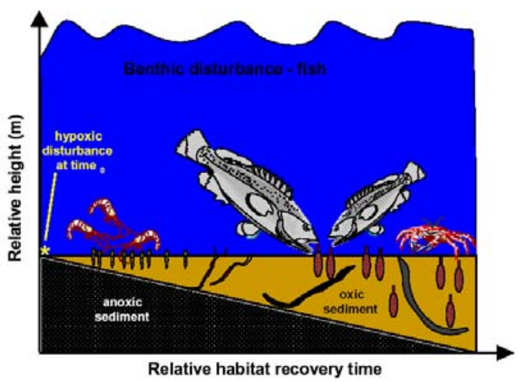
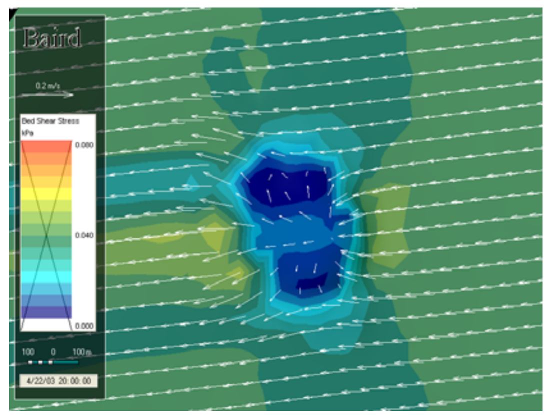
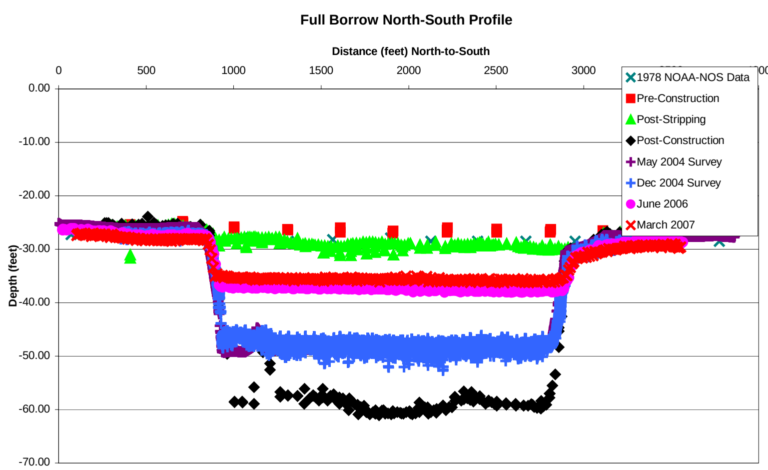
OCS STUDY
MMS 2007-048

EXAMINATION OF THE PHYSICAL AND BIOLOGICAL IMPLICATIONS OF USING BURIED CHANNEL DEPOSITS AND OTHER NON-TOPOGRAPHIC OFFSHORE FEATURES AS BEACH NOURISHMENT MATERIAL







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MMS U.S. Department of the Interior
Minerals Management Service

An Examination of the Physical and Biological Implications of Using Buried Channel Deposits and Other Non-Topographic Offshore Features as Beach Nourishment Material

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1.0 INTRODUCTION

1.1 Background

The Minerals Management Service (MMS), a bureau within the U.S. Department of the Interior, has jurisdiction over all mineral resources on the Outer Continental Shelf (OCS). Public Law 103-426, enacted October 31, 1994, gave the MMS the authority to convey, on a noncompetitive basis, the rights to OCS sand, gravel, or shell resources for shore protection, beach or wetlands restoration projects, or for use in construction projects funded in whole or part or authorized by the Federal Government. Since enactment of PL 103-426, MMS has provided Federal sand for beach nourishment projects in Maryland, Virginia, Florida, South Carolina, and Louisiana. Details on the MMS Sand and Gravel Program can be found on the Internet at http://www.mms.gov/sandandgravel/.

Areas that are dredged on the OCS generally fall into two geomorphic categories:

1. Shoals, banks and other topographic features that rise above the surrounding sea bed;

2. Non-topographic features consisting of either sand sheets or plains or buried channels.

The focus of this assessment relates to the second geomorphic category. Dredging non-topographic features will necessarily result in the creation of a dredge pit; therefore, this examination will consider the physical and biological impacts of dredging pits on the OCS.

At the writing of this report there has been one previous example of a dredge pit in order to access sand from a buried channel in OCS waters for beach nourishment (Holly Beach dredge pit for the Holly Beach Restoration Project in Cameron Parish, Louisiana in 2003), and one upcoming project (Sandy Point Dredge Pit off the west flank of the Mississippi River delta for the Coastal Wetlands Protection & Restoration Act (CWPRA) Pelican Island Restoration Project, which is being funded and managed by NOAA's Habitat and Conservation Division).

An initial investigation of the potential physical impacts of dredge pits on oil and gas infrastructure in the Gulf of Mexico was completed under OCS Study MMS 2005-043 "A Study to Address the Issue of Seafloor Stability and the Impact on Oil and Gas Infrastructure in the Gulf of Mexico" – see Nairn *et al*. (2005). This study completed an assessment of the background on the physical impacts of pits and the environmental conditions along the Gulf of Mexico shore. This current study will summarize but not repeat the background review completed in the aforementioned report written by Nairn *et al*. (2005).

Presently there are no established guidelines or rules to regulate the dredging of pits and manage the physical and biological impacts, with the exception of those presented in Nairn *et al*. (2005) for protecting oil and gas infrastructure located nearby dredge pits.

1.2 Project Goal and Objectives

The goal of this study is to develop an improved understanding of the physical and biological impacts of dredge pits and to provide a basis for the management of sand and gravel resources of the OCS along the Gulf of Mexico and Atlantic Coasts, specifically dredge pits.

The following are a list of the key objectives:

1. Define and describe the key physical, biological and biophysical impacts of dredge pits;

2. Provide recommendations on guidelines for approaches to evaluating the significance of these key impacts;

3. Develop recommendations for mitigation of impacts associated with dredge pits.

The following scientific questions will be addressed in order to achieve the listed objectives:

1. How do dredge pits in different settings evolve with time? In other words, how do the pit slopes adjust - do they migrate (and if so, at what rate), and at what rate do they fill in?

2. How do dredge pits influence waves that reach the shoreline?

3. What are the biological impacts of dredging buried channel sand deposits and other topographically negative features?

1.3 Study Approach

The project approach was comprised of the following five main areas of activities:

1. The first area of work consisted of collection and review of the literature and background information on this topic. This included collection of information on geological and environmental conditions for the Gulf of Mexico and Atlantic Coasts of the US to identify representative conditions for non-topographic features on the OCS of those coasts. Previous work on the physical and biological impacts of dredge pits in the US and

overseas was also reviewed. Much of the review of physical impacts was completed by Nairn *et al*. (2005) under OCS Study MMS 2005-043.

2. Field measurements and sampling at the Holly Beach dredge pit to define physical and biological conditions and impacts;

3. Analysis of the physical changes and impacts at the Holly Beach dredge pit including numerical modeling of waves, hydrodynamics, sediment transport and morphologic change;

4. Analysis of impacts to benthos and fish for the Holly Beach dredge pit;

5. Development of generic guidelines to mitigate the impacts of dredge pits for non-topographic features.

1.4 Team Organization

The team organization consisted of the following key personnel fulfilling the listed roles:

- Robert B. Nairn, Ph.D., P.Eng., Baird & Associates
  Principal Investigator and Primary Author of the final report

- Qimiao Lu, Ph.D., Baird & Associates
  Senior Numerical Modeler and Analyst

- Steve Langendyk, BES, Baird & Associates
  Senior GIS Analyst

- Michael J. Risk, Ph.D., Baird & Associates
  Marine Ecologist

- Phil Hanley, Environmental and GIS Consultants
  Hydrographic Surveyor

- Jacqueline Michel, Ph.D., Research Planning, Inc.
  Resource Specialist

- Miles Hayes, Ph.D., Research Planning Inc.

  Coastal Geomorphologist (Atlantic Coast), contributed to Sections 2.1 and 2.1.3 of the final report.

- Mark Kulp, Ph.D., U. of New Orleans

  Coastal Geomorphologist (Louisiana Coast), contributed to Section 2.1.2 of the final report.

- John Anderson, Ph.D., Rice University

  Coastal Geomorphologist (Texas Coast), contributed to Section 2.1.1 of the final report.

- Paul Montagna, Ph.D. (Texas A&M Corpus Christi, formerly with Marine Science Institute of the University of Texas)

  Benthic Ecologist, contributed to Sections 2.5.1, 3.1.4 and 3.2.3 of the final report.

- Terry A. Palmer, Ph.D., Harte Research Institute for Gulf of Mexico Studies, Texas A&M Corpus Christi

  Benthic Ecologist, contributed to Sections 2.5.1, 3.1.4 and 3.2.3 of the final report.

- Sean Powers, Ph.D., Dauphin Island Sea Lab, Alabama

  Fish Ecologist, contributed to Section 2.5, 3.2.3 and 3.2.4 of the final report.

1.5 Report Structure

The remainder of the report is subdivided into the following sections:

2.0 Review of Background Information on Dredge Pits

3.0 Holly Beach Dredge Pit Case Study Analysis

4.0 Synthesis of Findings and Recommendations

5.0 Guidelines for Evaluating and Mitigating Impacts of Dredge Pits

6.0 References Cited

2.0 REVIEW OF BACKGROUND INFORMATION ASSEMBLED FOR THE INVESTIGATION OF BURIED CHANNELS AND DREDGE PITS

This section provides a summary of the background information assembled and reviewed in support of this investigation. Section 2.1 provides a summary of three investigations into the existence and characteristics of buried channels along the coasts of Texas, Louisiana, and the Atlantic coast. Section 2.2 provides a summary of the environmental conditions with a focus on the Louisiana coast where the one existing dredge pit is located and another future location is planned. Section 2.3 provides a discussion of likely dredging equipment and techniques that will be applied to dredge sand from buried channels and other non-topographic features. Section 2.4 provides an overview of the background literature on the physical impacts of dredging and Section 2.5 discusses the biological impacts. Finally, Section 2.6 provides a summary of guidelines for regulating dredge pits in offshore areas from other countries.

2.1 Geology, Geomorphology, and Buried Paleo-Channels

The primary focus of this investigation is on buried paleo-channels, perhaps more appropriately referred to as lowstand valley fills, because in most cases they would have originally been created at lower sea level stands. For the purposes of this report these shall be referred to as “buried channels”. This class of geomorphic feature almost always has a muddy cap over the buried sand that is suitable for beach nourishment. Therefore, pits must be excavated to: 1) strip the unsuitable fine sediment; and 2) remove the required sand material. The report will also address pits generated through dredging non-topographic sandy features, although to a lesser degree owing to the fact these features have not been identified as potential OCS borrow deposits to date.

The purpose of this initial geologic and geomorphic review was to evaluate the characteristics of buried channels along the OCS of the Gulf of Mexico and Atlantic Ocean coasts.

An overview of the formation and evolution of lowstand valley sequences by M.O. Hayes is provided from Appendix A.1. A typical mid- to large-scale lowstand valley forms by the downward erosion or incision of a rejuvenated valley system caused by the lowering of the outlet or base level of the river. The greatest lowering of base level along the Gulf and Atlantic continental shelves occurred during the Pleistocene glaciations when sea level fell by several hundred feet. A key point here is that many of the valleys were eroded during at least four different glaciations when the sea level was lowered significantly. After the first glaciation, the valley became filled with sediments as the sea level rose. During the next lowering of the sea, some of that sediment may have been preserved. This process could have been repeated as many as three more times. Therefore, it is possible that the sandy sediments now preserved within a single valley could have been deposited during up to four different time intervals (highstands), making the final preserved sand “target” fairly complicated.

During the development of a conceptual model for lowstand valleys as presented in Appendix A.1 by Hayes, two primary classes of lowstand valleys were identified: those associated with upland or mountainous rivers and those associated with lowland or coastal plain rivers. The noted distinction between these two would be that the majority of the watershed exists within a steep upland zone or a flatter coastal plain zone. The coastal plain rivers lacked the supply of sandy sediment and were mostly filled with muddy sediments with few isolated sandy point bars, if any. Therefore, the coastal plain lowstand valleys would not be suitable targets for beach nourishment sand. A possible exception where lowstand valleys of coastal plains could yield suitable sand would be locations where tidal inlets formed and deposited sandy sediment.

On the other hand, lowstand valleys of upland rivers should be excellent targets for exploration for sand. The following sequence of events gives rise to present day conditions associated with these formations:

1. When sea level is low (during one of the glaciations), a valley as much as 100 ft deep was carved. Very little sediment carried by the river was deposited and retained during this initial valley incision period.

2. With the early rise of sea level, the river located within the valley begins to aggrade a flood plain. If the stream were braided in this earlier phase, a sheet-like deposit of coarse-grained sediments would fill the lower portions of the valley. Because of the steep gradient of the stream, fine sediment would be carried further seaward.

3. As the stream developed a flatter gradient later in the episode of rising sea level, the stream channel may have been meandering, in which case the sand would be deposited in the form of point bars that may not be as laterally continuous as the braided stream deposits; therefore, there would be some fine-grained sediment associated with the point bars. Also, the point bar deposits being distributed discontinuously along the river course would be more difficult to find.

4. The first two stages of sea level lowering and incision, followed by rise and deposition of finer sediment, would have been repeated for at least four glaciations for most rivers.

5. As the valley filled and the stream gradient decreased even more, extensive, muddy, flood-plain sediment would be present within the valley.

6. A possible last stage would have been the flooding of the valley with marine waters, forming an estuary resulting in the deposition of abundant estuarine mud.

7. As the sea level continued to rise, the so-called “ravinement surface” advanced landward, and some of the sediments higher up in the upper valley fill would have been eroded away. However, any valleys deeper than about 30 ft (the maximum depth of ravinement erosion) would retain some of the sediment even after the shoreline had passed further landward. The question is – how much of the finer-grained sediment in the upper valley fill will be eroded away during the process of landward migration of the ravinement surface?

This evolution process is described in more detail for Atlantic Coast rivers and lowstand valleys in Appendix A.1. A brief summary of the conceptual models for coastal plain and upland rivers and their application to the Texas, Louisiana and Atlantic coasts in terms of the likelihood of lowstand valley deposits providing feasible targets for beach nourishment sand is provided below.

There are many similarities between the lowstand valleys of Texas and those along the southeast and east-central shoreline of the Atlantic Ocean. Lowstand valleys created by rivers with watersheds restricted mostly to the coastal plain regions, such as the Nueces and Lavaca Rivers in Texas and the Edisto, Black and Ashepoo Rivers in South Carolina, have a paucity of sandy sediments that are usually restricted to the bottom of the valleys. These sandy sediments have a thick cap of flood plain and estuarine mud deposits. River deltas that project out onto the continental shelf are absent in these coastal plain river systems.

Lowstand valleys created by rivers with watersheds that extend into uplands well beyond the confines of the coastal plain have abundant sandy sediments deposited by braided and meandering streams. The mud caps over these sands are considerably thinner than those for the valleys formed by coastal plain rivers mostly due to the thickness of the sand deposits in the valley fills. All of the major river systems that created these types of valleys have river delta complexes that project out onto the continental shelf (e.g., Santee/Pee Dee, Savannah and Altamaha Rivers in the Georgia Bight and the Rio Grande, Brazos and Colorado River in Texas). Furthermore, abandoned delta lobes formed during stillstands in the period of sea level rise have been deposited in places on the continental shelf by these rivers. According to Anderson (Appendix A.2), the entire central continental shelf of Texas is covered by a relatively thick mud drape up to 130 ft. (40 m) thick, which is referred to the Texas mud blanket. Such thick mud deposits are not present on the continental shelf off the east coast.

Lowstand valleys in the Mississippi Delta Region and along the New England coasts are not analogous to the valleys of the rest of the east and Gulf coast of the USA, because of the downwarping of the shelf in the Mississippi Delta area and the effects of glacial deposits and glacial rebound on the New England coast.

The lowstand valleys that represent feasible borrow deposits (i.e. that have a relatively thin mud cap) will exhibit the following characteristics:

1. Valleys of rivers that have a significant supply of sand-and-gravel and are usually associated with watersheds that feature a significant upland zone;

2. The overlying mud deposit is relatively thin (less than approximately 10 ft) due to: a higher elevation sandy deposit; through erosion of the overlying mud during the transgression of the ravinement surface; due to tectonic uplift of a deposit; and/or due to a locally low mud or sand supply to the OCS;

3. Places where inlets or deltas have been present along old shoreline trends out on the shelf. Those inlets that occurred where the valleys intersected the shoreline should have filled in the upper part of the valley with sand. This should be true even for valleys made by rivers with a meager sand supply, because the sand in the inlet fill most likely was derived from longshore sand transport.

One of the original objectives of this geologic review was to provide some indication of the configuration of buried channel deposits and the range of likely muddy cap thickness. Two key findings of the review render this degree of generalization impossible:

1. Due to the multiple glaciations and repeated deposition-erosion-deposition the stratigraphy of these lowstand valley deposits are very complicated;

2. In most instances the level of detail required in terms of geophysical data and interpretation of that data is simply not available to resolve the complexity noted under (1) to provide generalized dimensions, even if they were possible.

Nevertheless the geologic review completed in support of this study has provided several important findings that will assist in the search for, and evaluation of, beach nourishment sand from OCS buried channels. Generally, the best targets will be associated with lowstand valleys of mountainous rivers and to a lesser degree, old deltas and tidal inlets. The muddy cap thickness for many locations on the Atlantic and Texas coasts are simply too thick to make the deposits feasible for beach nourishment. The muddy cap thickness will decrease in an offshore direction owing the transgression of the sloping ravinement surface.

2.1.1 Texas

Dr. John Anderson of Rice University, along with his co-workers, completed a review of the buried channels along the Texas coast in support of the overall assessment of buried channel characteristics on the OCS. The complete report is provided in Appendix A.2.

The report identified several low-stand fluvial valleys including the Rio Grande, Nueces, Lavaca, Colorado, Brazos, Trinity,and Sabine, as illustrated in Figure 2.1.

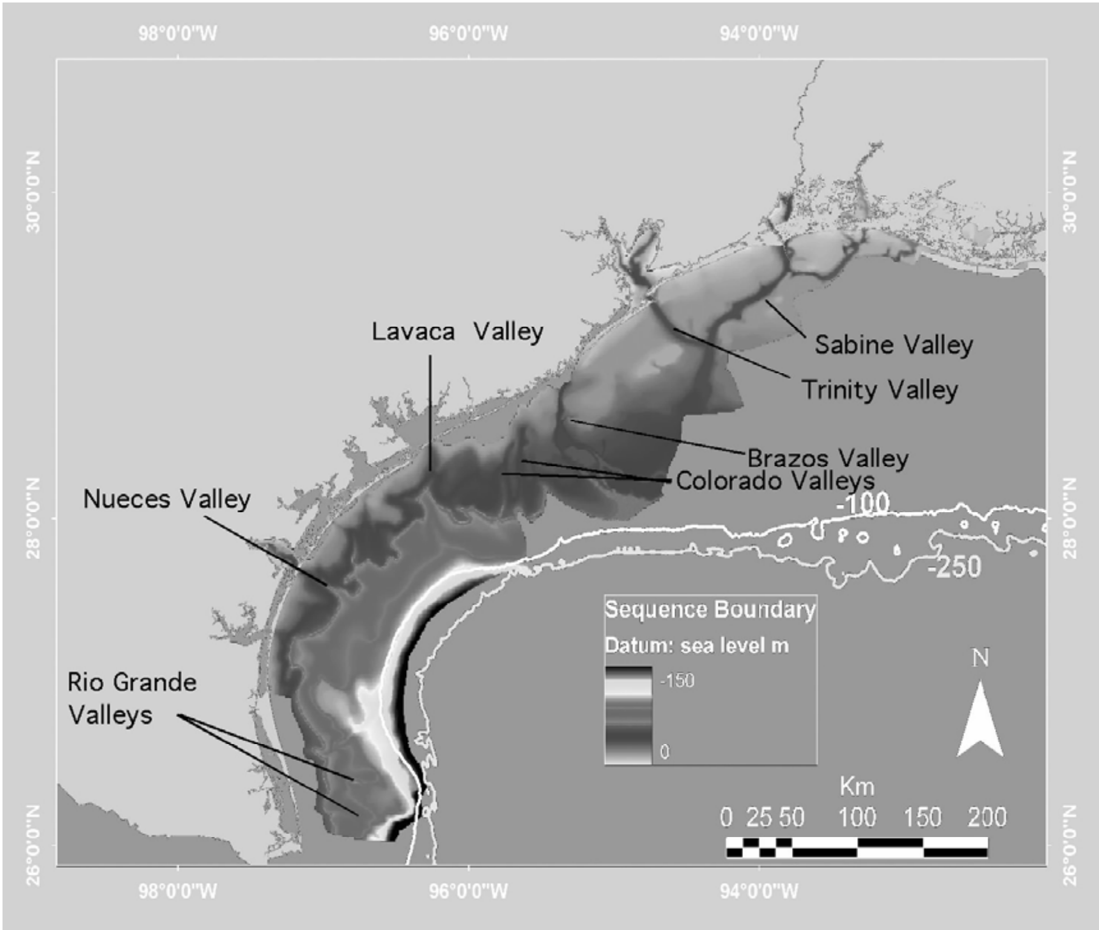

Figure 2.1. Digital Elevation Map Showing Lowstand Fluvial Channels (from Simms *et al.*, in press)

Existing information suggests that the fluvial sands of the Sabine and Trinity Valleys are capped with 30 to 60 ft (10 to 20 m) of marine and bay mud, implying that for the time being these are not economical sources of sand (owing to the extent of stripping that would be required). The Trinity and Sabine Rivers would fall somewhere between the upland and coastal plain classifications, though the coastal plain influence is greater, and thus would be expected to have minimal sand fill in the valleys and thick mud deposits. However, there are some areas in the Trinity Valley that are inlet and delta deposits that are within a few yards or meters of the seafloor (see Figure 5 in Appendix A.1) – and these deposits would have been created during lower stillstands in sea level

Based on the available limited information, the Brazos and Colorado Valleys have a cover of only a few meters of mud over fluvial sand. These deposits correspond to a valley fill associated with an upland river. The Colorado River also created a sizeable delta in 60 to 90 ft (20 to 30 m) of water approximately 15 to 30 miles (25 to 50 km) offshore, and this sandy feature is at or very near the seabed surface. This fits with the conceptual model case of a delta formed at a lower stillstand of sea level.

The Nueces Valley is only one of several along the Central Texas coast that has been surveyed and sampled and it has been found to have up to 80 ft (25 m) of bay and marine mud cover, suggesting it may not be economical for dredging as a borrow deposit. This river would fall under the coastal plain category and therefore is not expected to feature thick or continuous sand sources.

