	Apr 08	Day	0.0371
Ref	Apr 08	Night	0.3051
Ref	Aug 08	Day	0.2903
Ref	Aug 08	Night	4.7432
Ref	Oct 07	Day	11.1601
Ref	Oct 07	Night	1.8345

Discussion. This study evaluated the effectiveness of an offshore dredged material mound in terms of providing habitat functions for fishery resources. In this particular case, the dredged material mound was not originally designed with the intent of achieving a benefit to fishery resources. Instead material placement was dictated primarily by operational considerations such as long-term site management in terms of capacity, type of sediment to be placed, and scheduling concerns. Viewed from a fishery perspective, the resultant mound has several characteristics (e.g., side slopes, height above natural bottom) that mimic an artificial reef. Although the term “reef” is typically applied to a structure comprised of hard material such as rock, many bathymetric features that interrupt otherwise flat seabed terrains have been shown to attract fishes. Natural rock, if available, is often favored due to its durability and rapid colonization by benthic flora and fauna. One key difference between dredged material mounds and hard material reefs would be the lack of interstitial spaces afforded by the dredged material mound. Fish assemblage diversity and abundance might be limited by availability of shelter interstices (Alevison and Brooks 1975). Another notable difference is that dredged material mounds differ from most forms of artificial reef construction with respect to spatial scale. The mound in the current study represents one of the largest bathymetric features constructed in offshore waters, measuring 2.4 km x 1.2 km (1.5 x 0.75 miles) with a vertical lift of 7.6 m (25 ft). The mound, therefore, has a very large footprint when compared to most artificial reef structures.

Results of conventional netting and acoustic fisheries indicated that both the dredged material mound and nearby reference area were seasonally occupied by a fishery resource assemblage typical of the northern Gulf of Mexico continental shelf. Inspection of individual echograms of transects across the mound yielded evidence of associations between mid-water fishes and the mound crests (Figure 8). 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 a 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. Otter trawl catches contained fairly large numbers of bay and dusky anchovies, planktivores that would benefit from accumulating plankton in the shed eddies. Clarke and Kasul (1994) also reported attraction of mid-water fishes to the dredged material mound crests in the mid-1990's.

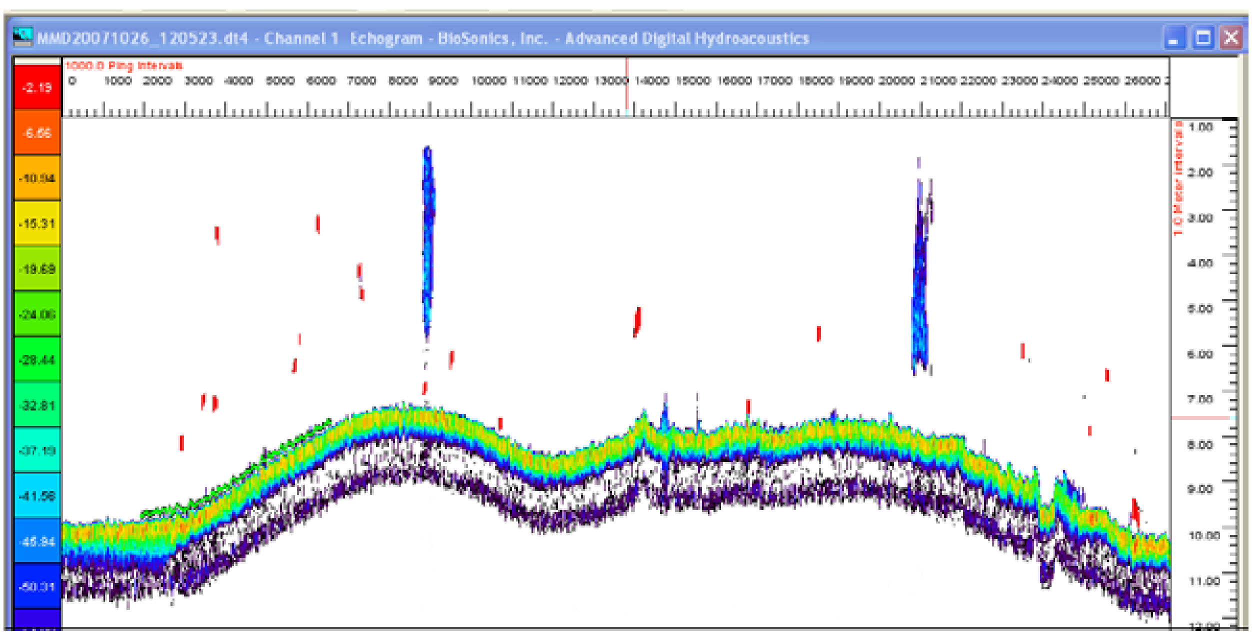

Figure 8. Example fisheries echogram showing schools of mid-water fishes associated with the mound crest.

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 echograms show the presence of schooling fishes on the leeward side of the mound in the lower depth strata (Figure 9). Bottom trawls along the toe of the side slope of the dredged material mound indicated that these fishes are likely benthic feeding fishes such as Atlantic croaker and threadfin, which typically are found in scattered to dense schools.