Two valleys along the ancestral Rio Grande River on the south coast of Texas have been mapped with seismic data but have not yet been sampled for grain size. The seismic information indicates the sand is within a few yards or meters of the seafloor.

The Anderson report in Appendix A.2 also provides a brief description of the only other sand deposits along the Texas coast: the larger Sabine and Heald Banks, and the smaller Shepard and Thomas Banks. All of these occur along the east Texas shelf; there are no bank deposits along the central and southwest sections of the Texas coast.

2.1.2 Louisiana

Dr. Mark Kulp of the University of New Orleans completed an evaluation of buried channels and sand deposits for the Louisiana coast; the report is provided in Appendix A.3.

During the Wisconsin sea level fall the most prominent incision across the Louisiana continental shelf resulted from the basinward extension of the Mississippi River alluvial valley to the shelf edge at the head of the Mississippi Canyon. However, this main valley channel is covered by 90 ft (30 m) or more of muddy sediment. The Mississippi River does not fit into the two main classifications of coastal plain and upland rivers owing to the size and heavy sand load carried by the river on the one hand (i.e. it is more like an upland river in terms of sand supply) and on the other, it exists within a zone of downwarping or subsidence resulting from the large delta.

There are also many fluvial channels across the western Chenier Plain of Louisiana resulting from lowstand valley fills. In the conceptual model of Hayes these would be associated with a coastal plain situation and would not usually be a good source for beach nourishment sand. However, one of these is the Peveto Channel on the OCS that was used as nourishment for the Holly Beach project; the resulting dredge pit is investigated in much greater detail in Section 3 of this report. The Peveto Channel deposit featured a mud cap thickness of 1 to 5 ft (0.3 to 1.5 m), and it is likely that this deposit was associated with a tidal inlet created at a lower sea level.

Another regional investigation was completed for the shoreline along Barataria Bight. The buried channels in this area are associated with fluvial progradation and delta lobe deposition with the Holocene. One of the deposits identified as part of this work was the Sandy Point borrow area, which is proposed as the source of sand for the CWPRA

Pelican Island Restoration project. The mud cap thickness of the Sandy Point borrow areas is approximately 8 ft (2.5 m).

2.1.3 Atlantic Coast

Dr. Miles Hayes of Research Planning, Inc. completed an assessment of the literature on low-stand valleys along the Atlantic Coast of the US and the full report is presented in Appendix A.1.

The following summary statements were provided for each of the States along the Atlantic seaboard from Florida to New Jersey:

> **Florida (Atlantic Coast):** This shoreline is not very relevant to the present study, because of the relative lack of mountainous relief and the lack of major river systems and associated lowstand valleys. The so-called sand sheets and plains may be present. No studies of lowstand valleys along the east coast of Florida were identified.
>
> **Georgia:** Although the presence of lowstand valleys has been established through previous work, there is no detail available on their sedimentary fill. The so-called sand sheets are probably not relevant either, because of the dominance of ebb deltas, etc.
>
> **South Carolina:** There is significant information available on lowstand valleys for this coast and this is presented together with maps of the deposit locations in Appendix A.1. Seven paleo-channel groups have been identified that are associated with the upland or mountainous Pee Dee River along the northern third of the SC coast. The valley fills offshore Myrtle Beach are the most northerly of this group and are likely a good target for sand for beach nourishment, because of the abundance of seismic and boring data on the these deposits. Also, the valley sediment has been used at least twice before for nourishment at Myrtle Beach.
>
> The mud cap for the northerly deposits of this group is quite thin (a few feet thick) due to: 1) the possible long-term uplift of Cape Fear; 2) the abundance of sandy sediment in the upland or mountainous Pee Dee; and 3) the general lack of supply of muddy sediment along this section of the SC coast.
>
> **North Carolina:** Although significant information and maps of lowstand valleys for this coast are presented in Appendix A.1, it is yet unclear whether there are any feasible deposits. The Roanoke/Albemarle Valley Fill near Kitty Hawk is probably not one of the better places to look for beach nourishment sand, unless tidal-inlet sand deposits are present. Boss and Hoffman (2001) state clearly that the valley sediments that they cored are "mud-prone." Their explanation of this fact is that "these sediments formed primarily as back-filling estuarine deposits during transgressions," a process

associated with the valley fill for coastal plain rivers. The mud cap for this deposit is at least 15 feet (3 m) thick and possibly much thicker.

The features off Wrightsville Beach, referred to as “quaternary fluvial channels” by Thieler *et al.* (2001), are as much as 30 to 60 feet (10 to 20 m) deep. Whereas a considerable amount of data was collected on the shoreface sediments in that area, some of which were of beach-nourishment quality, the valley sediments were not cored to any significant depth. Therefore, it is not clear if they are mud-filled or not.

It is unknown at this time how many valleys on the OCS of North Carolina have relatively thick mud caps like the major one off Kitty Hawk. The potential for abundant sand within mud-prone lowstand valleys would be greatly increased if: 1) the ravinement surface has eroded away the mud; or 2) processes, such as ridge-and-swale topography on the shelf or tidal-inlet sedimentation within the valley, have formed some sand deposits that either bury the valley fill or partly fill in the valley (in the case of tidal-inlet fill).

Virginia: Maps and descriptions of the lowstand valleys associated with Chesapeake Bay are provided in Appendix A.1. Despite the potential for beach nourishment sand to be present in the extensions of these lowstand valleys to the OCS of Virginia, it is not possible to give exact numbers on the thickness of the mud cap of these deposits because of their complex nature and paucity of geophysical data. The complexity of the deposits is caused, at least in part, by their association with an ancestral Chesapeake Bay entrance area.

Maryland: This shelf appears to be similar to Virginia and New Jersey; therefore, the muddy sediment cover over these lowstand valleys is probably too thick to be practical for dredging.

Delaware: A discussion of lowstand valleys and associated maps are presented in Appendix A.1. The sand and gravel appears to be too deep in the Delaware lowstand valleys to be a good source of sediment for beach nourishment. This probably means that the linear sand ridges and ebb-tidal delta sediments have completely buried and covered the valleys to such an extent that the valley sediment would not be a feasible source for beach nourishment sand. This observation illustrates the importance of the erosional nature of the shelf in question. If the shelf is highly eroded and there is little sandy shelf sediment available, such as linear sand ridges and abandoned ebb-tidal deltas, then the lowstand valley sediment may become a meaningful source of beach-nourishment sand. This does not appear to be the case on the Delaware OCS.

New Jersey: Limited information and maps on lowstand valleys for New Jersey are presented in Appendix A.1. In summary, the lowstand valleys do not appear to be a premier source of sand for beach nourishment on the New Jersey OCS (unless they contain tidal-inlet fill) due to the likely thick muddy cap deposits. Also, the lowstand valleys, where they exist, may be covered with excellent quality sand in the form of the linear sand ridges.

2.2 Environmental Conditions

A large body of spatial and temporal information on the central Gulf coast conditions (i.e. covering the area from the Mississippi River to the Texas/Louisiana border) was obtained and assembled in support of the Nairn *et al*. (2005) assessment of the potential impact of dredge pits on oil and gas infrastructure. This data included:

- Pipeline infrastructure;
- Federal lease blocks;
- Recent and historic bathymetry;
- MODIS satellite images giving qualitative estimates of suspended sediment levels;
- Mobile Bar Channel bathymetry data;
- Delray Beach dredge pit data;
- Nile River LNG dredged channel sedimentation data;
- Gulf of Mexico bed sediment data;
- River flow and sediment load from the Mississippi River from US Geological Survey (USGS) gages;
- Climatology, waves, tides, and sediment load from two WAVCIS stations (maintained by Louisiana State University) and the NOAA NDBC stations;
- Tide level and current information from the US Army Corps of Engineers (USACE) ADCIRC model;
- Currents and surface temperature from the Navy Coastal Ocean Model (NCOM), Naval Research Laboratory;
- Total suspended sediment sampling results from NOAA cruise survey reports.

Data that were assembled for this investigation included updates to meteorological and oceanographic measurements in the vicinity of the Holly Beach Dredge Pit. One of the areas of focus on updating local oceanographic information was related to the passage of Hurricane Rita. The right front quadrant of Hurricane Rita passed directly over the Holly Beach Dredge Pit in September 2005 between our December 2004 and June 2006 surveys of the pit (see Figure 2.2). The June 2006 survey was delayed because of Hurricane Rita as it knocked out the tidal station at Calcasieu Pass that provided the vertical reference for our hydrographic surveys of the pit.

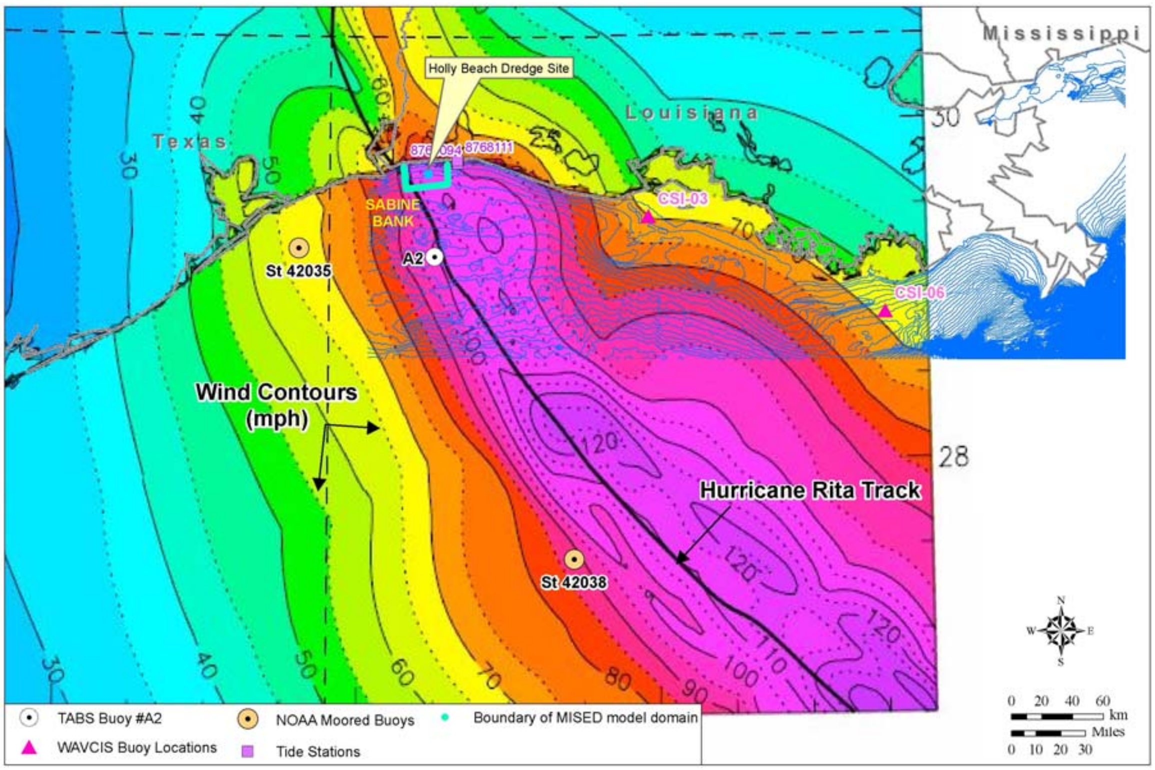

Figure 2.2 Wind Data During Hurricane Rita

Wind data for Hurricane Rita (shown in Figure 2.2) were obtained from the Atlantic Oceanography and Meteorological Laboratory of NOAA (http://www.aoml.noaa.gov/hrd/Storm_pages/rita2005/wind.html). Simulated wave data from the USACE WAM model were obtained for the Holly Beach Dredge Pit location from ERDC (Jane Smith, personal communication). The time history of predicted wave height, period and direction is shown in Table 2.1. Maximum wave height and period at the pit were predicted at Hs = 5 m and Tp = 16.3 s.

Table 2.1 Time History of Predicted Wave Height, Period, and Direction

Date	Height	Period	Direction		Date	Height	Period	Direction
m/dd/hh/mm	Meters	Seconds	Deg (from) clockwise from North		m/dd/hh/mm	Meters	Seconds	Deg (from) clockwise from North
9221830	2	14.9	150		9231830	4.9	16.3	151
9221900	2	14.9	150		9231900	5	16.3	151
9221930	2	14.9	150		9231930	5	16.3	152
9222000	2.1	14.9	150		9232000	5	16.3	152
9222030	2.1	14.9	150		9232030	4.9	16.3	152
9222100	2.2	14.9	150		9232100	4.7	16.3	152
9222130	2.3	14.9	150		9232130	4.5	16.3	152
9222200	2.4	14.9	150		9232200	4.3	16.3	152
9222230	2.5	14.9	151		9232230	4.6	14.9	152
9222300	2.5	14.9	151		9232300	4.2	14.9	152
9222330	2.6	14.9	151		9232330	4	14.9	152
9230000	2.7	14.9	151		9240000	3.8	14.9	152
9230030	2.7	14.9	151		9240030	3.7	14.9	151
9230100	2.8	14.9	151		9240100	3.5	12.3	151
9230130	2.8	14.9	151		9240130	3.3	12.3	150
9230200	2.8	16.3	151		9240200	3.2	11.2	150
9230230	2.8	16.3	151		9240230	3.1	11.2	149
9230300	2.8	16.3	151		9240300	3	10.2	148
9230330	2.8	14.9	151		9240330	3	10.2	147
9230400	2.8	14.9	151		9240400	2.9	10.2	147
9230430	2.9	14.9	151		9240430	2.9	10.2	146
9230500	2.9	14.9	151		9240500	3.2	11.2	182
9230530	2.9	16.3	151		9240530	3.3	11.2	177
9230600	2.9	16.3	151		9240600	3.3	10.2	167
9230630	2.9	16.3	151		9240630	3.4	10.2	148
9230700	3	16.3	151		9240700	3.6	10.2	142
9230730	3	16.3	151		9240730	3.6	10.2	140
9230800	3	16.3	151		9240800	3.6	10.2	139
9230830	3.1	16.3	151		9240830	3.7	10.2	139
9230900	3.2	16.3	151		9240900	3.4	9.2	140
9230930	3.3	16.3	151		9240930	3.2	9.2	144
9231000	3.4	16.3	151		9241000	3.1	9.2	149
9231030	3.6	16.3	151		9241030	2.9	9.2	155
9231100	3.7	16.3	151		9241100	2.8	9.2	161
9231130	3.8	16.3	151		9241130	2.6	9.2	165
9231200	3.9	14.9	151		9241200	2.6	9.2	168
9231230	4	14.9	151		9241230	2.5	9.2	169
9231300	4.1	14.9	151		9241300	2.5	9.2	171
9231330	4.1	14.9	151		9241330	2.5	9.2	171
9231400	4.2	14.9	151		9241400	2.4	9.2	170
9231430	4.3	14.9	151		9241430	2.3	10.2	172
9231500	4.3	14.9	151		9241500	2.3	10.2	172
9231530	4.4	14.9	151		9241530	2.2	10.2	174
9231600	4.5	14.9	151		9241600	2.2	9.2	176
9231630	4.5	16.3	151		9241630	2.2	9.2	176
9231700	4.6	16.3	151		9241700	2.1	9.2	176
9231730	4.9	16.3	151		9241730	2	9.2	176
9231800	4.9	16.3	151		9241800	2	9.2	177

2.3 Dredging Priorities, Equipment and Dredge Pit Dimensions

A review was completed of potential future borrow targets on the OCS. A brief discussion of dredging equipment and implications for borrow deposit dimension is also provided.

For the Atlantic coast the borrow deposits that have been identified as possible sources for future beach nourishment projects are all associated with shoal deposits (versus buried channels or sand sheets).

Along the Gulf coast the Pelican Island restoration project (CWPRA Project Fed No./BA-38) along the Barataria Plaquemines Barrier Island Complex is the closest to initiation. This project will access buried channel sand at Sandy Point 8 to 10 miles off Pelican Island on the west flank of the Mississippi River in OCS waters. A very deep pit is envisaged for this project (NOAA, 2003), with possible dredge depths of 40 ft (12 m)or more below the adjacent seafloor. Details of this dredge pit are provided in Nairn *et al*. (2005).

With the erosion damage caused by Rita along the west coast of Louisiana, it is possible that future nourishment may be required and the Peveto buried channel on the OCS used for the Holly Beach Restoration Project may again provide the most economical source of sand as it did for the initial nourishment project completed in April 2003.

The highest priority for beach nourishment on the Texas coast is the Galveston area and the general thought is that OCS sand is too far offshore to be under serious consideration at this time.

In the presentation of the Khalil *et al*. (2007) paper at Coastal Sediments 07, Khalil reported that the Louisiana Department of Natural Resources have three primary target areas on the OCS for additional geological investigations, in order of priority: 1) Ship Shoal; 2) Tiger and Trinity Shoals; and 3) in cooperation with Texas, Sabine Bank. All are shoals and not buried channels or sand sheets.

The most likely dredging equipment for excavating sand from buried channels will be either a Cutter Suction Dredge (CSD) or a Trailing Suction Hopper Dredge (TSHD). Advantages of the CSD are the following: 1) these dredges are better able to dispose of the stripped muddy sediment near the seafloor to minimize dispersion and suspended sediment plumes; and 2) these dredges are better able to remove sand from a confined pit area. The TSHD option becomes more favorable with greater distances from shore and in areas with higher wave energy. It is possible for a TSHD to dredge from one location only providing the sand runs to the intake pipe. If the TSHD needs to use its drag head, the optimal run distance is about 6000 ft, which may be considerably longer than the width and length dimensions of a deep dredge pit. Since the primary factor determining the long-term impacts of dredge pits is how they evolve, the choice of dredging equipment does not have an over-riding impact on the nature of the impacts.

2.4 Physical Impacts

Direct and indirect physical impacts resulting from dredging on the OCS have been described in RPI *et al*. (2001) and summarized in Nairn *et al*. (2004). This investigation focuses on those physical (and biological) impacts that are most pronounced for projects that involve relatively deep dredge pits, as would be the case when dredging buried channels and other non-topographic sand features. These areas of focus are summarized below:

2.4.1 **Pit dredging and evolution.** The dredging process itself results in the removal and defaunation of the seabed. The evolution of the dredge pit form can lead to additional impacts to benthic communities and fish habitat. Ultimately, the evolution, including possible infilling, determines the longevity of the impacts.

2.4.2 **Potential impacts associated with disposal of stripped sediment.** The disposal of any stripped muddy sediment represents a form of ocean floor dumping and will have an impact on benthic communities.

2.4.3 **Impact of pits on waves and shoreline change.** Dredge pits of the size required for moderate to large beach nourishment projects may have an impact on wave transformation, possibly altering the wave climate along the shore in the lee of the pit, and thus, possibly modifying longshore sand transport gradients and shoreline change.

2.4.4 **Impact of pits on sediment transport pathways.** This impact will only be a potential concern where sand sheets are dredged. In the case of channels buried below a mud cap, mud transport processes will not be measurably influenced.

The literature on each of these four topics is reviewed under the headings below.

2.4.1 Pit Dredging and Evolution

The biological impacts associated with the removal of substrate and defaunation of the dredged area has been addressed by many others (see the summary presented by RPI *et al*., 2001). The key issues of concern are: what is ecosystem value of the lost benthic communities and fish habitat; how fast will the area recover; and will the physical conditions and benthic communities fully recover to before-dredging conditions. Many others have addressed these issues. The main topic to be addressed under this investigation is how the pits evolve both in terms of how the indirect impacts of changing pit morphology change with time (i.e. due to pit migration, slope erosion and infilling) and how fast the pit fills in, if it fills in. Where a pit does fill in, the potential exists for complete recovery of a dredged area eliminating near-field and far-field impacts.

Van Rijn *et al*. (2005) provide a comprehensive review of the evolution of dredge pits in sandy seafloor settings. These authors report on the findings of the three-year European Community SANDPIT study. A summary of the findings is also presented in Nairn *et al*. (2005). The rate at which pits infill (if at all) and migrate (if at all) was shown to be related to the local sediment transport potential and any residual transport rate, respectively. Methods were presented and tested to evaluate the rate of infilling and potential migration rates. Nairn *et al*. (2005) applied some of the SANDPIT techniques to a possible dredge pit in Block 88 of Ship Shoal and found that the pit would only migrate slowly in an onshore direction and possibly alongshore at rates of less than 15 ft/year (5 m/year). It was estimated that the pit would fill in within approximately five years. It is possible the sediment within a pit dredged on Ship Shoal may become finer initially, but as the pit fills in the grain size characteristics would return to the pre-dredge conditions.

Nairn *et al*. (2005, 2006) present new findings on the morphologic evolution of pits dredged in muddy settings, as would be the case for most buried channels. This muddy-capped class of pits was not addressed in the SANDPIT study reported by Van Rijn *et al*. (2005). Nairn *et al*. (2005) showed that pits in muddy settings do not migrate and that the slopes do not significantly change. The main morphologic responses include rapid infilling of the pit and pit margin erosion (i.e. beyond the edge of the pit). Based on monitoring and modeling of the Holly Beach Dredge Pit offshore western Louisiana, it was estimated that this 30 ft deep pit (below the seafloor) would fill completely within about six years from dredging. The pit margin erosion ranged from a maximum of 2 ft. (0.6 m) near the edge of the pit to 0.6 ft (0.2 m) approximately 985 ft (300 m) beyond the edge of the pit. The infilling and pit margin erosion processes will be investigated further in this study through additional monitoring and modeling of the Holly Beach Dredge Pit described in Section 3 of this report, respectively.

Wilbur and Iocco (2003) evaluated the sedimentation rates for three dredge pits in the New York Harbor area. The pits resulted from historic sand mining activities and are in approximately 30 ft (10 m) of water and had dredge depths (below the seabed) of 30 to 50 ft (10 to 15 m). Sedimentation rates were found to be 2.3 to 4.7 in/year (6 to 12 cm/year) between the 1979 and 1995 bathymetry snap shots. Related studies have been made to evaluate the use of pits as disposal areas for contaminated sediment (Bokuniewicz, 1982).

2.4.2 Potential Impacts Associated with Disposal of Stripped Sediment

At locations where sand is buried under a cap of sediment too fine for beach nourishment this material must be stripped and disposed. Managing and regulating dredged sediment is a shared responsibility of EPA and the US Army Corps of Engineers (USACE), under both the Clean Water Act (CWA) and the Marine Protection, Research, and Sanctuaries Act (MPRSA, or Ocean Dumping Act -P.L. 92-532). The Ocean Dumping Act preempts the CWA in coastal waters or open oceans, and the CWA controls in estuaries. Permits issued by the USACE for dredged material under the Ocean Dumping Act specify the type of material to be disposed, the amount to be transported for dumping, the location of the dumpsite, the length of time the permit is valid, and special provisions for surveillance.

There have been many investigations of ocean dumping of dredged sediment and the impacts are well-known. For clean sediment, which will typically be the case at OCS sites, the key impacts are:

1. The generation of a suspended sediment plume through the disposal process either through a pipe from a CSD (discharging within the water column or at the sea bed) or through overspill and/or split hull dumping from a TSHD. In areas muddy sediment is being stripped it is likely that elevations to the background suspended sediment levels will be well within the natural range of suspended sediment levels.

2. The burial of benthic communities at the dump site.

Numerical models have been developed by the US Army Corps of Engineers to evaluate the impact during disposal (STFATE) and to evaluate the long-term fate of a dredge disposal mound (LTFATE).

The EA for the proposed Sandy Point Borrow Site for the CWPRA Pelican Island barrier island restoration project in Louisiana (NOAA, 2003) discusses the possibility of: a) dumping at some distance from the borrow pit to eliminate the potential of the dredged mound contributing to infilling of the pit, ostensibly preserving the pit for future dredging; and b) returning the stripped sediment to the dredge pit. Regarding the first alternative, it is noted that these pits are located in muddy areas and as Nairn *et al*. (2005) have demonstrated natural infilling will be rapid, so locating the mound some distance from the pipe is not helpful or necessary. The second alternative is problematic as the stripped sediment must be stored while the sand is removed from the pit and this is unlikely to be viable for that reason.

2.4.3 Impact of Pits on Waves and Shoreline Change

Dredge pits act much the same as a shoal in transforming waves that pass over them. Depending on geometric characteristics of the pit (size, depth and side slope steepness) and the distance from shore, the pit may significantly modify the waves that reach the shoreline. Changes to the nature of the waves that reach the shore can in turn alter longshore and cross-shore sand transport processes, and as a result, shoreline evolution. Considering that almost all OCS borrow deposits provide sand for beach nourishment to mitigate shoreline erosion, the possibility that the borrow deposit itself may cause beach erosion requires careful assessment.

Price *et al*. (1978) describe an investigation of the impacts of dredging along the south coast of England where the well-known case of beach erosion at Worthing was directly related to a nearshore dredge pit. Using radioactive tracer tests these authors found sand movement at 30 and 40 ft (9 and 12 m) water depths, but negligible for 60 ft (18 m) and deeper, so dredging in water deeper than 60 ft (18 m) was deemed to be acceptable. Motyka and Willis (1974) present one of the earliest applications of a refraction model to evaluate the impact of a dredge pit on shoreline evolution along the UK coast.

Combe and Soileau (1987) document the formation of two salients or cuspate forms along Grand Isle in Louisiana in response to refraction/diffraction processes over the two deepest sections of a borrow pit. The borrow pit was dredged about 0.5 miles (0.8 km)offshore and the pit depth was approximately 20 ft (6 m) at either end of the shore parallel pit opposite the salients. Gravens and Rosati (1994) applied a refraction model with GENESIS to "predict" the salient or cuspate formations that developed in the lee of the borrow pits for the Grand Isle, LA project.

A critical review of the approaches taken in MMS projects to evaluate the potential impact of dredging in the OCS on shoreline evolution was recently undertaken by Michel *et al*. (2007). RPI *et al*. (2001) recommends the application of GENESIS to evaluate the influence of changes to longshore sand transport gradients caused by changes to wave transformation patterns on shoreline change. Several recent studies for MMS of North Carolina, New York/New Jersey and the Central East Florida shelf (Byrnes *et al*., 2003, 2004 and 2005, respectively) rely on the approach of Kelly *et al*. (2004) that evaluates whether the predicted LST under the post-dredge conditions remains within an envelope of 0.5 times the standard deviation of average annual sand transport (for a 20-year period) moving along the shore, in which case the change is deemed to be insignificant. In other words, it is considered to be within the year-to-year changes of LST.

Another approach used to evaluate the significance of changes to wave patterns on shoreline change for MMS includes Cutter *et al*. (2000) for the Virginia coast. Cutter *et al*. (2000) implement an approach to quantify the change in maximum wave height gradient along the area of interest (it is referred to as the Breaking Wave Height Modulation - BHM). This does not directly quantify the implication of changes to wave climate on shoreline change and therefore does not provide a direct measure of what might be acceptable in terms of change.

Of all the MMS studies reviewed, the Kelly *et al*. (2004) approach is the most rigorous. However, a concern with this approach is that it neglects the fact that the long-term gradient in LST will be permanently altered. It is important that this method or others be evaluated to determine whether the somewhat arbitrary selection of 0.5 times the standard deviation is indeed acceptable.

Work *et al*. (2004) evaluated the possible impact of a proposed dredge pit offshore Folly Island, South Carolina. The proposed pit was located approximately 3 miles (5 km) from shore, had a dredged depth of less than 3 ft (1 m) in water depths of about 25 ft (8 m), and had dimensions of 2.5 miles (4 km) (along the shore) by 0.3 miles (0.5 km) wide. Using the SWAN wave model (without diffraction), combined with the EPA 3D hydrodynamic model EFDC and the USACE GENESIS (one-line) model, the authors found that the predicted shoreline changes were small (3 to 6 ft or1 to 2 m) compared to the annual range of natural variability on the order of 0 to 260 ft (0 to 80 m).

Demir *et al*. (2004) present an excellent literature review on the potential impact of dredge pits. These authors also investigated the impact of hypothetical dredge pits on the Black Sea near Istanbul. The initial condition consisted of a pit 0.6 miles (1 km) long by 0.3 miles (0.5 km) wide by 10 ft (3 m) deep in a water depth of 50 ft (15 m). Subsequently, Demir *et al*. (2004) evaluated the sensitivity of shoreline response to length, width, pit depth and water depth. The wave transformation models, REF/DEF 1 and SWAN (without diffraction), were applied together with GENESIS. They found that for water depth/closure depth ratios of less than 5 there is little impact and pit depth and width are the most important parameters. They also found that diffraction is expected to be less important than refraction when the pit depth is small compared to the water depth or side slopes are mild – diffraction results in undulations along the shore caused by wave scattering from the pit slopes.

Benedet *et al*. (2006, 2007) investigate the impact of borrow pits dredged offshore Delray Beach in southeast Florida on the various beach nourishment projects along that shoreline. The pits were dredged in 1973, 1978, 1984, 1992 and 2002 to support beach nourishment projects in those years. The pits are located from 0.3 to 0.5 miles (0.5 to 0.8 km) offshore in water depths of 30 to 50 ft (10 to 15 m). Pit depths range from 15 to 30 ft (5 to 10 m). Through the application of the SWAN and Delft3D models (the latter in 2D mode), the erosion hot spots within the beach nourishment project are shown to be a result refraction/diffraction processes caused by the dredge pits. These pits were investigated by Nairn *et al*. (2005) and shown to be relatively stable with little or no infilling or migration due to: 1) very low background suspended load; and 2) relatively low transport potential along the sea bed adjacent to the pits.

Bender and Dean (2003a) reviewed several examples of borrow deposits offshore completed beach nourishment projects at Grand Isle LA, Anna Maria Key, FL and Martin County FL. Bender and Dean (2003b) also reviewed the history of lab tests associated with dredge pits. Finally, the authors reviewed the available numerical models for the evaluation of dredge pit impacts including the wave models RCPWAVE, RED/DIF 1, MIKE21 EMS, STWAVE, SWAN and various longshore sand transport models.

Bender and Dean (2003b) evaluated reflection and transmission from dredge pits slopes using analytical and numerical model techniques, including the Boussinesq model FUNWAVE. Bender and Dean (2004) applied the analytical treatment from their two previous papers for wave reflection, transmission and refraction/diffraction linked to a simple modified CERC type sediment transport predictor that includes the longshore wave height gradient term (that accounts for the lack of direct prediction of longshore currents driven by setup gradients). The results of this approach were compared to laboratory results. The approach developed by Bender and Dean (2004) can only address very simple conditions of uniform depth inshore/offshore of pit, but being an analytical approach can provide a rapid assessment of many different possible conditions.

Bender and Dean (2005) identified and evaluated the four key transformation processes associated with the interaction of waves and dredge pits: reflection, dissipation over soft bottom in the pit (once partly infilled), refraction and diffraction. Reflection coefficients were found to be in the range of 5 to 25 %.

In the final report of the European Community SANDPIT project, Van Rijn *et al*. (2005) describe the application of various numerical modeling approaches to evaluate the impact of pits on shoreline change through changes to waves and longshore sand transport. Models included Delft3D coupled with SWAN, the DHI models, the French model TELEMAC and several others. Numerical model tests were completed with a hypothetical pit dredged along the 30 ft (10 m) depth contour with a pit depth of 30 ft (10 m), dimensions at the seabed of 0.8 miles long by 0.3 miles wide (1.3 km by 0.5 km) with a total volume of 124 million ft^3 (3.5 million $m^{3)}$, and located approximately 1 mile (1.5 km) offshore. The site was representative of the PUTMOR dredge pit located on the Dutch coast of the North Sea. An example of the difference in wave heights with and without pit is shown in Figure 2.3.

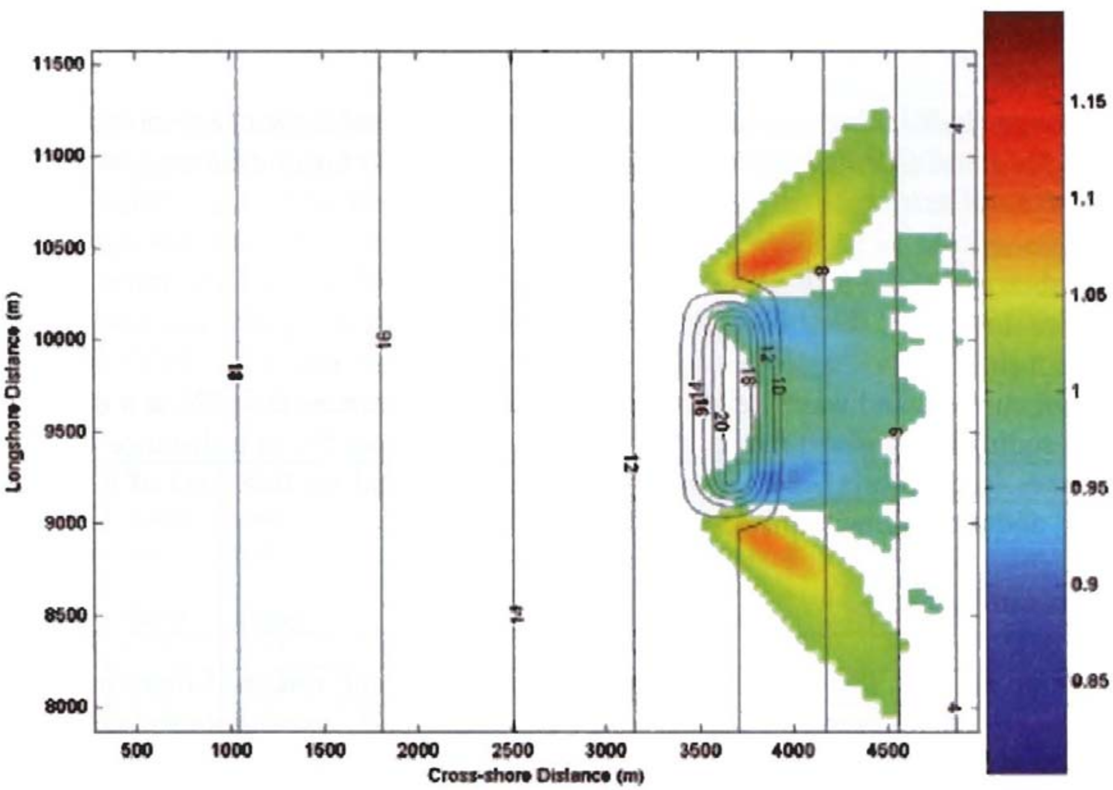

Figure 2.3 Ratio of Computed Wave Height of Baseline Pit Case and Reference Pit Case (without pit)

(pit at 10 m depth contour; offshore wave: H_s=3.36 m, T_p=8.8 s, Dir=270°; coast on right side)
Figure courtesy of van Rijn et al (2005). SANDPIT. Figure 7.3.5, p.99

This is the typical pattern of modification to waves as they pass over a pit with focusing occurring along two rays extending off the edges of the pit (due to refraction) and sheltering in the lee of the pit. For this pit and the North Sea wave conditions, the longshore transport rate at the coast is influenced in the range of +50 % to –50 %, and up to 200 % when wave-driven currents were considered (i.e. in addition to the influence on waves alone). The impact to longshore sand transport is reduced to 15 % as the pit is moved to a distance of 1.5 miles (2.4 km) offshore.

In summary, there has been an evolution of the methodology to evaluate the potential impact of dredge pits with the most recent approaches consisting of a combination of wave transformation, hydrodynamic and sediment transport models.

2.4.4 Impacts of Pits on Sediment Transport Pathways

In zones of active sediment transport, pits can intercept sand or finer sediment that is being transported. This becomes a concern where the trapping of sediment influences shoreline stability. As such, this is only a concern where a pit is dredged at a sandy seafloor location and will fill in with sand. This is because sediment finer than sand does not have a significant role in preserving shoreline stability, and where it does, the supply of fine sediment is abundant. In summary, there are two aspects to this possible impact: (1) where sand is drawn from the beach to fill the pit (offshore transport is caused); and (2) where sand that would otherwise have been supplied to the shore is intercepted by the pit (onshore transport is prevented).

Kojima *et al*. (1986) investigated a possible link between erosion of the beach along the Genkai Sea in southwest Japan and offshore dredging. The dredge pits were located in 50 to 130 ft (15 to 40 m) of water and are approximately 1.8 miles (3 km) offshore for the closest pits to shore. The seabed in the area was generally sandy and the pits infilled with sand. Therefore, this represents a case where the shoreline impacts were related to a direct impact on the sediment budget, versus a change to wave climate reaching the shore.

Capobianco *et al*. (1991) and Stive and de Vriend (1991) describe a model for evaluating long-term shore profile evolution. The approach explains that dredging beyond the depth of closure may have an influence on the stability of the upper parts of the nearshore profile (i.e. at and near the shoreline) by causing profile slope adjustments that translate from deepwater towards the shore. Therefore, where dredging occurs on the outer part of a continuous slope back to shore, careful consideration should be given to possible shoreline impacts.

RPI *et al*. (2001) indicate that in almost all cases that have been dredged or are under consideration for dredging on the OCS do not display characteristics that would suggest there should be concern for impact to a sediment transport pathway.

2.5 Biological Impacts

As the need to restore and replenish highly eroded areas of the U.S. coastline continues to increase, so does the demand for sand from nearshore areas. Historically, state and local municipalities have relied on sand deposits within state waters to accomplish local beach renourishment projects. As these sand resources become depleted, expansion further offshore into federally managed outer continental shelf areas seas will be necessary to locate suitable sand recourses (Nairn *et al*., 2004). The extraction of this sand will result in negative impacts to the local benthic community. Because the benthic community represents a critical link in coastal foodwebs, impacts to the benthic community have the potential to radiate out to other components of the ecosystem. In this section, the following topics are reviewed: 1) the linkages between marine benthic communities and demersal fish and crabs; 2) the potential biological and water quality impacts of dredging of sand in areas of the inner continental shelf; and 3) the potential implications of these impacts on biological resources of the Gulf of Mexico and Atlantic coasts.

2.5.1 Linkages Between Benthic Habitats and Fisheries

Nearshore areas of the U.S. Gulf of Mexico and Atlantic coasts are highly productive systems that support an abundance of demersal (bottom feeding) and pelagic (water column) species, many of which provide the basis for valuable fisheries (Chesney and Baltz, 2001). In 2004, commercial fishermen landed 1.6 million lbs (730 million kg) of finfish and shellfish worth $683 million from the Gulf of Mexico. Commercial landings in the South Atlantic were 194 million lbs (88 million kg) and worth $153 million (National Marine Fisheries Service, 2005). With the notable exception of Gulf and Atlantic menhaden, the majority of these fish and shellfish utilize bottom habitats for feeding and/or shelter at some point in their life cycle (demersal).

The rich abundance of benthic invertebrates that reside within (benthic infauna) or on the surface (benthic epifauna) of bottom sediments of the inner continental shelf areas of the Gulf of Mexico and Atlantic coasts provide an abundant and accessible prey base for these demersal consumers. The productivity of this abundant benthic invertebrate community is maintained in turn by riverine or coastal inputs of nutrients and organic matter that stimulate high primary production (Rowe, 1971; Turner and Rabalais, 1991). Because the input of nutrients and thus primary production decreases with distance from the coast, a distinct gradient of secondary productivity also exists along the shelf regions: secondary production decreases with distance from the shoreline and depth. For example, over 60 % of shellfish and almost 1/3 of finfish harvest in the Gulf of Mexico and Atlantic coasts occur within 3 miles (4.8 km) of the shoreline (National Marine Fisheries Service, 2005). The vast majority of the remaining shellfish and finfish are harvested between 3 and 200 miles (4.8 and 322 km) from the coast.

The tight linkages between water column conditions, benthic invertebrates, and demersal fish in nearshore areas provide the mechanism by which changes in water quality or benthic habitat quality are transferred to higher trophic levels (Peterson *et al*., 2000;

Powers *et al*., 2005). Although the nature of the disturbance event varies, marine benthic communities normally follow a similar trajectory of recovery following a disturbance event. The successional model for benthic communities described by Rhoads *et al*. (1978), and later illustrated for dredging studies by Newell *et al*. (1998), describes a series of stages in the recovery of a typical marine benthic community. Following the end of the disturbance, or in the case of chronic disturbance (such as high sedimentation rates) a relaxation of the disturbance event, the benthic community is rapidly colonized by small opportunistic infauna, generally small polychaetes and nematodes). In the absence of disturbance, succession should proceed with small infaunal clams as well as amphipod crustaceans colonizing bottom habitat.

During later stages of succession, deeper burrowing, larger invertebrates colonize the habitat and inhibit the settlement of the small opportunistic species. The species composition and duration of different succesional stages may also influence trophic transfer during the recovery process and affect the condition and relative abundance of mobile consumers (Peterson *et al*. 2000). The benthic community characteristic of early successional stages or those that persist under chronic disturbance provides an ideal food source for small shrimp that feed on deposit feeding polychaetes (Figure 2.4). During the latter successional stages, bivalve and large tube dwelling polychaetes provide a prey resource for portunid crabs and fishes of the family Sciaenidae (croaker and drums).

The timing and duration of these various successional stages as well as species composition will be dictated by a variety of factors including, larval supply (Santos and Simon, 1980; Powers *et al*., 2001; Lundquist *et al*., 2004), resuspension of nearby adult populations (Commito *et al*., 1995; Thrush *et al*., 2003), local species richness, and the spatial scale of disturbance (Thrush *et al*., 2005). Chief among these factors are the temporal duration and spatial extent of habitat degradation. Chronic disturbance may cause the benthic community to remain in an early successional stage (dominated by small opportunistic polychaetes). Small scale disturbances (cm – m’s) may require relatively short time periods for recovery (days – weeks) because adult migration via passive or active redispersal of macrofauna can facilitate recovery. In contrast, larger scale disturbances (km’s) that require larval recruitment to replenish the macrobenthic community will require extended periods of time (months – years) for full recovery to occur.

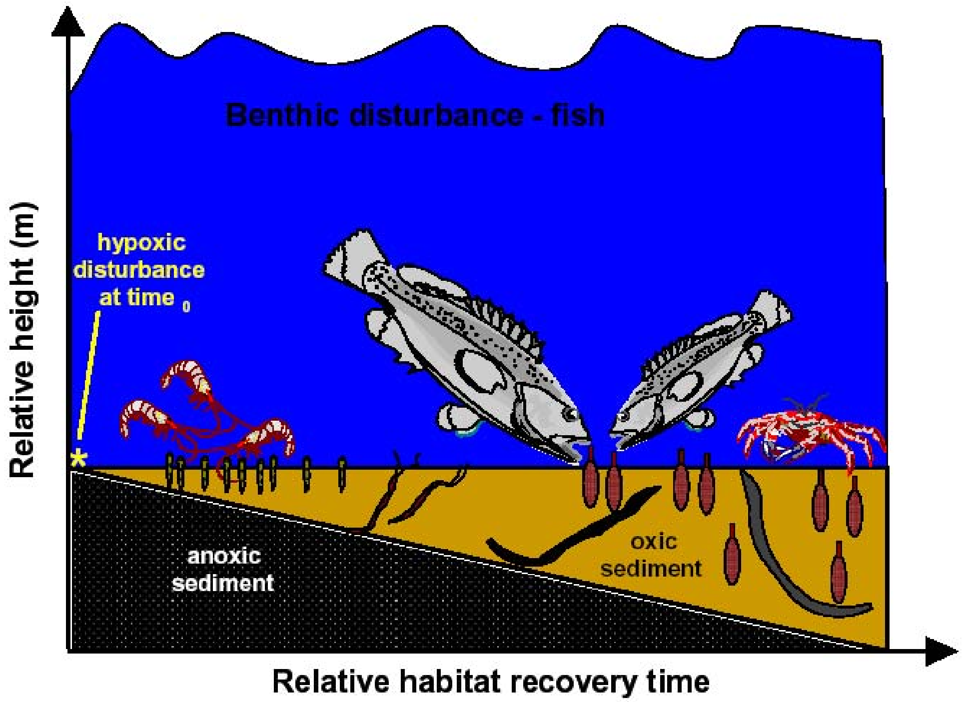

Figure 2.4 Conceptual Diagram of Benthic Recovery Following a Disturbance Event Indicating Changes in both Benthic Infauna and Demersal Fish and Crab Communities

2.5.2 Potential Impacts of Sand Mining on Benthic and Pelagic Resource

Negative impacts to marine benthic communities that result from dredging marine bottom sediments are well documented throughout estuarine and coastal areas (Hall, 1994; Newell *et al*., 1998, 2004; Boyd *et al*., 2005).

Dredging directly causes defaunation of sediment. Colonizers of defaunated sediment are typically dominated by fast growing, opportunistic *r*-selected macrofauna species (Pearson and Rosenberg, 1978, Rhoads *et al.*, 1978, Thistle, 1981, Lu, 2000). Benthic colonizers are often small polychaetes, especially from the Spionidae and Capitellidae families (Grassle and Grassle, 1974, Pearson and Rosenberg 1978, Montagna and Kalke, 1992, Palmer *et al.*, 2002). Unless there is subsequent frequent disturbance, succession occurs where colonizers are replaced or joined by a more diverse range of larger *k*-selected species (Pearson and Rosenberg, 1978, Ritter *et al.*, 2005).