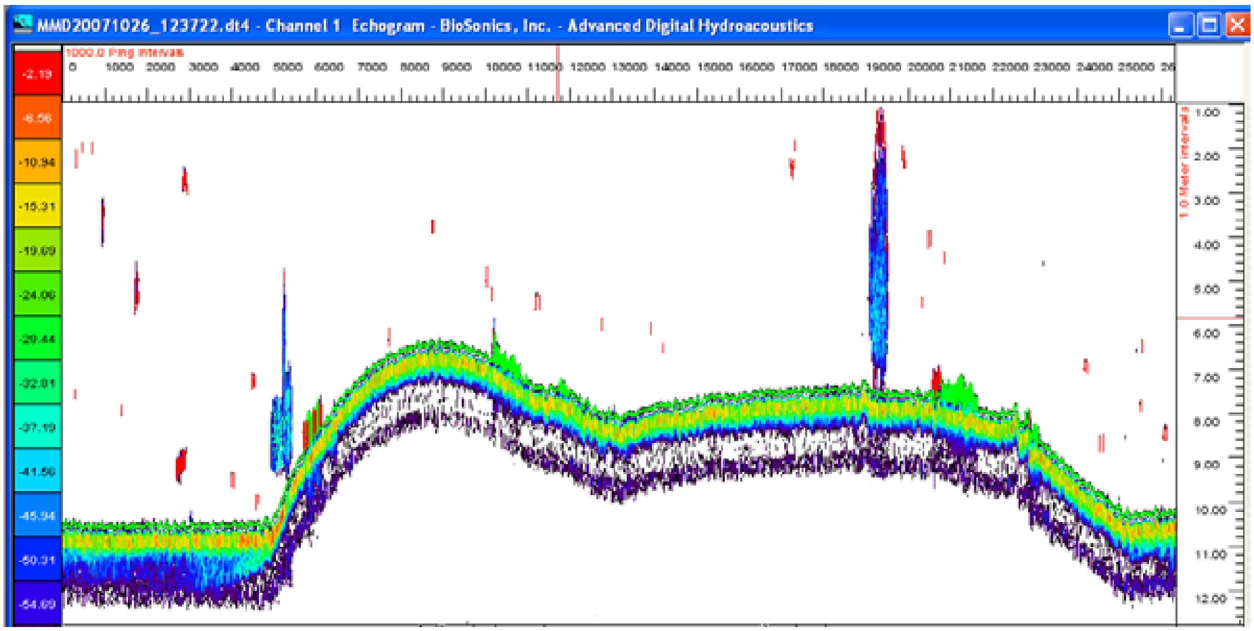

Figure 9. Example fisheries echogram showing a school of fish in the lower water column on the leeward side (left side of echogram) of the mound.

In terms of species composition, the fishery assemblage did not differ greatly between the mound and reference area. Twenty-three species were caught in otter trawls at both sites. Of these, six species were exclusive to the mound. At the mound, demersal fishes such as the Atlantic threadfin and sand seatrout were collected during spring and summer surveys, whereas spadefish and lane and mutton snapper were caught at the mound only during the fall. Notably absent from the mound during the fall was spot, which was captured, albeit in low numbers, at the reference area. Trawl catches at the reference area included six species not taken at the mound. These included small numbers of benthic fishes such as Gulf flounder and bank sea bass. A comparison of otter trawl catches obtained in the present study to those reported by Clarke and Kasul (1994) indicated little overall difference in species assemblages.

Although no significant difference in fish density was found between the dredged material mound and a nearby reference area, the mound did support several fish species known to inhabit natural or artificial reefs, particularly red snapper. The diverse assemblage of demersal fishes present across seasons indicated that the mound provided an excellent source of benthic habitat. The presence of high CPUE pelagic species (e.g., Atlantic bumper, harvestfish, and bay anchovies) in mid-water schools associated with the mound crest indicated that the structure served as an attractant to these fish species, possibly as a result of a lee wave phenomenon. Schooling fishes associated with the mound crest and portions of the lower side slopes of the dredged material mound give some indication of the presence of shed eddies and current shadows. The mound does appear to have attributes of an artificial reef, with no evidence of loss of pre-existing fish habitat functions.

The vast majority of dredged material by volume produced annually consists of sand, clay, and silt that satisfy regulatory criteria as clean, uncontaminated sediment. If even a fraction of these sediments can be used successfully in the construction or restoration of essential fish habitat, numerous opportunities to derive fishery resource benefits could be identified. Rather than considering designated open-water placement sites as open-ended receptacles simply for storage of a navigation project byproduct, it should be feasible to design placement sites to accommodate fishery habitat functions. Such functions can be derived not only as the site receives dredged material on an intermittent basis, but also as the final configuration of a site that reaches full capacity. The functional value of future dredged material mounds as Essential Fish Habitat may be optimized by consideration of design features such as location, height, side slope, footprint, configuration, and orientation to prevailing water currents.

Acknowledgments

The authors thank Dr. Gary Ray and Dr. Dale Magoun for providing guidance in statistical analysis of the fisheries hydroacoustic data. They also thank the captains and crew members of the R/V *A. E. Verrill* from the Dauphin Island Sea Lab for their cooperation and support of the field activities.

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> Reine, K. J., D. Clarke, and C. Dickerson. 2012. *Fishery resource use of an offshore dredged material mound*. DOER Technical Notes Collection (ERDC TN DOER-E31), Vicksburg, MS: U.S. Army Engineer Research and Development Center.

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