Reductions in species richness of 30 -70 %, individual abundance, and biomass of 40 – 95 % are all common impacts of dredging operations (see Table 2.2). The most pronounced effects of this habitat degradation are usually limited to the immediate vicinity of the dredged area (Newell *et al*., 2004). Impacts to adjacent, non-dredged areas will vary in relation to the size and advection of any plume created by the dredging activities, the quantity of dredge material discarded in adjacent areas and modification to the local hydrodynamic environment that result from creation of deep pits or channels.

The degree to which adjacent areas experience elevated suspended solid concentrations in the water column, sediment deposition, organic enrichment from resuspension, or discard of dredged sediments will influence the degree of impact. The presence of a dredge plume has been detected at distances from 1.8 to 5 miles (3 to 8 km) away from the actual dredge operation (Dickson and Rees, 1998; Hitchcock *et al*., 2002). In general, adjacent areas will experience substantially less loss of benthic species richness and biomass than dredged areas and this "spill-over" impact will quickly decrease with distance. This impact of sedimentation beyond the dredged area is usually only a concern where there is nearby hard bottom or live bottom (e.g. coral in the latter case).

Recovery of the benthic community in the dredged area and adjacent non-dredged but impacted areas is of considerable importance when examining the potential for transfer of impacts to other components of the foodweb. The rate of recovery is dependent to a large extent on the type of substrate dredged (Newell *et al.*, 2004), the degree to which the post-dredging substrate matches the original substrate (Newell *et al*., 1998), the persistence of bathymetric changes (Blake *et al*., 1996), as well as the spatial scale of disturbance (Thrush *et al*., 2005).

Recovery is relatively easy to assess when the substrate remaining after dredging activities cease (or after infilling is complete) is similar to the pre-dredge condition or return to pre-dredge substrate type occurs after some period of particle resorting (Newell *et al*., 1998). Newell and Seiderer (2003) reviewed 19 dredging studies that examined recovery of the benthic invertebrate community and found that recovery, which was generally defined by 80 % return of species richness or biomass, occurred most rapidly (< 1yr) for estuarine and freshwater habitats with muddy substrates. Substrates composed of coarser material (sand, gravel or shell material), required an average of 2 – 4 yrs to recover, although a large range (2-12 years) existed (Table 2.3).

Recovery is more difficult to evaluate for dredged areas in which substrate is permanently altered. Changes in sediment type, normally replacement of coarse material with fine particles, result in substantially different species composition. Because reestablishment of a benthic community similar to the pre-dredging environment does not occur, other metrics (e.g., similar biomass) must be used to gauge "recovery" and the effect of the new community on higher trophic levels must also to be examined and considered (Nairn *et al*., 2004).

Table 2.2 Summary of Impacts on Benthic Invertebrate Populations Within Dredged Areas for Selected Studies
(From Newell and Seiderer, 2003)

LOCALITY	HABITAT TYPE	% REDUCTION AFTER DREDGING			SOURCE
		Species	Individuals	Biomass	
Chesapeake Bay	Coastal Embayment Muds-sands	70	71	65	Pfitzenmeyer, 1970
Goose Creek, Long Island, NY	Shallow Lagoon Mud	26	79	63-79	Kaplan *et al*, 1975
Tampa Bay, Florida	Oyster shell	40	65	90	Conner & Simon, 1979
Moreton Bay, Queensland, Australia	Sand	51	46	-	Poiner & Kennedy, 1984
Dieppe, France	Sands-gravels	50-70	70-80	80-90	Desprez, 1992
Klaver Bank, Dutch Sector, North Sea	Sands-gravels	30	72	80	van Moorsel, 1994
Lowestoft, Norfolk, UK	Gravels	62	94	90	Kenny & Rees, 1994
Hong Kong	Sands	60	60	-	Morton, 1996
Lowestoft, Norfolk, UK	Sands-gravels	34	77	92	MESL, 1997
Dieppe, France	Sands-gravels	80	90	90	Desprez, 2000
Bayou Texar, Florida	Mud	55	77	-	Lewis *et al*, 2001
North Nab, UK	Gravels	66	87	80-90	Newell *et al*, 2001b; 2003 Hitchcock *et al*, 2002
Area 408, North Sea.	Sandy gravel	0	0	82	Newell *et al*, 2002

Of specific interest for this review is the impact associated with dredging of sand deposits for beach replenishment. Such projects have generally targeted nearby surficial areas of coarse sand in order to match the grain size of beach sand. Because these surficial areas normally experience high current velocities, accumulation of finer sediment particles is not expected and rapid filling of the excavated pit is anticipated. However, examples of depressions and pits left by dredging activities filling with fine sediments (see Van Dolah *et al*., 1998, Blake *et al*., 1996) and/or not filling after several years (Blake *et al*., 1996) do exist.

In their study of relatively shallow pits (3 ft to 10 ft or1 to 3 m in depth) dredged from sand sheets off South Carolina, Van Dolah *et al*. (1998) found that pits filled in with finer sediment and that this change is sediment composition resulted in an altered benthic community. Blake *et al*. (1996) found little or no change in grain size, minimal pit infilling and no clear evidence of change to benthic communities for pits dredged offshore of Tampa Bay from a sand sheet setting for beach nourishment purposes. Sandy pits generally expand and infill through flattening of the pit slopes with variability in the rate of infilling of sandy pits dependent on wave energy available for sand transport sediments.

In contrast, based on their experience with surveying and modeling the Holly Beach dredge pit offshore the west coast of Louisiana, Nairn *et al*. (2006) showed that muddy-capped pits evolve differently. These pits feature very little slope change (primarily because of the greater stability of partially consolidated cohesive sediment underwater) and fill through deposition from the general background turbidity and from erosion of the pit margins (i.e. beyond the pit edge).

Given the results of Blake *et al*. (1996), Van Dolah *et al*. (1998), Newell and Seiderer (2003) and Nairn *et al.* (2006) that changes in bathymetry and sediment type greatly influence the trajectory of recovery for benthic communities, the possibility of negative impacts from mining of buried sand deposits does exist. Also, correlations between sediment grain size and benthic organisms are strong and well documented (Young and Rhoads, 1971, Rhoads, 1974, Mannino and Montagna, 1997, Palmer, 2006). So a change in sediment type will ultimately influence the type of community that eventually recovers.

Table 2.3 Summary of Recovery Time for Selected Dredging Studies

(From Newell and Seiderer, 2003)

LOCALITY	HABITAT TYPE	RECOVERY TIME	SOURCE
James River, Virginia	Freshwater semi-liquid muds	±3 weeks	Diaz, 1994
Coos Bay, Oregon	Disturbed muds	4 weeks	McCauley *et al*, 1977
Gulf of Cagliari, Sardinia	Channel muds	6 months	Pagliai *et al*, 1985
Mobile Bay, Alabama	Channel muds	6 months	Clarke *et al*, 1990
Chesapeake Bay	Muds-sands	18 months	Pfitzenmeyer, 1970
Goose Creek, Long Island, NY	Lagoon muds	>11 months	Kaplan *et al*, 1975
Klaver Bank, Dutch Sector, North Sea	Sands-gravels	1-2 years (ex-bivalves)	van Moorsel, 1994
North Sea (Area 408)	Sands-gravels	1 year	Newell *et al*, 2002
English Channel (North Nab)	Coarse gravel	>2 years	Newell *et al*, 2001b Hitchcock *et al*, 2002
Dieppe, France	Sands-gravels	>2 years	Desprez, 1992
Lowestoft, Norfolk, UK	Gravels	>2 years	Kenny & Rees, 1994, 1996
Dutch Coastal Waters	Sands	3 years	de Groot, 1979, 1986
Tampa Bay, Florida	Oyster shell (complete defaunation)	>4 years	US Army Corps of Engineers, 1974
Tampa Bay, Florida	Oyster shell (incomplete defaunation)	6-12 months	Conner & Simon, 1979
Boca Ciega Bay, Florida	Shells-sands	10 years	Taylor & Saloman, 1968
Beaufort Sea	Sands-gravels	12 years	Wright, 1977
Florida	Coral reefs	>7 years	Courtenay *et al*, 1972
Hawaii	Coral reefs	>5 years	Maragos, 1979
Area 222 Isle of Wight, English Channel	Gravel	>4 years	Boyd *et al,* 2003

Predicting the overall magnitude of impacts to benthic and demersal biological resources resulting from mining of buried sand deposits is challenging because such impacts will likely vary based on a number of physical factors associated with the dredging operation as well as site-specific environmental variables. Further, differences in the physical recovery between surficial sand deposits and buried sand deposits as illustrated in the previous paragraph limit the applicability of previous studies to the current assessment. Factors likely to be determinants of recovery are the depth of the dredge pit, size of the pit, rate of infilling from the pit, as well as the potential for low dissolved oxygen to occur within the pit. Assuming that fine muds are present above the buried sand and the adjacent area is dominated by similar fine muds (as is the case in many areas of buried sand deposits) differences in sediment grain size between pre and post-recovery conditions are not likely. Over time the pit should fill; however, the time period for this will be determined by the rate of sediment deposition within the pit. A rapid deposition rate will result in a relatively short infilling period, but greatly inhibit benthic fauna from colonizing the area. Conversely, a reduced deposition rate may allow for benthic fauna to colonize the pit throughout an extended recovery period.

The persistence of a deep pit may also increase the frequency or duration of low dissolved oxygen events. Because these deep pits experience limited horizontal and vertical mixing they are prone to stratification and may become hypoxic or anoxic when deposition of organic matter from surface water is high (Stanley and Nixon, 1992, Diaz and Rosenberg, 1995, Paerl *et al*., 1998, Ritter and Montagna, 1999, Rabalais *et al.,* 2002, Applebaum *et al.*, 2005). Low dissolved oxygen levels have been documented in excavation pits in a sand mining study in estuaries (Johnston, 1982). The occurrence of low oxygen conditions would be expected to further limit the ability of benthic organisms to colonize the recovering area. Hypoxic conditions are generally defined in the northern Gulf of Mexico as water with oxygen levels less than 2 mg/l^{-1} (Pokryfki and Randall, 1987, Rabalais *et al*,. 2002). The threshold was defined as 2 mg/l^{-1} because bottom-dragging trawls do not usually capture shrimp or demersal fish below this concentration (Renaud, 1986). At low oxygen levels, pericaridean crustaceans, echinoderms, bivalves and larger fauna are replaced or outlasted by small opportunistic polychaetes (Harper *et al.*, 1981, Gaston, 1985, Rabalais *et al.*, 2002, Montagna and Ritter, 2006).

Based on the analysis of previous studies of the impact of sand mining on benthic communities as well as inclusion of those issues of particular concern for excavation of buried sand deposits discussed earlier, the biological impacts of dredging buried sand deposits may be separated into six specific areas listed below (see Nairn *et al*., 2004).

1. Removal of the original substrate and defaunation of the associated benthic community is the most obvious biological impact for both raised topographic and nontopographic deposits. Because the deposits intended for excavation are buried, an impact unique to muddy pits results from dumping of muddy sediment from the stripping process, covering and likely destroying adjacent benthic communities.

2. Water column impacts include elevated levels of total suspended solids (TSS) during the dredging operation (short term) and the potential for hypoxic (oxygen levels less than 2 mg/l) anoxic (oxygen levels of 0 mg/l) conditions to develop in the pit (long-term). Eventually, as the pit fills in this impact will be diminished or eliminated.

3. In the case of deep pits, high sedimentation rates may delay or prevent the recovery of the benthic community. A high rate of sedimentation will result in constant burial of the benthic organisms that recruit to the area. Although some small, rapidly burrowing invertebrates may survive in such habitats depending on the fluidity of the substrate, overall species diversity and biomass will be suppressed for some time. As the pit fills in, the rate of sedimentation will slow and allow for greater colonization of benthic invertebrates.

4. Another potential biological impact that is unique to dredge pits in muddy deposits is the margin erosion. Benthic organisms that colonize these pit areas may be subject to erosion and scour. High rates of erosion could prevent establishment of many benthic organisms and prolong recovery.

5. For pits in relatively sandy settings, the main biological concern will be the change in substrate from coarse sand to finer sediment, if it occurs.

6. Finally, impacts to the benthic community could be transferred to other components of the food web. The removal and delayed recovery of the benthic community as a result of sedimentation, erosion or low dissolved oxygen represents a loss of prey base for demersal fish and crabs. Changes in benthic community structure as a result of differing sediment type may also represent a potential loss of feeding opportunities for some demersal consumers, although other consumers may experience enhanced feeding. Further, some areas may have previously served as spawning grounds or habitat for juvenile and adult stages. The loss and/or degradation of these areas may result in decreased production of these higher trophic levels (Eby *et al*., 2005; Powers *et al*., 2005).

2.5.3 Review of Relevant Water Quality Conditions in the Gulf of Mexico and Atlantic Coast

The potential for dredge pits to become hypoxic or anoxic exists in many areas of the Gulf of Mexico and Atlantic coasts, particularly for deeper pits in muddy areas near river plumes, and may represent a significant impact to demersal fish and crabs. Low oxygen conditions may develop and be sustained as long as the pit remains below some critical depth where sufficient stratification can occur and be maintained (i.e. without mixing with the water column above). Low dissolved oxygen concentrations are a symptom of declining water quality in a growing number of estuarine and coastal environments worldwide (Cooper and Brush, 1991, Diaz and Rosenberg, 1995; Paerl *et al*., 1998, Rabalais *et al*., 2002). Changing land use patterns (such as riparian wetland conversion and the growth of industrial animal farming operations) and other consequences of increasing human development (such as sewage spills and polluted stormwater runoff) are resulting in increased nutrient (primarily N) loading of coastal waters. This intensifies eutrophication and the frequency, duration, and spatial scale of hypoxic and anoxic events (Officer *et al*., 1984, Rosenberg, 1985, Cooper and Brush, 1991, Rabalais *et al*., 1994).

Periods of severe hypoxia and anoxia are a natural result of water column stratification in conjunction with a high sediment oxygen demand caused by the presence of decomposing organic matter (Stanley and Nixon, 1992, Diaz and Rosenberg, 1995). Meteorological conditions (wind, temperature, large storms) and freshwater runoff directly affect the strength of stratification and, depending on the nutrient load of the runoff, can also stimulate algal blooms (Officer *et al*., 1984, Seliger *et al*., 1985). As a large amount of organic matter (phytoplankton and/or terrestrial detritus) sinks and begins aerobic microbial decomposition, the resultant elevated rates of microbial oxygen consumption can cause rapid depletion of dissolved oxygen near the sediment-water interface (Stanley and Nixon, 1992, Diaz and Rosenberg, 1995, Paerl *et al*., 1998). When combined with strong water column stratification, which prevents mixing with well-oxygenated surface waters, aerobic degradation in bottom sediments can result in prolonged periods of hypoxia and/or anoxia.

Several nearshore areas of the Gulf of Mexico and Atlantic coasts experience episodic and/or prolonged periods of hypoxia and anoxia due to high levels of primary production coinciding with periods of stratification (see Table 2.4). Hypoxia and anoxia are frequent occurrences in the Northwestern and Central Gulf of Mexico (Texas to Alabama) and shallow bay systems of the entire Gulf of Mexico (e.g., Harper *et al*., 1981; Diaz and Rosenberg, 1995; Ritter and Montagna, 1999; Rabalais *et al*., 2002). Hypoxic and anoxic areas along the Florida coastline are restricted primarily to estuarine areas along the Gulf of Mexico and Atlantic Coast (e.g., Perdido Bay [Livingston, 2001]; Ft. Charlotte Harbor [Pierce *et al*., 2004]; St. John's River [Mason, 1998]). Along the U.S. Atlantic coast, hypoxic coastal areas have been reported in the New York bight (offshore New Jersey, Swanson and Parker, 1988) and within Long Island Sound (Anderson and Taylor, 2001). Small areas of coastal hypoxia may occur near the mouths of major estuaries such as Chesapeake Bay or Pamlico Sound, although the majority of hypoxia occurs within the estuary.

Table 2.4 Hypoxic or Anoxic Areas Along the Gulf of Mexico and Atlantic Coast (excluding estuarine systems)

SYSTEM	HYPOXIC TYPE	HYPOXIA LEVEL[a]	AREAL EXTENT	REFERENCE
Eastern Texas Shelf	Aperiodic	Severe-Moderate	> 400 km2	Harper *et al.* (1981)
Louisiana Shelf	Seasonal	Severe	20,700 km^2	Rabalais *et al.* (2002)
Chesapeake Bay	Seasonal	Moderate-Severe		Seliger (1985)
New York Bight, NJ	Aperiodic	Severe	8,600 km^2	Swanson and Parker (1988)
Long Island Sound, NY	Seasonal	Moderate	130 km^2	Anderson and Taylor (2001)

a) Severe – periods of hypoxia or anoxia last for several days or weeks. Moderate – hypoxic conditions occur for relatively short periods (hours – days).

Along both the Gulf of Mexico and Atlantic, hypoxic and anoxic areas are usually associated with river plumes. The most widely cited examples being the influence of the Mississippi and Atchafalaya Rivers on the Louisiana shelf hypoxic zone (Rabalais *et al.*, 1994, 2002) and the influence of the Hudson River plume on the New York bight hypoxic zone (Falkowski *et al*., 1980; Swanson and Parker, 1988). Freshwater inflow is also one of the principal drivers of hypoxia within estuarine systems (Ritter and Montagna 1999; Buzelli *et al*., 2002). The timing of hypoxic zones reflects the role of freshwater inflow as well as high surface water temperatures. Along the U.S. Atlantic and Gulf of Mexico coastal hypoxic/anoxic bottom zones appear in the summer when high discharge of freshwater from rivers, high atmospheric temperatures and low wind stress enhance water column stratification, although hypoxia on the Louisiana shelf has been reported as early as February and as late in the year as October (Rabalais *et al*., 2002). Size of the hypoxic area off the Louisiana shelf also appears to be correlated with riverine discharge: years of higher discharge tend to have the largest volume of hypoxic waters (Rabalais *et al*. 2002). Although variable in size (4,000 – 20,000 km^2 over 1990 – 2001), several areas particularly those west of the Mississippi and Atchafalaya Rivers appear to be within the hypoxic zone in most years (see Figure 2.5).

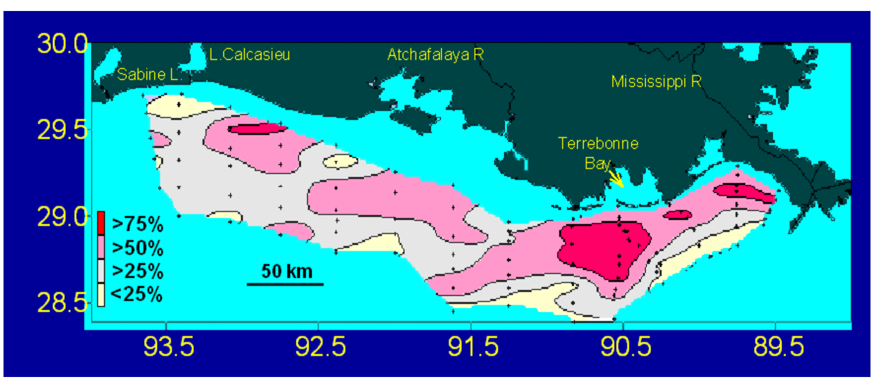

Figure 2.5 Distribution of the Frequency of Occurrence of Bottom Water Hypoxia from 1985-2001
(From Rabalais et al., 2002)

Figure 2.5 presents the percent of annual surveys conducted in mid-summer where hypoxic conditions were detected at a specific station (black dots). The survey area is restricted to Louisiana coastal waters. Hypoxic areas have been reported west of the study area (Harper *et al*., 1981); however, no annual survey is conducted off the Texas coast.

2.5.4 Review and Analysis of Biological Resources at Risk

Direct and indirect effects on benthic invertebrates and demersal fish and invertebrates are likely to result from the dredging of sand deposits (Nairn *et al*., 2004). Direct impacts include loss of benthic organisms as a result of excavation and/or burial and the delay in recovery as a result of increased erosion, high sedimentation or low dissolved oxygen. Direct impacts to demersal species include loss of foraging habitat, nursery habitat and/or loss of spawning habitat. Because of the mobility of organisms, several impacts resulting from dredging operation may have relatively minor effects on demersal and pelagic fish. For example fish may avoid areas of increased turbidity during dredge operations thereby reducing their exposure to potentially harmful particles in the water column. However, visual predators that remain in the area may experience decreased foraging success as a result of turbidity (Benfield and Minello, 1996).

The direct impact of hypoxic or anoxic waters will also vary as a function of mobility of the organism. Mobile consumers of benthic macroinvertebrates usually emigrate out of areas where dissolved oxygen concentrations reach hypoxic levels (Pihl *et al*., 1991, Rabalais *et al*., 2001). If low-oxygen conditions are relatively mild, some of these demersal consumers may remain in the area and exploit stunned or moribund benthic prey resources not normally available (Pihl *et al*., 1992, Pihl, 1994). Most animals can tolerate some moderate duration of hypoxia (hours to days depending on the species), but few animals can persist for long in anoxic conditions (partly as a response to hydrogen sulfide produced by bacteria in these conditions, which is poisonous). Consequently, fish or crabs that cannot migrate from hypoxic water generally suffer high mortality (Rabalais *et al*., 2001).

In order to evaluate the potential importance of the possible direct and indirect effects resulting from sand dredging, a matrix was assembled of demersal fish and invertebrate species likely to occur in nontopographic sand/mud habitat along the inner continental shelf of the Gulf of Mexico and Atlantic. Next, information was reviewed regarding their life history and foraging behavior to determine the potential susceptibility of each to one of the three potential impacts: 1) loss and or modification to benthic prey resources, 2) degradation of nursery or spawning area, and 3) susceptibility to the bottom water hypoxia (evaluated based on mobility). Information on species distribution, relative abundance and life history was assembled following an extensive review of relevant journal articles, technical reports and agency databases. In the event that specific information was lacking, the information was derived from the knowledge of Dr. S. Powers (report co-author) on the species in question or the expertise of colleagues from the National Marine Fisheries Service (MS Laboratory). Potential impacts were ranked as none (no possibility) or on a scale of low, medium or high. A low ranking indicates there is some possibility of an effect on an individual of that species; however, habitat and or foraging preferences would likely result in minimal impacts. In contrast, a ranking of high indicates that an individual of that species has habitat or foraging preferences that make it vulnerable to impacts. The ranking does not account for the scale of disturbance, simply the potential for an adverse impact. If the spatial extent of the disturbance is small and sufficient resources area available in the surrounding non-impacted area, then the resulting impact may be inconsequential. Ultimately both the spatial extent of the impact and the mobility of the organisms will largely determine the impact on benthic and demersal animals.

Several groups of fish or invertebrates were classified as susceptible to one of the three categories of impacts. Table 2.5 lists 154 species of fish and 40 species of epibenthic (echinoderms) or mobile invertebrates (shrimps and crabs) that are likely to occur along inner continental shelf areas (15-100 ft or 5 – 30 m). Species distribution data came principally from seven sources: Darnell *et al*. (1983, 1987), Williams (1984); Murdy *et al*. (1997), Hoese and Moore (1998), Schwartz (2003), Bigelow & Schroeder (1948), and the National Marine Fisheries Service Southeast Area Monitoring and Assessment Program (NMFS SEAMAP). NMFS SEAMAP performs semi-annual bottom trawl and long-line surveys in selected areas throughout the Southeast. Information on regional and site specific abundances (CPUE) can be obtained from the SEAMAP data set that extends from 1983 to the present.

The majority of fish identified as likely to occur in areas of non-topographic features along the inner shelf were judged to have fairly low susceptibility to the direct impacts of low dissolved oxygen. The majority of these fish and all sharks exhibit sufficient mobility to avoid low oxygen areas. For fish, worm and cusk eels along with tonguefishes probably lack sufficient mobility to escape large areas of hypoxic bottom water, although these species would be expected to have some tolerance to hypoxia of relatively modest duration (i.e. less than 24 hours). In contrast to the majority of fishes, most species of invertebrates were determined to have medium to high risk because of their limited mobility. These classifications could be refined to a greater degree when data on the dynamics of low oxygen water masses in dredge pits (level of oxygen depletion, frequency, and spatial extent) are obtained. Additionally, information regarding the dynamics of low oxygen conditions could also be used to determine the potential for the formation of sulfide compounds in and around pit areas (Cooper and Morse, 1996), which could delay recovery of the benthos.

Impacts to spawning/nursery grounds are difficult to assess for many taxa because significant gaps exist in our knowledge of the early history of many fish – particularly those of limited commercial or recreational value. Of those species whose life history is reasonably well documented, members of the family Sciaenidae (drums, croakers, weakfish) could potentially be impacted since many of these species utilize offshore and nearshore sandy habitat near tidal inlets to spawn (e.g. Wilson and Nieland, 1994; Roumillat and Brouwer, 2004). The majority of sciaenids recruit to estuarine habitats as juveniles, so impact to nursery areas would be minimal with the exception of kingfish and stardrum, which do utilize nearshore habitat as nursery grounds. Several flounder and eel species would also be expected to use offshore sand/mud habitat as nursery grounds; consequently, their potential impact under the spawning/nursery ground category is ranked as medium to high.

The most probable mechanisms by which higher trophic levels are impacted by dredging, are through the lost prey resources or changes in the prey base (Table 2.5). Similarly, one of the largest impacts of hypoxia is the loss of benthic invertebrate production (Powers *et al.*, 2005). In several areas of the Gulf of Mexico, particularly along the Louisiana and eastern Texas Continental shelf (see Figure 2.5), the possibility exists that dredge pits may co-occur with hypoxia. Theoretically, dredging could be timed to coincide with annual defaunation events resulting from hypoxia. Consequently, it is possible that dredging in these temporary dead zones would result in minimal additional loss of benthic invertebrates because most of this fauna has succumbed to hypoxia-induced death. While seasonal dredging is a potential tool for minimizing the acute effects of dredging, the uncertainty in predicting dissolved oxygen concentrations and the lack of complete understanding of what proportion of infauna dies as opposed to consumed by opportunistic scavengers result in uncertainty of the benefits of this strategy. Further, the potential for synergistic (e.g., additive) effects between the two disturbances would need to be examined prior to any recommendations. Finally, the post-dredging sedimentation impact would not be mitigated by this strategy.

Quantifying the impact of loss of benthic invertebrate production to higher trophic levels as a result of either disturbance (hypoxia or dredging) is difficult. For dredging, impact to benthic infauna occurs directly through removal or burial of sediments during the dredging process. Loss of prey resource may extend for some time in the impacted area due to the occurrence of low dissolved oxygen within the pit and/or high levels of sedimentation inhibiting colonization. While conceptually the linkage between prey and their predators is easy to appreciate, quantifying the effect of habitat degradation on mobile consumers is difficult.

Bioenergetic approaches that assume static trophic transfer efficiency could be used to translate the loss in benthic organisms to higher trophic levels (French McCay and Rowe, 2003). Such an approach requires measurement of the difference in benthic biomass (from either before dredging or from a reference area – biomass after dredging) and uses published estimates of trophic efficiency and demographic rates. The key assumption of this approach is it assumes that loss of prey production is proportional to net loss in production of predators. In other words, predators are food limited (French McCay and Rowe, 2003; Peterson and Lipcius, 2003). Peterson *et al*. (2003) argued that habitat and food limitation assumptions are more defensible for species that utilize unique habitats in an estuarine landscape. Peterson *et al*. (2003) argued that the assumption of habitat limitation and consequently positive trophic consequences of habitat restoration is plausible for oyster reef; however, substantial uncertainty would result from adopting this assumption for mud bottom areas, which are the dominant habitat type in estuaries. A similar argument could be made for offshore regions where unstructured mud bottom areas are the most abundant habitat compared to topographically complex features (rocky out cropping) or elevated sandy substrates (shoals). In this case, arguments for habitat limitation are much stronger for topographically complex and shoal areas than mud bottom areas. Because the trophic efficiency approach is designed to assess impacts to entire trophic levels, another limitation of the approach is the lack of species level responses. An alternative approach that eliminates many of the problems is one that relies on direct measurements of changes in consumer diets as a result of habitat degradation. Such an approach is costly but could be conducted by sampling demersal consumers and benthic invertebrates at the post-dredging area over time.

Table 2.5 Fish and Crab Species Common on Nearshore Sand/Mud Bottom Habitat in the Gulf of Mexico and Atlantic (Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high)

Species/Taxonomic Grouping	Common Name	Foraging Impact	Hypoxia Impact	Spawn/Nursery Impact	Depth Range/ Shelf Distribution	Benthic Habitat	Foraging Habits	Occurrence (absent/rare/sporadic/common/abundant)	Citation
Cartilaginous Fishes									
Ginglymostomatidae	NURSE SHARKS								
Ginglymostoma cirratum	nurse shark	LOW	NONE	NONE	inner shelf	ubiquitous	mollusks/crustaceans/urchins/squids/bony fish	ATL/GOM - sporadic	A,E,F
Caracharhinidae	REQUIEM SHARKS								
Carcharhinus acronotus	blacknose shark	LOW	NONE	LOW	estuary/inner shelf	coarse sand-shell	bony fish	ATL/GOM - sporadic/ FLA common	A,B,C,E,F
Carcharhinus brevipinna	spinner shark	LOW	NONE	LOW	estuary/inner shelf	ubiquitous	squids/octopus/sharks/bony fish	ATL/GOM - sporadic	A,E,F,G
Carcharhinus isodon	finetooth shark	LOW	NONE	LOW	estuary/inner shelf	ubiquitous	squids/bony fish	ATL/GOM - sporadic	A,E,F
Carcharhinus leucas	bull shark	LOW	NONE	LOW	estuary/inner shelf	ubiquitous	mollusks/crustaceans/squids/sharks/bony fish	ATL/GOM - common	A,D,E,F
Carcharhinus limbatus	blacktip shark	MED	NONE	LOW	estuary/inner shelf	ubiquitous	crustaceans/squids/sharks/bony fish	ATL/GOM - abundant	A,B,C,E,F,G
Rhizoprionodon terraenovae	Atlantic sharpnose shark	MED	NONE	LOW	estuary/inner shelf/mid shelf	ubiquitous	polychaetes/mollusks/crustaceans/ bony fishes	ATL/GOM - abundant	A,B,C,D,E,F,G
Sphyrnidae	HAMMERHEAD SHARKS								
Sphyrna tiburo	bonnethead	MED	NONE	LOW	estuary/inner shelf	ubiquitous	mollusks/crustaceans/squids/bony fish	ATL/GOM - common	A,B,C,D,E,F
Triakidae	DOGFISHES								
Mustelus canis	smooth dogfish	MED	NONE	LOW	estuary/inner shelf	ubiquitous	mollusks/crustaceans/squids/urchins/bony fish	ATL/GOM - abundant	A,B,C,D,E,F
Mustelis norrisi	Florida smooth hound	MED	NONE	LOW	inner shelf	ubiquitous	crustaceans/bony fish	ATL/NEGOM to West GOM - sporadic	A,E,F
Rhinobatidae	GUITARFISHES								
Rhinobatos lentiginosus	Atlantic guitarfish	MED	LOW	LOW	estuary/inner shelf	ubiquitous	crustaceans/bony fish	ATL/GOM - common	A,B,C,E,F
Narcinidae	LESSER ELECTRIC RAYS								
Narcine brasiliensis	lesser electric ray	LOW	LOW	LOW	estuary/inner shelf	ubiquitous	crustaceans/bony fish	ATL-common/GOM - sporadic	A,B,C,E,F,G
Rajidae	SKATES								
Raja eglanteria	clearnose skate	MED	LOW	LOW	estuary/inner shelf	ubiquitous	polychaetes/amphipods/crustaceans/bony fish	ATL/NE GOM - common/NW GOM - rare	A,C,D,E,F
Raja teevani (Raja floridana)	Caribbean skate	MED	LOW	LOW	inner shelf/mid shelf	ubiquitous	polychaetes/amphipods/crustaceans/bony fish	ATL-absent/GOM-sporadic	D,E,F
Raja texana	roundel skate	MED	LOW	LOW	inner shelf/mid shelf	ubiquitous	polychaetes/amphipods/crustaceans/bony fish	ATL-absent/NWGOM-abundant/NEGOM-common	A,B,C,G
Dasyatidae									
Dasyatis americana	southern stingray	MED	LOW	LOW	estuary/inner shelf	ubiquitous	mollusks/polychaetes/crustaceans/ bony fish	ATL/GOM - common	A,C,D,E,F,G
Dayatis centroura	roughtail stingray	MED	LOW	LOW	estuary/inner shelf	ubiquitous	mollusks/polychaetes/crustaceans/ bony fish	ATL/GOM - common	B,D
Dasyatis sabina	Atlantic stingray	MED	LOW	LOW	estuary/inner shelf	ubiquitous	polychaetes/crustaceans/bony fish	ATL/GOM - abundant	A,B,C,D,E,F,G
Dasyatis say	bluntnose stingray	MED	LOW	LOW	estuary/inner shelf	ubiquitous	mollusks/polychaetes/crustaceans/ bony fish	ATL/GOM - common	A,B,C,D,E,F
Gymnuridae									

Gymnura micrura	smooth butterfly ray	MED	LOW	LOW	estuary/inner shelf	ubiquitous	mollusks/crustaceans/bony fish	ATL/GOM - common/LA shelf - sporadic	A,B,C,D,E,F
Myliobatidae									
Rhinoptera bonasus	cownose ray	MED	NONE	LOW	estuary/inner shelf	ubiquitous	mollusks/crustaceans	ATL/GOM - abundant	A,B,C,D,E,F,G
Bony Fishes									
Megalopidae	TARPONS								
Megalops atlanticus	tarpon; silver king	LOW	NONE	LOW	estuary/inner shelf	ubiquitous	bony fish/crabs/shrimp	SEATL/NWGOM-sporadic/NEGOM-common	A,D
Elopidae	LADYFISHES								
Elops saurus	ladyfish; skipjack	MED	LOW	LOW	estuary/inner shelf	ubiquitous	crustaceans/bony fish	ATL/GOM - abundant	A,D
Albulidae	BONEFISHES								
Albula vulpes	bonefish	MED	LOW	LOW	estuary/inner shelf	ubiquitous	polychaetes/mollusks/crustaceans/bony fish	SEATL/NEGOM-common/NWGOM-rare	A,D
Muraenidae	MORAYS								
Gymnothorax nigromarginatus	blackedge moray	MED	MED	NONE	estuary/inner shelf	?	crustaceans/polychetes/mollusks/bony fish	ATL/GOM - common	A,C,G
Nettastomatidae	DUCKBILL EELS								
Hoplunnis macrura	freckled pike-conger	MED	MED	NONE	inner shelf/mid shelf	?	crustaceans/polychetes/mollusks/bony fish	ATL/NWGOM - common/NEGOM - rare	A,B,C,G
Congridae	CONGER EELS								
Rhynochoconger flavus	yellow conger	MED	MED	NONE	inner shelf/mid shelf	mud	crustaceans/polychetes/mollusks/bony fish	ATL/NWGOM - common/NEGOM - rare	A,C
Ophichthidae	SNAKE EELS								
Myrophis punctatus	speckled worm eel	HIGH	HIGH	?	estuary/inner shelf/mid shelf	mud	polychaetes/amphipods/crustaceans	ATL/GOM - common	A,B,C
Ophichthus gomesi	shrimp eel	HIGH	HIGH	?	estuary/inner shelf/mid shelf	mud	polychaetes/amphipods/crustaceans	ATL/GOM - common	A,C,G
Synodontidae	LIZARDFISHES								
Saurida brasiliensis	largescale lizardfish	HIGH	HIGH	?	inner shelf/mid shelf	ubiquitous	crustaceans/bony fish	ATL/GOM - common	A,B,C,G
Saurida normani	shortjaw lizardfish	HIGH	HIGH	?	inner shelf/mid shelf	ubiquitous	crustaceans/bony fish	ATL/GOM - common	A,G
Synodus foetens	inshore lizardfish	HIGH	HIGH	MED	estuary/inner shelf/mid shelf	sand/mud/shell/grass	crustaceans/bony fish	ATL/GOM - common	A,B,C,D,G
Synodus intermedius	sand diver	HIGH	HIGH	?	inner shelf/mid shelf	ubiquitous	crustaceans/bony fish	ATL/GOM - common	A,B,C
Trachinocephalus myops	snakefish	HIGH	HIGH	?	inner shelf/mid shelf	coarse sand	crustaceans/bony fish	ATL/GOM - common	A,B,C,G
Ariidae	SEA CATFISHES								
Arius felis	hardhead catfish	MED	LOW	LOW	estuary/inner shelf	ubiquitous	polychaetes/crustaceans/bony fish	ATL - common /GOM - abundant	A,B,C,D,G
Bagre marinus	gafftopsail catfish	MED	LOW	LOW	estuary/inner shelf	ubiquitous	polychaetes/crustaceans/bony fish	GOM-abundant	A,B,C,D,G
Batrachoididae	TOADFISHES								
Opsanus beta	gulf toadfish	MED	MED	LOW	estuary/inner shelf	sand/mud/shell/grass	crustaceans	GOM-abundant	A,C
Opsanus tau	oyster toadfish	MED	MED	LOW	estuary/inner shelf	sand/mud/shell/grass	crustaceans	ATL-abundant	A,C,D
Porichthys plectrodon	Atlantic midshipman	HIGH	MED	MED	inner shelf/mid shelf	sand	crustaceans	GOM-common	A,B,C,G
Gobiesocidae	CLINGFISHES								
Gobiesox strumosus	skilletfish	MED	MED	LOW	estuary/inner shelf	sand/mud/shell/grass	polychaetes/crustaceans	ATL/GOM - abundant	A,C,D
Atennariidae	FROGFISHES								
Antennarius ocellatus	ocellated frogfish	LOW	LOW	?	inner shelf/mid shelf	?	jellyfish/squid/crustaceans/bony fish	ATL/GOM - sporadic	A,C,G

Antennarius radiosus	singlespot frogfish	LOW	LOW	?	inner shelf/mid shelf	?	jellyfish/squid/crustaceans/bony fish	ATL/GOM - sporadic	A,B,C,G
Ogcocephalidae	BATFISHES								
Halieutichthys aculeatus	pancake batfish	LOW	LOW	?	inner shelf/mid shelf	?	crustaceans/bony fish	ATL/GOM - sporadic	A,B,C,G
Ogcocephalus spp.	batfishes	LOW	LOW	?	inner shelf/mid shelf	?	crustaceans/bony fish	ATL/GOM - sporadic	A,B,C,D,G
Gadidae	CODFISHES								
Urophycis cirrata	gulf hake	HIGH	HIGH	?	inner shelf/mid shelf	sand/mud/shell/grass	crustaceans/squid/bony fish	NEGOM/FLA-common/NWGOM-sporadic	A,B,C
Urophycis floridana	southern hake	HIGH	HIGH	?	estuary/inner shelf/mid shelf	sand/mud/shell/grass	crustaceans/squid/bony fish	ATL/GOM-abundant	A,B,C
Urophycis regia	spotted hake	HIGH	HIGH	HIGH	inner shelf/mid shelf	sand/mud/shell/grass	crustaceans/squid/bony fish	ATL-common/NEGOM-common	A,B,C,D
Ophidiidae	CUSK-EELS								
Brotula barbata	bearded brotula	HIGH	HIGH	?	inner shelf/mid shelf	mud	polychaetes/crustaceans/bony fish	GOM-common	A,B,C
Lepophidium graellsi	blackedge cusk-eel	HIGH	HIGH	?	inner shelf/mid shelf	?	polychaetes/crustaceans/bony fish	GOM-abundant	A,B,C,G
Lepophidium jeannae	mottled cusk-eel	HIGH	HIGH	?	inner shelf/mid shelf	?	polychaetes/crustaceans/bony fish	SEATL-sporadic/NEGOM-common	A,C
Ophidion grayi	blotched cusk-eel	HIGH	HIGH	?	inner shelf/mid shelf	?	polychaetes/crustaceans/bony fish	ATL/NEGOM-sporadic	A,C
Ophidion holbrooki	bank cusk-eel	HIGH	HIGH	?	inner shelf/mid shelf	?	polychaetes/crustaceans/bony fish	GOM-common	A,B,C
Ophidion welshi	crested cusk-eel	HIGH	HIGH	?	inner shelf/mid shelf	?	polychaetes/crustaceans/bony fish	ATL/GOM - abundant	A,B,C,G
Otophidium omostigmum	polka-dot cusk-eel	HIGH	HIGH	?	inner shelf/mid shelf	?	polychaetes/crustaceans/bony fish	ATL/NEGOM-sporadic	C
Syngnathidae	PIPEFISHES								
Hippocampus erectus	lined seahorse	LOW	LOW	LOW	estuary/inner shelf	sand/grass/sponge	zooplankton/crustaceans	ATL/GOM-common	A,C,D,G
Hippocampus zosterae	dwarf seahorse	LOW	LOW	LOW	estuary/inner shelf	grass/sponge	zooplankton/crustaceans	ATL/GOM-common	A,C
Micrognathus criniger	fringed pipefish	LOW	LOW	LOW	estuary/inner shelf	sand/grass/sponge	zooplankton/crustaceans	ATL/NEGOM-sporadic/NWGOM-absent	A,C
Syngnathus floridae	dusky pipefish	LOW	LOW	LOW	estuary/inner shelf	grass/sponge	zooplankton/crustaceans	ATL/GOM-sporadic	A,C,D
Syngnathus louisianae	chain pipefish	LOW	LOW	LOW	estuary/inner shelf	sand/grass/sponge	zooplankton/crustaceans	ATL/GOM-abundant	A,C,D
Syngnathus scovelli	gulf pipefish	LOW	LOW	LOW	estuary/inner shelf	sand/grass/sponge	zooplankton/crustaceans	ATL/GOM-common	A,C
Centropomidae	SNOOKS								
Centropomus undecimalis	common snook	LOW	LOW	LOW	estuary/inner shelf	ubiquitous	crustaceans/squids/mollusks/polychaetes/bony fish	subtropical ATL/GOM-common	A,D
Moronidae	STRIPED BASSES								
Morone saxatilis	striped bass	MED	LOW	MED	estuary/inner shelf	ubiquitous	crustaceans/squids/mollusks/polychaetes/bony fish	ATL-common/GOM-sporadic	A,D
Serranidae	SEA BASSES								
Centropristis philadelphica	rock sea bass	LOW	LOW	LOW	inner shelf/mid shelf	sand/mud	crustaceans/mollusks/squid/bony fish	ATL/GOM-common	A,B,C,G
Centropristis stiata	black sea bass	LOW	LOW	LOW	estuary/inner shelf	sand/shell	crustaceans/mollusks/squid/bony fish	ATL/GOM-common	A,B,C
Diplectrum bivittatum	dwarf sand perch	MED	LOW	LOW	inner shelf/mid shelf	sand/shell	crustaceans/mollusks/squid/bony fish	ATL/GOM-sporadic	A,B,C,G
Dipelctrum formosum	sand perch	MED	LOW	LOW	inner shelf/mid shelf	coarse sand	crustaceans/mollusks/squid/bony fish	ATL-common/GOM-sporadic	A,B,C,G
Myctoperca microlepis	gag	LOW	LOW	LOW	estuary/inner shelf	sand/shell/grass/structure	crustaceans/mollusks/squid/bony fish	ATL/GOM-common	A,C,D
Serranus atrobranchus	blackear bass	LOW	LOW	LOW	inner shelf/mid shelf	sand/shell	crustaceans/mollusks/squid/bony fish	NEGOM/NWGOM-sporadic	A,B,C,G
Serranus subligarus	belted sandbass	MED	LOW	LOW	inner shelf/mid shelf	sand/shell	crustaceans/mollusks/squid/bony fish	ATL/GOM-common	A,C
Pomatomidae	BLUEFISHES								

Pomatomus salatrix	bluefish	MED	LOW	MED	estuary/inner shelf	ubiquitous	bony fish	ATL-abundant/NEGOM-sporadic/NWGOM-absent	A,B,C,D,G
Rachycentridae	COBIAS								
Rachycentron canadum	cobia	LOW	LOW	HIGH	estuary/inner shelf	ubiquitous	crustaceans/squid/bony fish	ATL/GOM-common	A,C,D,G
Carangidae	JACKS								
Caranx hippos	crevalle jack	MED	LOW	LOW	estuary/inner shelf/mid shelf	sand/shell/structure	crustaceans/squid/bony fish	ATL/GOM-abundant	A,B,C,D,G
Chloroscombrus chrysurus	Atlantic bumper	MED	LOW	MED	estuary/inner shelf	ubiquitous	crustaceans/squid/bony fish	ATL/GOM-common	A,B,C,D,G
Seriola dumerili	greater amberjack	MED	NONE	NONE	inner shelf/mid shelf	sand/shell/structure	crustaceans/squid/bony fish	ATL/GOM-common	A,C,D,G
Trachinotus carolinus	Florida pompano	MED	LOW	MED	estuary/inner shelf	sand	crustaceans/mollusks/squid	ATL/GOM-abundant	A,B,D
Trachinotus falcatus	permit	MED	LOW	MED	estuary/inner shelf	sand	crustaceans/mollusks/squid/bony fish	ATL/GOM-sporadic	A,D
Lutjanidae	SNAPPERS								
Lutjanus campechanus	red snapper	LOW	LOW	LOW	inner shelf/mid shelf	sand/shell/structure	crustaceans/bony fish	ATL/GOM-abundant	A,B,C,G
Lutjanus griseus	gray snapper	LOW	LOW	LOW	estuary/inner shelf/mid shelf	sand/shell/grass/structure	crustaceans/bony fish	ATL/GOM-abundant	A,B,C,D
Gerreidae	MOJARRAS								
Eucinostomus argenteus	spotfin mojarra	MED	LOW	LOW	estuary/inner shelf	ubiquitous	epibenthic inverts/polychaetes	ATL/GOM-abundant	A,B,C,D
Eucinostomus gula	silver jenny	MED	LOW	LOW	estuary/inner shelf	ubiquitous	epibenthic inverts/polychaetes	ATL/GOM-abundant	A,B,C,D,G
Haemulidae	GRUNTS								
Haemulon macrostomum	Spanish grunt	LOW	LOW	LOW	estuary/inner shelf	sand/shell/grass/structure	polychaetes/mollusks/crustaceans/bony fish	ATL-sporadic/FLA-abundant/GOM-abundant	A,C
Orthopristis chrysoptera	pigfish	MED	LOW	MED	estuary/inner shelf	sand/shell/grass/structure	polychaetes/mollusks/crustaceans/bony fish	ATL/GOM-abundant	A,B,C,D,G
Sparidae	PORGIES								
Archosargus probatocephalus	sheepshead	MED	MED	MED	estuary/inner shelf	sand/shell/grass/structure	mollusks/crustaceans	ATL/GOM-abundant	A,B,C,D
Calamus arctifrons	grass porgy	LOW	LOW	LOW	estuary/inner shelf	sand/shell/grass/structure	plants/sponges/hydroids/polychaetes	ATL-rare/NEGOM-common/NWGOM-rare	A,C
Diplodus holbrooki	spottail pinfish	MED	MED	MED	estuary/inner shelf	sand/shell/grass/structure	plants/sponges/hydroids/polychaetes	ATL/NEGOM-abundant/NWGOW-sporadic	A,C,D
Lagodon rhomboides	pinfish	MED	MED	HIGH	estuary/inner shelf	ubiquitous	plants/sponges/hydroids/polychaetes	ATL/GOM-abundant	A,B,C,D,G
Stenotomus caprinus	longspine porgy	LOW	LOW	LOW	inner shelf/mid shelf	ubiquitous	plants/sponges/hydroids/polychaetes	ATL/NEGOM-rare/NWGOM-common	A,B,C,G
Sciaenidae	DRUMS								
Bardiella chrysoura	silver perch	HIGH	LOW	HIGH	estuary/inner shelf	ubiquitous	crustaceans/polychaetes/bony fish	ATL/GOM-abundant	A,B,C,D,G
Cynoscion arenarius	sand seatrout	HIGH	LOW	HIGH	estuary/inner shelf	ubiquitous	crustaceans/bony fish	ATL-absent/GOM-abundant	A,B,C,G
Cynoscion nebulosus	spotted seatrout	HIGH	LOW	HIGH	estuary/inner shelf	ubiquitous	crustaceans/bony fish	ATL/GOM-abundant	A,B,C,D,G
Cynoscion nothus	silver seatrout	HIGH	LOW	HIGH	estuary/inner shelf	ubiquitous	crustaceans/bony fish	ATL/GOM-abundant	A,B,C,D,G
Cynoscion regalis	weakfish	HIGH	LOW	HIGH	estuary/inner shelf	ubiquitous	crustaceans/bony fish/squid	ATL-abundant/GOM-absent	D
Larimus fasciatus	banded drum	HIGH	LOW	LOW	inner shelf/mid shelf	sand	crustaceans	ATL/GOM-abundant	A,B,C,D,G
Leiostomus xanthurus	spot	HIGH	MED	HIGH	estuary/inner shelf	ubiquitous	polychaetes/crustaceans/mollusks	ATL/GOM-abundant	A,B,C,D,G
Menticirrhus americanus	southern kingfish	HIGH	MED	HIGH	estuary/inner shelf	sand	crustaceans/polychaetes	ATL/GOM-abundant	A,B,C,D,G
Menticirrhus littoralis	gulf kingfish	HIGH	MED	HIGH	estuary/inner shelf	sand	crustaceans/polychaetes	ATL/GOM-abundant	A,B,C,D
Menticirrhus saxatilis	northern kingfish	HIGH	MED	HIGH	estuary/inner shelf	sand	crustaceans/polychaetes	ATL/GOM-abundant	A,C,D
Micropogonias undulatus	Atlantic croaker	HIGH	MED	HIGH	estuary/inner shelf	ubiquitous	polychaetes/crustaceans/bony fish	ATL/GOM-abundant	A,B,C,D,G

Pogonias cromis	black drum	HIGH	MED	HIGH	estuary/inner shelf	ubiquitous	crustaceans/bony fish/mollusks	ATL/GOM-abundant	A,C,D
Sciaenops ocellatus	red drum	HIGH	LOW	HIGH	estuary/inner shelf	ubiquitous	crustaceans/bony fish	ATL/GOM-abundant	A,B,C,D,G
Stellifer lanceolatus	star drum	HIGH	LOW	HIGH	inner shelf/mid shelf	sand	epibenthic crustaceans	ATL/GOM-abundant	A,B,C,D,G
Mullidae	GOATFISHES								
Upeneus parvus	dwarf goatfish	LOW	LOW	?	inner shelf	?	?	ATL/GOM-common	A,B,C,G
Ephippidae	SPADEFISHES								
Chaetodipterus faber	Atlantic spadefish	LOW	LOW	?	estuary/inner shelf	ubiquitous	hydroids/polychaetes/amphipods/jellyfish	ATL/GOM-abundant	A,B,C,D
Labridae	WRASSES								
Hemipteronotus novacula	pearly razorfish	MED	MED	?	inner shelf	sand-coarse sand	polychaetes/crustaceans	ATL-sporadic/GOM-common	A,B,C
Mugilidae	MULLETS								
Mugil cephalus	striped mullet	LOW	LOW	LOW	estuary/inner shelf	ubiquitous	detritus/zooplankton/algae	ATL/GOM-abundant	A,B,C,D
Polynemidae	THREADFINS								
Polydactylus octonemus	Atlantic threadfin	MED	MED	MED	estuary/inner shelf	sand	zooplankton/epibenthic inverts	ATL/GOM-abundant	A,B,C,D,G
Uranoscopidae	STARGAZERS								
Astroscopus y-graecum	southern stargazer	HIGH	HIGH	HIGH	inner shelf	sand	crustaceans/bony fish	ATL/GOM-common	A,B,C
Blenniidae	COMBTOOTH BLENNIES								
Chasmodes saburrae	Florida blenny	MED	MED	LOW	estuary/inner shelf	sand/grass/shell	epibenthic inverts/mollusks/tunicates	ATL-absent/NEGOM-sporadic/NWGOM-absent	A,C
Hypleurochilus geminatus	crested blenny	MED	MED	LOW	estuary/inner shelf	sand/grass/shell	epibenthic inverts/mollusks/tunicates	ATL/GOM-common	A,C
Hypsoblennius hentzi	feather blenny	MED	MED	LOW	estuary/inner shelf	mud/grass/shell	epibenthic inverts/mollusks/tunicates	ATL/GOM-common	A,C,D
Gobiidae	GOBIES								
Bollmannia communis	ragged goby	MED	MED	LOW	estuary/inner shelf	mud	epibenthic inverts/mollusks/tunicates	ATL-absent/NWGOM-sporadic/NEGOM-rare	A,B,C,G
Gobiosoma robustum	code goby	MED	MED	LOW	estuary/inner shelf	sand/mud/grass	epibenthic inverts/mollusks/tunicates	ATL/GOM-common	A,C,D
Stromateidae	BUTTERFISHES								
Peprilis alepidotus	harvestfish	LOW	LOW	MED	estuary/inner shelf	sand	jellyfish/crustaceans/polychaetes/bony fish	ATL/GOM-common	A,B,C,D,G
Peprilis burti	gulf butterfish	LOW	LOW	MED	estuary/inner shelf	sand	jellyfish/crustaceans/polychaetes/bony fish	ATL/GOM-common	A,B,C,D,G
Scorpaenidae	SCORPIONFISHES								
Pontinus longispinis	longspine scorpionfish	MED	LOW	LOW	inner shelf/mid shelf	mud	crustaceans/bony fish	ATL/GOM-sporadic	A,B,C
Scorpaena brasiliensis	barbfish	MED	LOW	LOW	estuary/inner shelf/mid shelf	?	crustaceans/bony fish	ATL/NWGOM-sporadic/NEGOM-common	A,B,C,G
Scorpaena calcarata	smoothhead scorpionfish	MED	LOW	LOW	inner shelf	?	crustaceans/bony fish	ATL/GOM-common	A,B,C,G
Triglidae	SEAROBINS								
Prionotus ophyras	bandtail searobin	MED	LOW	LOW	inner shelf/mid shelf	ubiquitous	crustaceans/polychaetes/squid	ATL/GOM-sporadic	A,B,C,G
Prionotus paralatus	Mexican searobin	MED	LOW	LOW	inner shelf/mid shelf	ubiquitous	crustaceans/polychaetes/squid	ATL-absent/NEGOM-sporadic/NWGOM-abundant	A,B,C,G
Prionotus alatus	spiny searobin	MED	LOW	LOW	inner shelf/mid shelf	ubiquitous	crustaceans/polychaetes/squid	ATL/NEGOM-abundant/NWGOM-absent	A,G
Prionotus rubio	blackwing searobin	MED	LOW	LOW	inner shelf	ubiquitous	crustaceans/polychaetes/squid	ATL/GOM-common	B,C,D,G
Prionotus scitulus	leopard searobin	MED	LOW	LOW	estuary/inner shelf	ubiquitous	crustaceans/polychaetes/squid	ATL/GOM-common	A,B,C,D,G
Prionotus tribulus	bighead searobin	MED	LOW	LOW	estuary/inner shelf	ubiquitous	crustaceans/polychaetes/squid	ATL/GOM-abundant	A,B,C,D,G
Bothidae	LEFTEYE FLOUNDERS								
Ancylopsetta quadrocellata	ocellated flounder	MED	LOW	MED	estuary/inner	ubiquitous	crustaceans/polychaetes/bony fish	ATL/GOM-common	A,B,C,G

					shelf/mid shelf				
Bothus robinsi	twospot flounder	MED	LOW	MED	inner shelf	ubiquitous	crustaceans/polychaetes/bony fish	ATL/NWGOM-absent/NEGOM-sporadic	A,C
Citharichthys macrops	spotted whiff	MED	MED	MED	inner shelf/mid shelf	coarse sand/shell	crustaceans/polychaetes/bony fish	ATL/NEGOM-common/NWGOM-rare	A,B,C,G
Citharichthys spilopterus	bay whiff	MED	MED	MED	estuary/inner shelf	ubiquitous	crustaceans/polychaetes/bony fish	ATL/GOM-abundant	A,B,C,D,G
Cyclopsetta chittendeni	Mexican flounder	MED	LOW	?	inner shelf/mid shelf	ubiquitous	crustaceans/polychaetes/bony fish	ATL-absent/GOM-common	A,B,C,G
Etropus crossotus	fringed flounder	MED	LOW	MED	inner shelf	ubiquitous	crustaceans/polychaetes/bony fish	ATL/GOM-sporadic	A,B,D,G
Etropus microstomus	smallmouth flounder	MED	LOW	?	estuary/inner shelf	mud	crustaceans/polychaetes/bony fish	ATL-common/GOM-absent	C,D
Etropus rimosus	Gray flounder	MED	LOW	?	estuary/inner shelf	ubiquitous	crustaceans/polychaetes/bony fish	ATL/NWGOM-absent/NEGOM-sporadic	B,C,D
Paralichthys albigutta	Gulf flounder	MED	LOW	MED	estuary/inner shelf	sand/grass	crustaceans/polychaetes/bony fish	ATL/GOM-common	A,B,C
Paralichthys dentatus	summer flounder	MED	MED	MED	estuary/inner shelf	ubiquitous	crustaceans/polychaetes/bony fish	ATL-abundant/GOM-absent	D
Paralichthys lethostigma	southern flounder	MED	MED	MED	estuary/inner shelf	ubiquitous	crustaceans/polychaetes/bony fish	ATL/GOM-abundant	A,B,C,D,G
Paralichthys squamilentus	broad flounder	MED	LOW	MED	estuary/inner shelf/mid shelf	ubiquitous	crustaceans/polychaetes/bony fish	ATL/GOM-sporadic	A,B,C,G
Syacium gunteri	shoal flounder	MED	LOW	LOW	inner shelf/mid shelf	ubiquitous	crustaceans/polychaetes/bony fish	ATL-absent/GOM-common	A,B,C,G
Syacium papillosum	dusky flounder	MED	LOW	LOW	inner shelf/mid shelf	ubiquitous	crustaceans/polychaetes/bony fish	ATL/NEGOM-common/NWGOM-rare	A,B,C
Soleidae	SOLES								
Achirus lineatus	lined sole	MED	MED	MED	estuary/inner shelf	ubiquitous	crustaceans/polychaetes	ATL/GOM-abundant	A,B,C
Gymnachirus texae	fringed sole	MED	MED	MED	inner shelf/mid shelf	mud	crustaceans/polychaetes	ATL/NEGOM-absent/NWGOM-common	A,B,G
Gymnachirus melas	naked sole	MED	MED	MED	inner shelf/mid shelf	mud	crustaceans/polychaetes	ATL/NEGOM-common/NWGOM-absent	A,C
Trinectes maculatus	hogchoker	MED	MED	MED	estuary/inner shelf	ubiquitous	crustaceans/polychaetes	ATL/GOM-abundant	A,B,C,D,G
Cynoglossidae	TONGUEFISHES								
Symphurus civitatus	offshore tonguefish	HIGH	HIGH	MED	inner shelf	ubiquitous	crustaceans/polychaetes	ATL/GOM-common	A,B,C
Symphurus diomedianus	spottedfin tonguefish	HIGH	HIGH	MED	inner shelf	ubiquitous	crustaceans/polychaetes	ATL/GOM-sporadic	A,B,C
Symphurus plagiusa	blackcheek tonguefish	HIGH	HIGH	MED	estuary/inner shelf	ubiquitous	crustaceans/polychaetes	ATL/GOM-abundant	A,B,C,D,G
Balistidae	LEATHERJACKETS								
Aluterus schoepfi	orange filefish	LOW	LOW	LOW	estuary/inner shelf	sand/shell/grass	plants/algae	ATL/GOM-common	A,B,C,D,G
Aluterus scriptus	scrawled filefish	LOW	LOW	LOW	estuary/inner shelf	sand/shell/grass	epibenthic inverts	ATL/GOM-common	A,C
Balistes capriscus	gray triggerfish	LOW	LOW	LOW	estuary/inner shelf	sand/shell/structure	crabs/mollusks/sea urchins/corals	ATL/GOM-abundant	A,B,C,D,G
Monacanthus ciliatus	fringed filefish	LOW	LOW	LOW	estuary/inner shelf	sand/shell/grass	epibenthic inverts/mollusks/polychaetes/sea urchins	ATL/NEGOM-common/NWGOM-absent	A,B,C
Monacanthus hispidus	planehead filefish	LOW	LOW	LOW	estuary/inner shelf	sand/shell/grass	epibenthic inverts/mollusks/polychaetes/sea urchins	ATL/GOM-abundant	A,B,C,D,G
Ostraciidae	BOXFISHES								
Lactophrys quadricornis	scrawled cowfish	LOW	LOW	LOW	estuary/inner shelf	sand/shell/grass	epibenthic inverts/mollusks/polychaetes/sea urchins	ATL/GOM-common	A,B,C
Tetraodontidae	PUFFERS								
Lagocephauls laevigatus	smooth puffer	MED	MED	MED	estuary/inner shelf/mid shelf	ubiquitous	sponge/crustactean/sea urchin/polychaetes/hydroids	ATL/GOM-common	A,B,C,D,G

Sphoeroides dorsalis	marbled puffer	MED	MED	LOW	inner shelf	ubiquitous	sponge/crustacean/sea urchin/polychaetes/hydroids	ATL/GOM-sporadic	A,B,C
Sphoeroides nephelus	southern puffer	MED	MED	MED	estuary/inner shelf	ubiquitous	sponge/crustacean/sea urchin/polychaetes/hydroids	ATL/GOM-common	A,C
Sphoeroides parvus	least puffer	MED	MED	MED	estuary/inner shelf	ubiquitous	sponge/crustacean/sea urchin/polychaetes/hydroids	ATL/GOM-common	A,B,C,G
Diodontidae	PORCUPINEFISHES								
Chilomycterus schoepfi	striped burrfish	LOW	LOW	LOW	estuary/inner shelf	ubiquitous	hermit crabs	ATL/GOM-common	A,B,C,G
MacroInvertebrates									
Shrimps									
Farfantepenaeus aztecus	brown shrimp	HIGH	HIGH	MED	estuary/inner shelf/mid shelf	ubiquitous	detritus/epiphytes/infaunal inverts	ATL/GOM-abundant	C,D,G,H
Farfantepenaeus duorarum	pink shrimp	HIGH	HIGH	MED	estuary/inner shelf/mid shelf	sand/shell-sand/muddy sand	detritus/epiphytes/infaunal inverts	ATL/NWGOM-abundant/NEGOM-common	C,D,G,H
Gibbesia neglecta	mantis shrimp	HIGH	HIGH	MED	inner shelf/mid shelf	mud bottoms	mollusks/crustaceans/bony fishes	ATL/GOM-sporadic	G
Litopenaeus setiferus	white shrimp	HIGH	HIGH	MED	estuary/inner shelf	ubiquitous	detritus/epiphytes/infaunal inverts	ATL/GOM-abundant	C,D,G,H
Parapenaeus longirostris	deepwater pink shrimp	HIGH	HIGH	LOW	inner shelf/mid shelf	ubiquitous	detritus/epiphytes/infaunal inverts	ATL/GOM-sporadic	D
Sicyonia brevirostris	brown rock shrimp	HIGH	HIGH	MED	estuary/inner shelf/mid shelf	sand/shell-sand	detritus/epiphytes/infaunal inverts	ATL/NWGOM-common/NEGOM-abundant	C,D,G,H
Sicyonia dorsalis	lesser rock shrimp	HIGH	HIGH	LOW	estuary/inner shelf/mid shelf	mud/shell	detritus/epiphytes/infaunal inverts	ATL-common/GOM-abundant	C,G,H
Sicyonia laevigata	rock shrimp	HIGH	HIGH	LOW	estuary/inner shelf	mud/muddy sand/shell	detritus/epiphytes/infaunal inverts	ATL/GOM-common	C,D,H
Sicyonia typica	Kinglet rock shrimp	HIGH	HIGH	MED	inner shelf/mid shelf	sand/muddy sand/shell	detritus/epiphytes/infaunal inverts	ATL/GOM-common	C,H
Solenocera atlantidis	dwarf humpback shrimp	HIGH	HIGH	MED	inner shelf/mid shelf	ubiquitous	detritus/epiphytes/infaunal inverts	ATL/GOM-common	D,H
Squilla chydaea	mantis shrimp	HIGH	HIGH	MED	inner shelf/mid shelf	mud bottoms	mollusks/crustaceans/bony fishes	SEATL/GOM-common	G
Squilla empusa	mantis shrimp	HIGH	HIGH	MED	estuary/inner shelf/mid shelf	mud bottoms	mollusks/crustaceans/bony fishes	ATL/GOM-abundant	G
Trachypenaeus constrictus	roughneck shrimp	HIGH	HIGH	MED	inner shelf/mid shelf	sand/muddy sand/shell	detritus/epiphytes/infaunal inverts	ATL/GOM-common	C,D,G,H
Trachypenaeus similis	broken neck shrimp	HIGH	HIGH	MED	inner shelf/mid shelf	sand/muddy sand/shell	detritus/epiphytes/infaunal inverts	ATL/GOM-common	C,G
Xiphopeneus kroyeri	seabob	HIGH	HIGH	HIGH	estuary/inner shelf	ubiquitous	detritus/epiphytes/infaunal inverts	ATL/NEGOM-sporadic/NWGOM-common	D,H
Crabs									
Arenaeus cribrarius	speckled crab	HIGH	HIGH	HIGH	estuary/inner shelf	sand	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-abundant	G,H
Calappa flammea	box crab	HIGH	HIGH	HIGH	inner shelf	sand	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-abundant	G,H
Calappa sulcata	shame face crab	HIGH	HIGH	HIGH	inner shelf	sand	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Callinectes sapidus	blue crab	HIGH	HIGH	HIGH	estuary/inner shelf	ubiquitous	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-abundant	G,H
Callinectes similus	portunid crab	HIGH	HIGH	HIGH	estuary/inner shelf	ubiquitous	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-abundant	G,H
Collodes robustus	spider crab	HIGH	HIGH	?	estuary/inner shelf	ubiquitous	epiphytes/infaunal	ATL/GOM-common	G,H

							inverts/mollusks/crustactans		
Dromidia antillensis	hairy sponge crab	HIGH	HIGH	HIGH	estuary/inner shelf	ubiquitous	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Hepatus epheliticus	calico box crab	HIGH	HIGH	HIGH	estuary/inner shelf	sand	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Libinia emarginata	portly spider crab	HIGH	HIGH	HIGH	estuary/inner shelf	ubiquitous	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-abundant	G,H
Neopanope sayi	mud crab	HIGH	HIGH	MED	estuary/inner shelf	mud/shell/grass	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-abundant	G,H
Ovalipes floridanus	Florida lady crab	HIGH	HIGH	?	estuary/inner shelf	sand	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G
Pagurus pollicaris	flatclaw hermit crab	HIGH	HIGH	MED	estuary/inner shelf	ubiquitous	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-abundant	G,H
Parthenope granulata	bladetooth elbow crab	HIGH	HIGH	?	inner shelf/mid shelf	ubiquitous	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Persephona crinita	pink purse crab	HIGH	HIGH	?	estuary/inner shelf	mud/shell	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-sporadic	G
Persephona mediterranea	mottled purse crab	HIGH	HIGH	?	estuary/inner shelf	mud/shell	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Portunus gibbsei	portunid crab	HIGH	HIGH	HIGH	estuary/inner shelf	mud/sand/shell	epiphytes/infaunal inverts/mollusks/crustactans	ATL/NEGOM-common/NWGOM-rare	G,H
Portunus spinicarpis	portunid crab	HIGH	HIGH	HIGH	inner shelf	mud/sand/shell	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Portunus spinimanus	blotched swimming crab	HIGH	HIGH	HIGH	inner shelf	sand/muddy sand	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Starfish									
Luidia alternata	banded sea star	HIGH	HIGH	HIGH	inner shelf/mid shelf	sand	epiphytes/detritus/mollusks/echinoderms/tunicates	ATL/GOM-common	G
Luidia clathrata	sand star fish	HIGH	HIGH	HIGH	inner shelf/mid shelf	sand	epiphytes/detritus/mollusks/echinoderms/tunicates	ATL/GOM-common	G
Ophiolepis elegans	elegant brittle star	HIGH	HIGH	HIGH	estuary/inner shelf/mid shelf	ubiquitous	epiphytes/detritus	ATL/GOM-common	G

(Citation: A= Hoese and Moore, 1998, B= Darnell *et al*., 1993, C= Darnell *et al*., 1987, D= Murdy *et al*., 1997, E= Schwartz, 2003, F= Bigelow & Schroeder, 1948, G= SEAMAP 2004, H= Williams, 1984)

3.0 HOLLY BEACH DREDGE PIT CASE STUDY ANALYSIS

The Holly Beach Dredge Pit on the OCS offshore western Louisiana provides an ideal case study to evaluate the physical, biological and biophysical impacts of dredge pits in muddy seafloor settings. As noted earlier in this document much less is known about the morphologic evolution and related biological impacts for pits in muddy seafloor settings, as compared to those in sandy settings. Also, the immediate concern of MMS will be pits in muddy settings to support future demands for beach nourishment sand along the Louisiana coast, where the OCS mostly consists of a muddy seafloor.

The Holly Beach Pit was dredged in April 2003 and had filled to more than two-thirds of its capacity by the March 2007 survey completed for this project. Section 3.1 provides a description the data collected as part of this investigation and previous investigations of this pit. Section 3.2 describes the analysis and numerical modeling of the processes associated with the physical and biological changes in and around the pit. This leads to the development of an improved understanding of impacts for dredge pits in muddy seafloor settings and the development of guidelines for investigation and mitigation of impacts.

3.1 Field Investigations at the Holly Beach Dredge Pit

3.1.1 Hydrographic Surveys

3.1.1.1 Bathymetry - Historical

The authoritative source for historical raw sounding survey data is from the Geophysical Data System (GeoDAS) for Hydrographic Survey Data, National Geophysical Data Center, National Ocean Service, NOAA. The GeoDAS collection was accessed using the online Internet web interface to gather multiple surveys from many different time periods. Coverage for Holly Beach borrow area is provided by these two datasets:

- Sabine Bank, NGDC# 03071083, surveyed in 1964, at a mapping scale of 1:40,000

- Between Calcasieu Pass and Sabine Pass, NGDC# 03091067, surveyed in 1978, at a mapping scale of 1:20,000

3.1.1.2 Bathymetry – Recent

Multiple detailed surveys at the Holly Beach borrow site were conducted by Weeks Marine, Inc. relating to the April 2003 dredging, including:

1. Pre-construction/dredging borrow area (transects at 300 ft or 90 m spacing);

2. Post-stripping borrow area (transects at 50 ft or 15 m spacing); and

3. Post-construction borrow area (transects at 50 ft or 15 m spacing).

A limited survey of the dredge pit was completed in May 2004 which consisted of only 4 transect lines (3 East-West and 1 North-South) – this particular survey was not suitable for a surface creation, only for profile comparison.

All these 2003 to 2004 hydrographic survey datasets were provided via Coastal Planning & Engineering, Inc. (CP&E), Boca Raton, Florida.

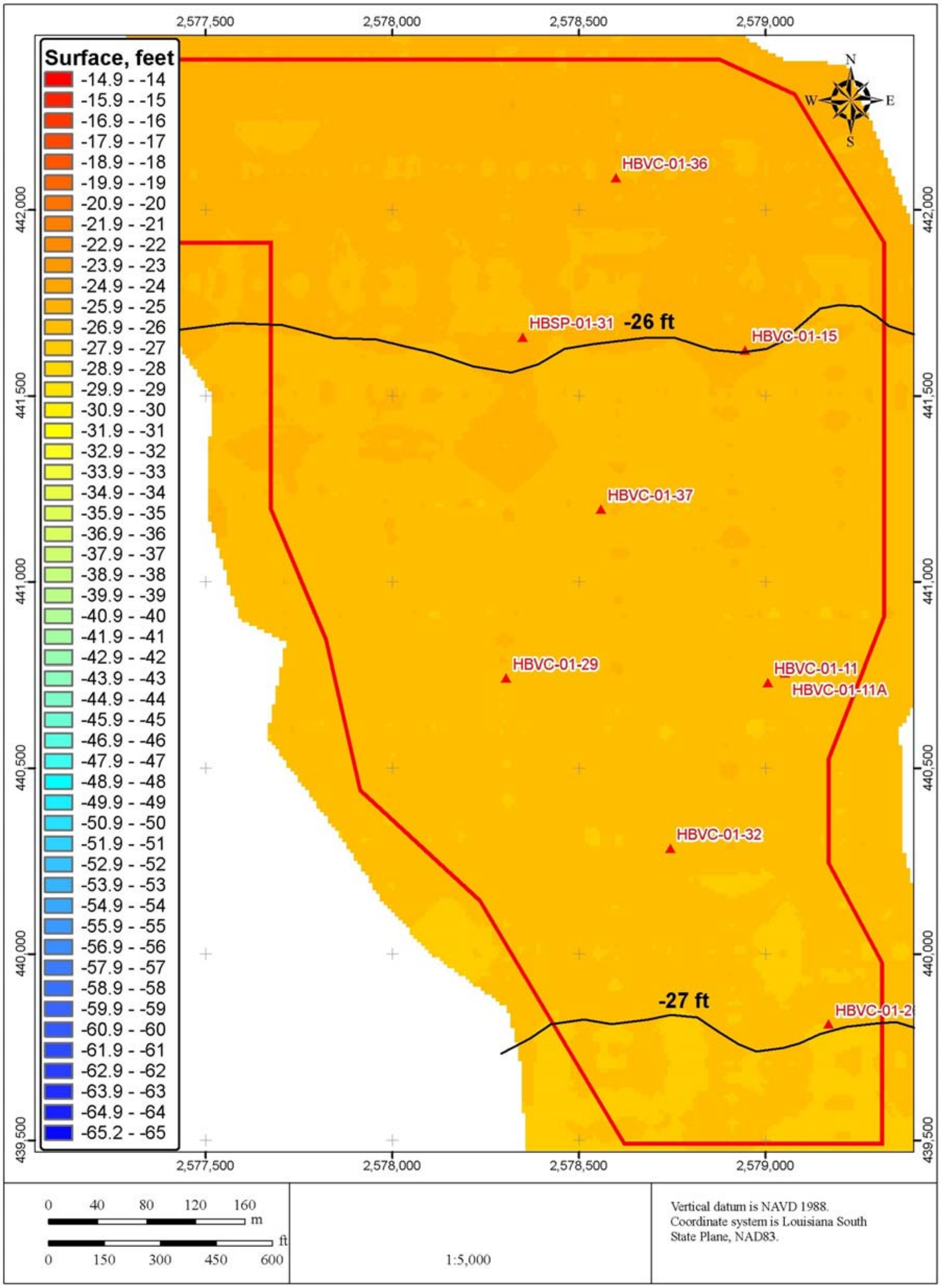

Figure 3.1 Holly Beach Dredge Pit - Bathymetry Before Dredging (April 2003)

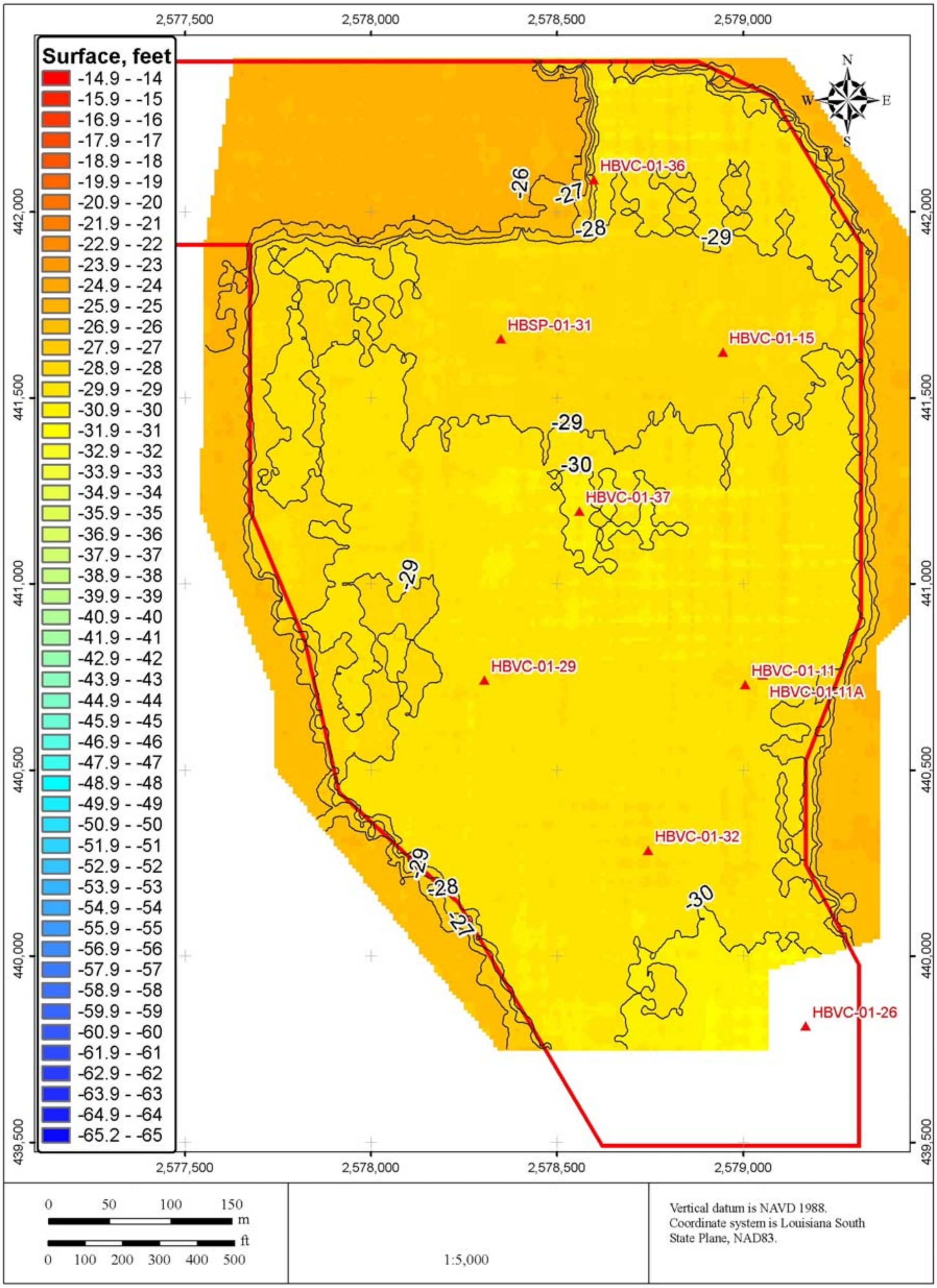

Figure 3.2 Holly Beach Dredge Pit - Bathymetry After Stripping (April 2003)

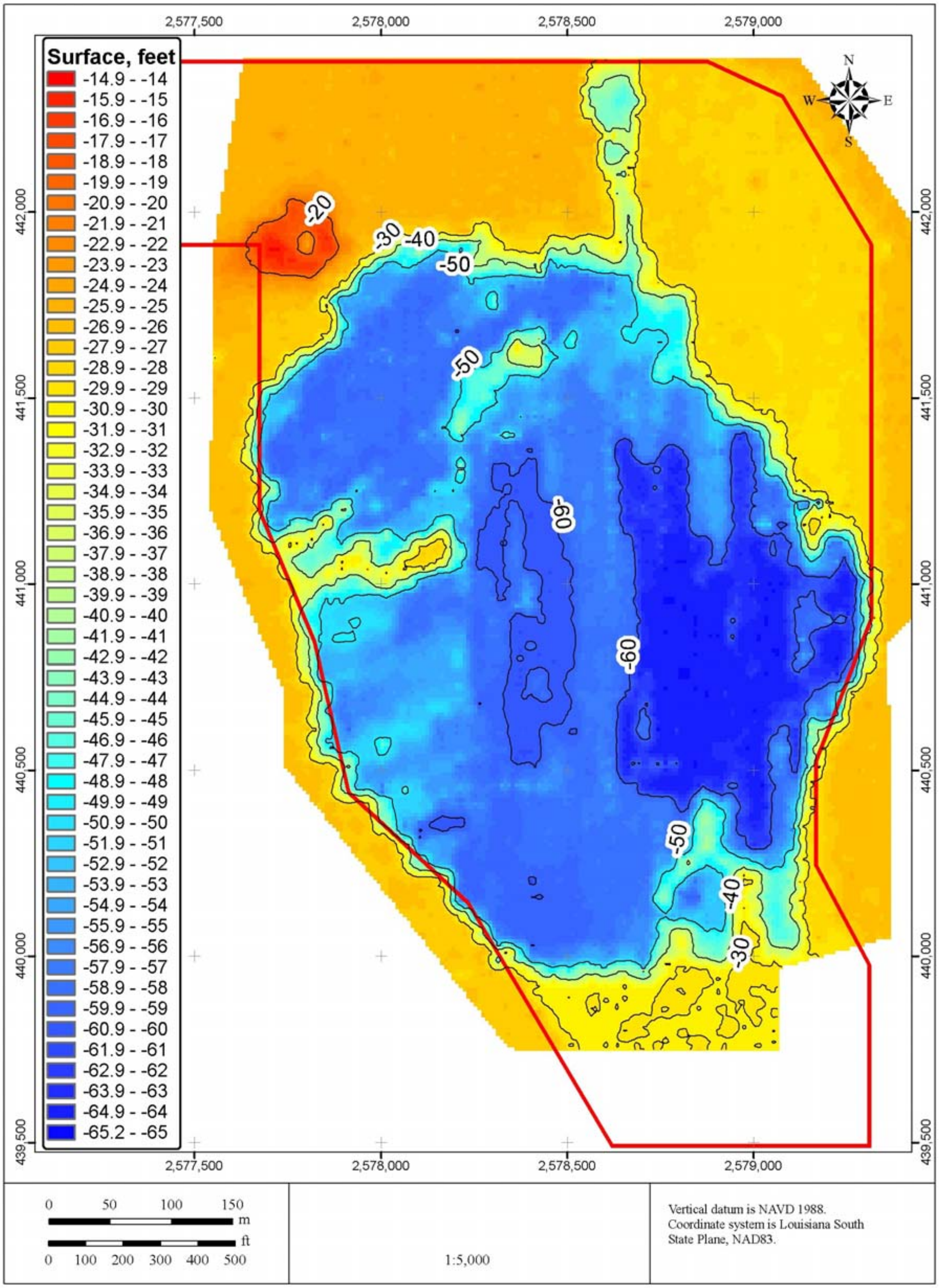

Figure 3.3 Holly Beach Dredge Pit – Bathymetry After Dredging (April 2003)

3.1.1.2.1 New Hydrographic Surveys and Methodology

A series of new, very specific hydrographic surveys were commissioned by Baird, as part of a larger field collection program. Environmental Resource Information Services (ERIS), Environmental and GIS Consultants, of Port Aransas, Texas, conducted these at the Holly Beach dredge pit. These hydrographic surveys were conducted in December 2004, June 2006 and May 2007.

Bathymetric data were acquired using a single-frequency (200 kHz) echo sounder (Odom Hydrotrac) affixed to a 26 ft (8 m) survey vessel. The survey vessel was equipped with a narrow-beam (3-degree) transducer and survey-grade Differential GPS (DGPS) which provided sub-meter dynamic position accuracy throughout the survey. Position data were logged as X and Y coordinates in feet referenced to State Plane. The vertical datum was referenced to MLLW at Calcasieu Pass and these elevations were converted to NAVD88 using the conversion relationship for Galveston Pier (a conversion was not available for Calcasieu Pass but a comparison of the tidal range and levels at Galveston and Calcasieu indicated a difference of less than 1 inch). Therefore, the conversion relationship for Galveston was used where NAVD88 is 0.6 ft (0.186 m) higher than MLLW.

Data synchronization and recording was performed by a PC-based navigation system (HYPACK from Coastal Oceanographics). The pre-plotted survey lines, and the actual survey lines traversed by the vessel, were displayed in real-time on a video monitor. As a measure of quality control, digitized depth soundings recorded by HYPACK were checked against the analog paper record produced by the echo sounder. All data acquisition systems, including the echosounder and the on-board computer systems were calibrated before and after each survey day, including the use of bar checks.

The raw XYZ data were examined post-survey to verify there were no anomalous values or data gaps. Data were then cleaned, filtered, and tide-corrected to generate a final processed data set, then merged into a common XYZ file. This file was then used to generate a 3-dimensional digital surface, from which contours were plotted for the entire project area.

Filtering of the data was performed by using a specific distance value along transect lines to establish an average depth value for the chosen distance interval. Through analysis of the sea-state and subsequent boat motion during the data collection period, a 20-ft (6 m) horizontal filtering value was selected. This value accounted for the rolling period of the survey vessel and produced the best data quality.

Cleaning of the data was also necessary due to the soft nature of the muddy seabed in the bottom of the borrow-pit. Using the 200kHz echosounder frequency, some acoustic penetration generated digital depth values deeper than the initial seabed layer. These values were removed from each survey transect to generate a more consistent first-return data set.

Following data processing there are still present some artifacts of boat motion and sub-bottom penetration that could not be effectively removed from the data set. This is a fairly common occurrence in offshore data collection programs using small survey vessels. It has been estimated that the vertical accuracy of the depth soundings is approximately +/- 4 to 6 inches (or +/-10 to 15 cm) with greater accuracy outside the pit and less inside the pit (the latter due to the soft nature of the surface sediment). Fluctuations in seabed elevations were checked both inside and outside the pit through diver observations and were found to be consistent with echosounder recordings.

December 2004

This survey consisted of survey lines that corresponded with the previous detailed surveys (post stripping and post construction), which had transect lines spaced about 50 ft (15 m) between lines. Over 500,000 soundings were originally collected, but only approximately 21,000 soundings were used.

June 2006

The original survey consisted of over 535,000 soundings. The transect lines are spaced on a 100 by 100 ft (30 by 30 m) grid, which is double the spacing compared to the December 2004 survey, but the sounding frequency along the lines is much higher, with a sounding less than every 8 in (20 cm) along the lines. A re-sampled point layer was created, selecting out every 10^{th} point (only 53,000 points).

March 2007

Whereas previous surveys provided a series of transect lines on an overall grid pattern, this survey provided only a few transects that matched with previous transects across the dredge pit area. This survey instead focused on radial lines extending from the pit's inner edge outward to see the pit in the context of localized surface change.

This most recent survey did not provide a series of lines covering the complete dredge pit area in a grid pattern because previous surface change reviews showed that the pit infilling was relatively consistent across the entire dredge pit. The few full-borrow transects completed in this survey did in fact confirm this to still be the case.

Upon review of the hydrographic survey, a small scatter, about 0.5 feet (15 cm) in height, has been observed in the area surrounding the borrow pit. The scatter is due both to waves during the survey to some extent due to irregularity of the bottom.

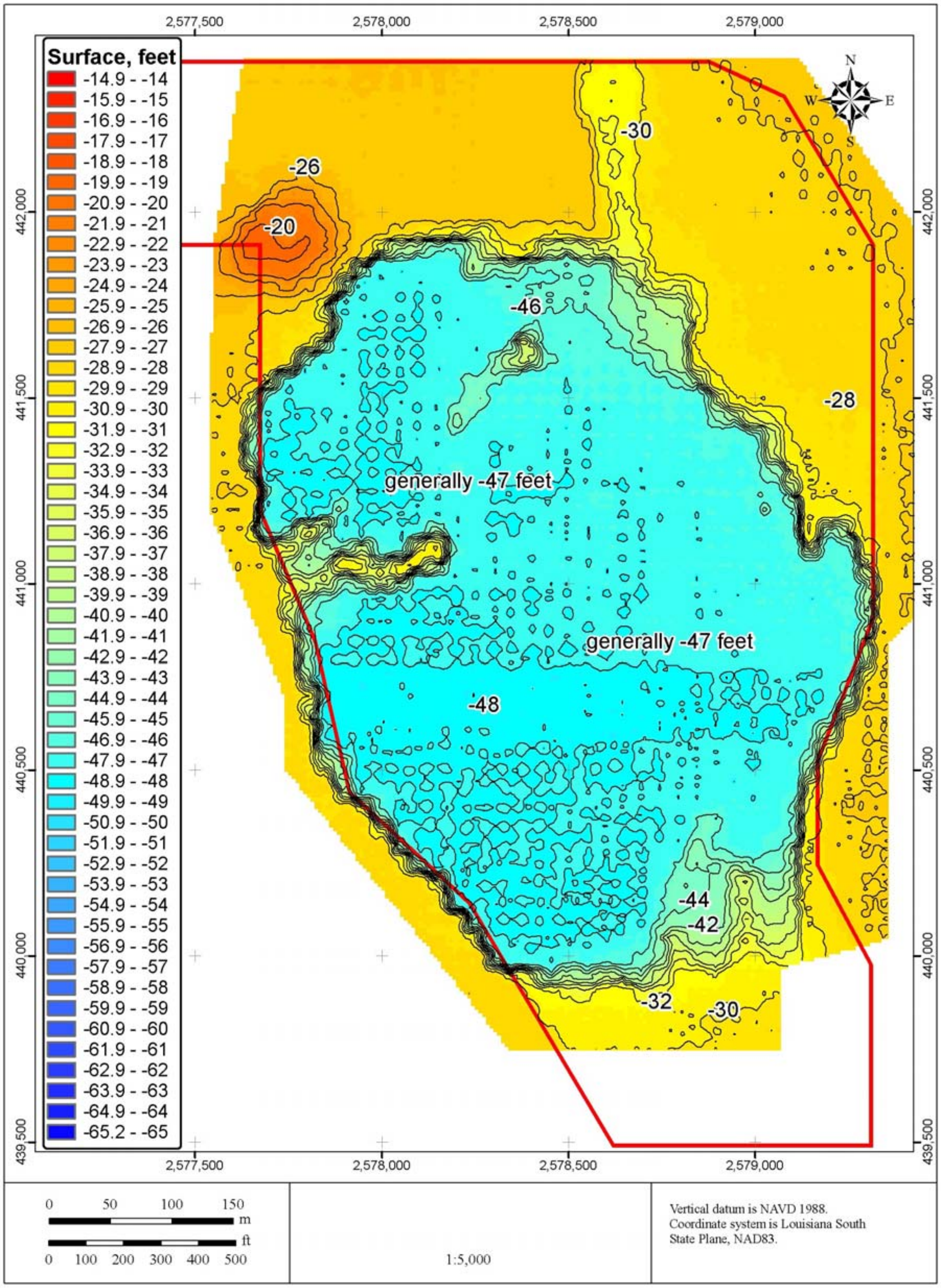

Figure 3.4 Holly Beach Dredge Pit – Bathymetry Dec. 2004 (20 Months After Dredging)

3.1.1.3 Comparison and Interpretation

Seafloor surface change from immediately post-dredging to the December 2004 survey and from December 2004 to the June 2006 survey are shown in Figures 3.5 and 3.6, respectively. Both show significant pit infilling, some pit slope change and in the earlier period, pit margin erosion.

Direct profile comparisons were completed to provide a more detailed view of the changes to pit slopes and the pit margin. The profile locations are shown in Figure 3.7.

A detailed discussion of the profile changes between the April 2003 post-dredging survey and the December 2004 survey are presented in Nairn *et al*. (2005). The profile locations are shown in Figure 3.7. Examples of profile change are shown in Figures 3.8 to 3.11. In addition, the geology of the pit is also presented in the noted report. It was shown that main areas of change included:

1. Infilling of the pit to a near horizontal surface;

2. Slope flattening in areas where the pit edges were sandy (such as South 1 in Figure 3.8);

3. The observation of little or no slope adjustment from the immediate post-dredge slopes for areas where the pit slope (or at least the upper part) consisted of clay/silt (see West 1 for example in Figure 3.9);

4. Pit margin erosion (of up to 3 ft 90.9 m0 at the edge of the pit tapering away from the pit edge) generally around the outer edge of the pit over a distance of distance of at least 500 to 650 ft (150 to 200 m); and

5. Minor erosion and perhaps some migration towards the northwest of the dredge disposal mound (for stripped sediment) was evident.

Between the December 2004 and June 2006 surveys the primary and common change at all profiles related to ongoing infilling of the pit itself with approximately 12 to 14 ft (3.6 to 4.3 m) of accumulation. The sandy pit edge locations (e.g. South 1) showed more flattening of the slope whereas the pit slopes in muddy areas continued to hold the original dredged steep slopes. The rate of pit margin erosion reduced during in this period.

One of the most pronounced differences in the rate of change between the initial and second comparison periods was the erosion of the dredge disposal mound at the northwest edge of the pit. As it protruded above the seabed by 3 to 4 ft (0.9 to 1.2 m) it was likely influenced primarily by the wave and current conditions generated during the passage of Hurricane Rita in September 2005.

The results of the final survey in March 2007, which completed only for selected full east-west and north-south lines are shown Figures 3.12 and 3.13, respectively. The profile locations are shown in Figure 3.7. There were another 2 or 3 ft (0.6 to 0.9 m) of accumulation in the pit and limited pit margin erosion, otherwise the trends in change remained the same. There was some indication that pit margin erosion resumed during this latest period; however, there was insufficient survey information to confirm this finding.

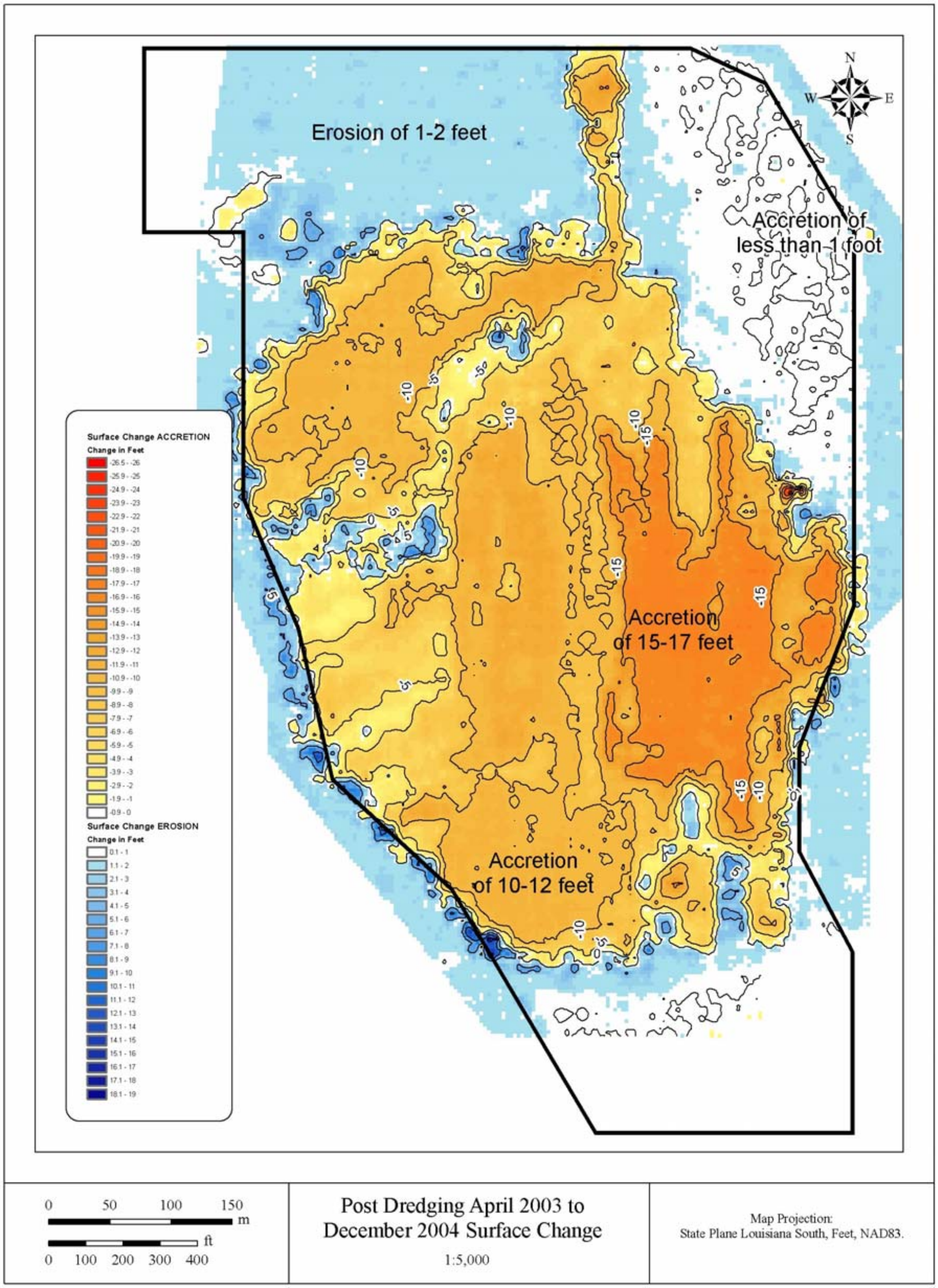

Figure 3.5 Seafloor Surface Elevation Change April 2003 to December 2004

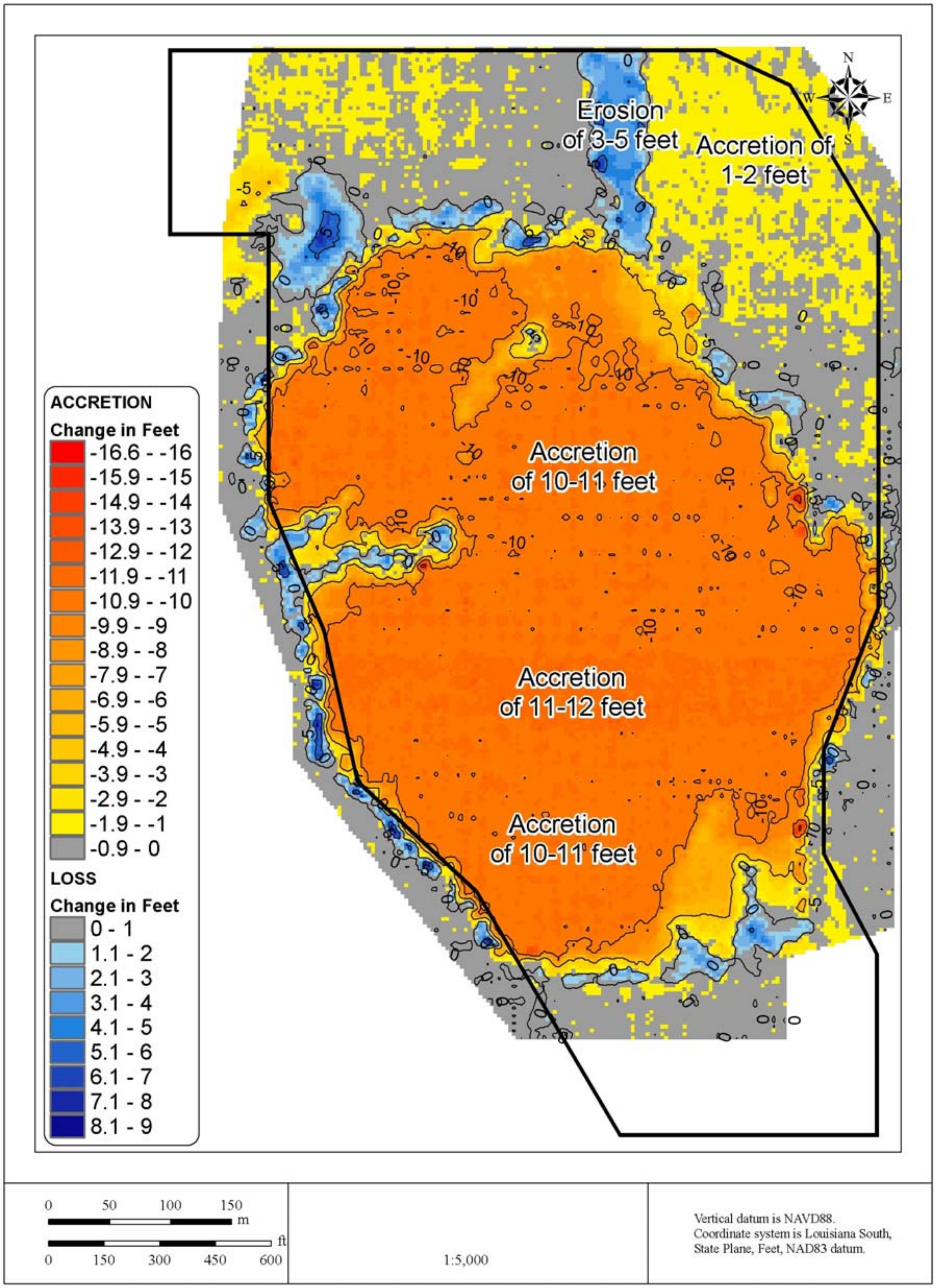

Figure 3.6 Seafloor Surface Elevation Change December 2004 to June 2006

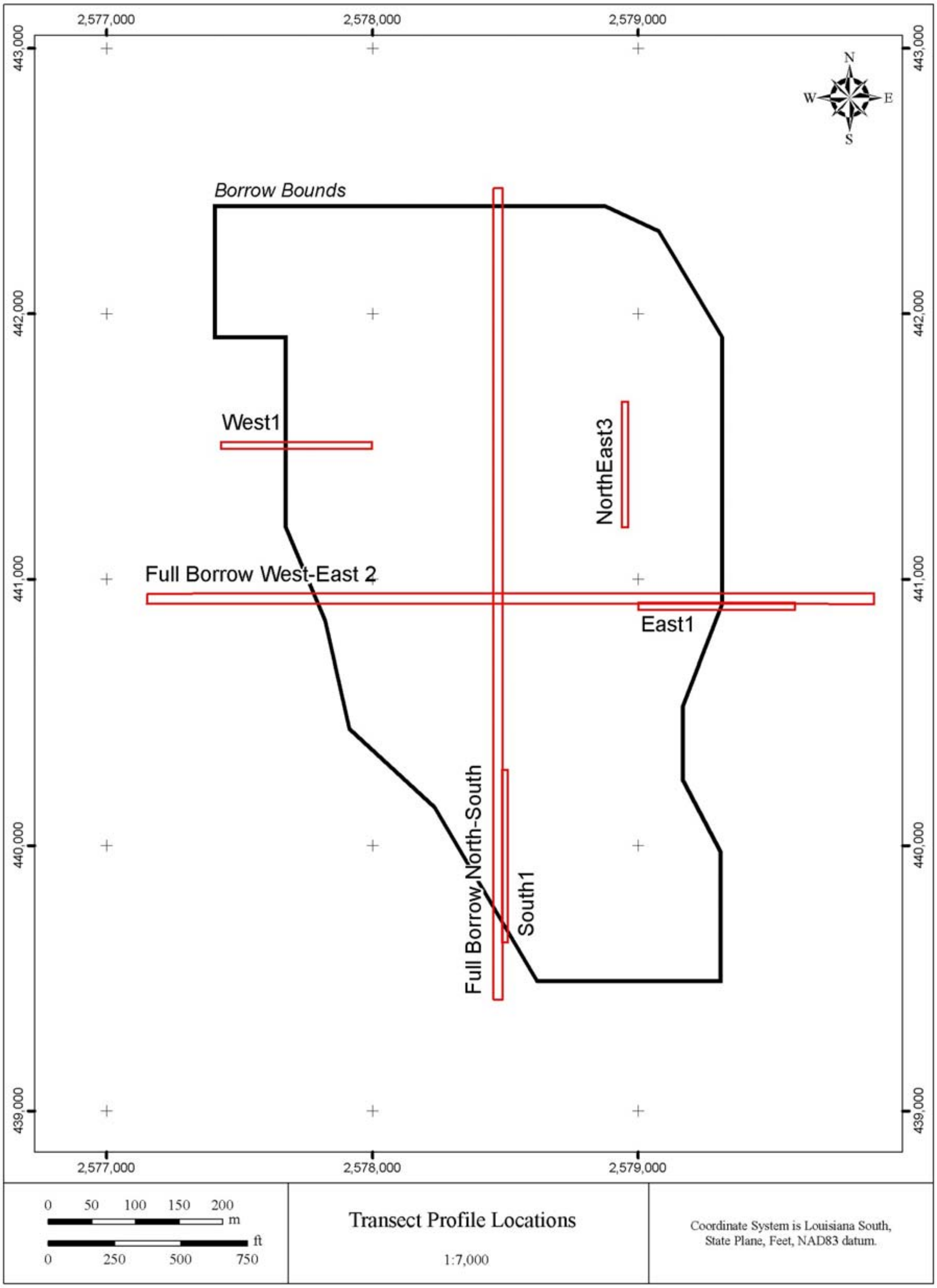

Figure 3.7 Location of the Profile Comparisons for the Holly Beach Dredge Pit

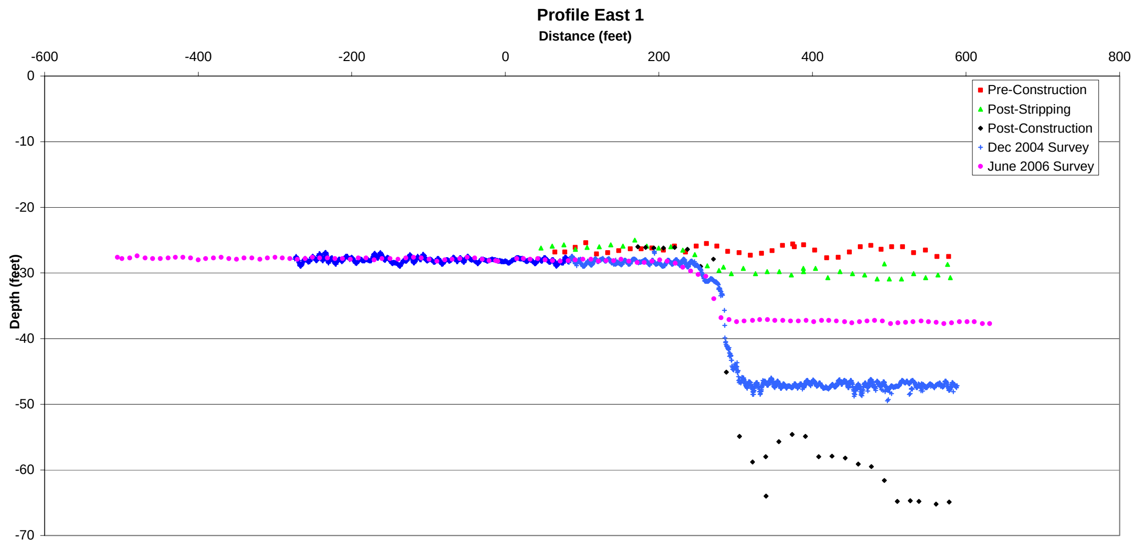

Figure 3.8 Profile East 1

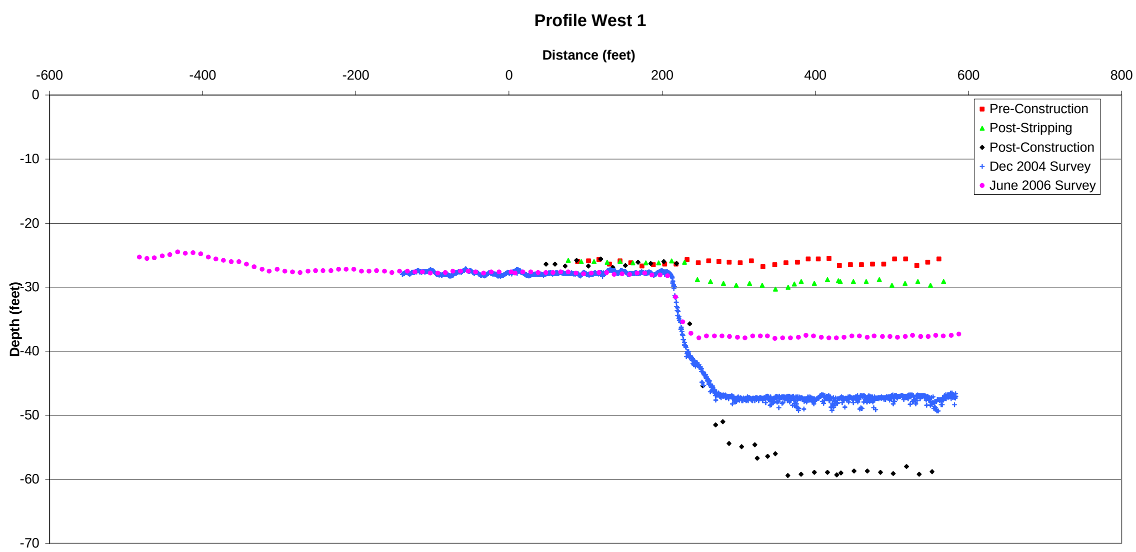

Figure 3.9 Profile West 1

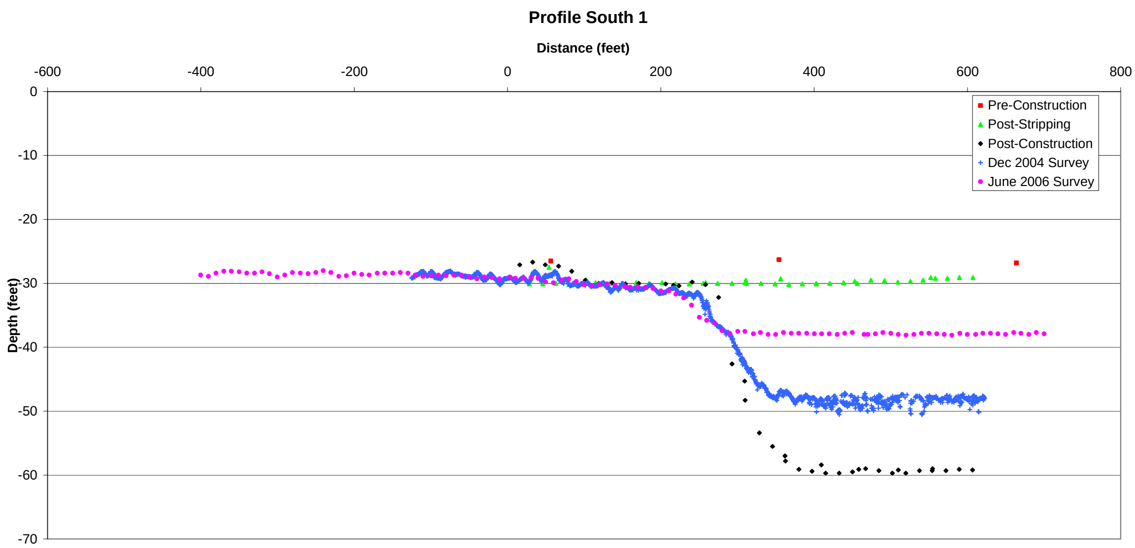

Figure 3.10 Profile South 1

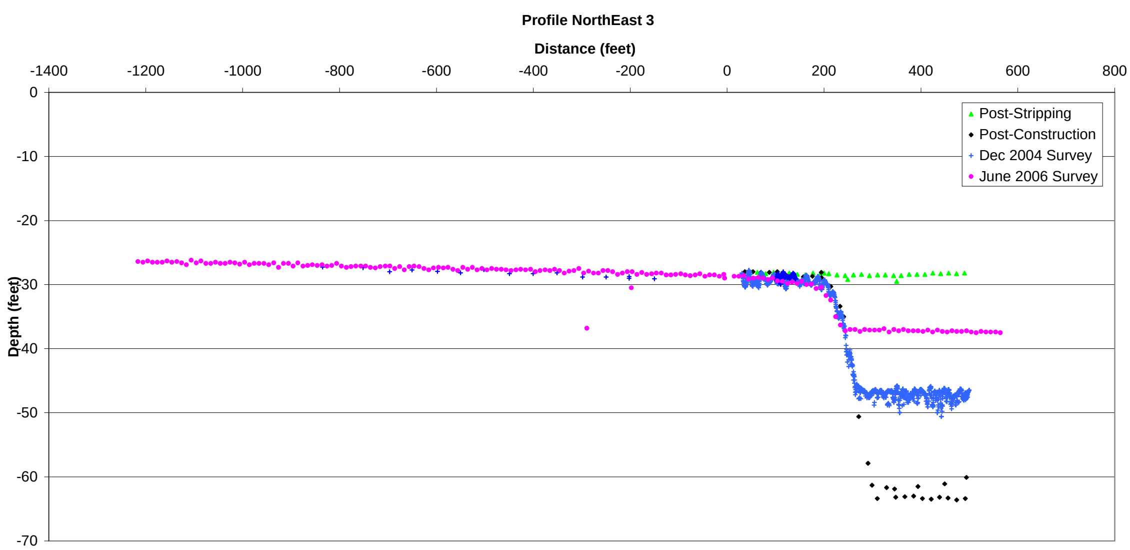

Figure 3.11 Profile NorthEast 3

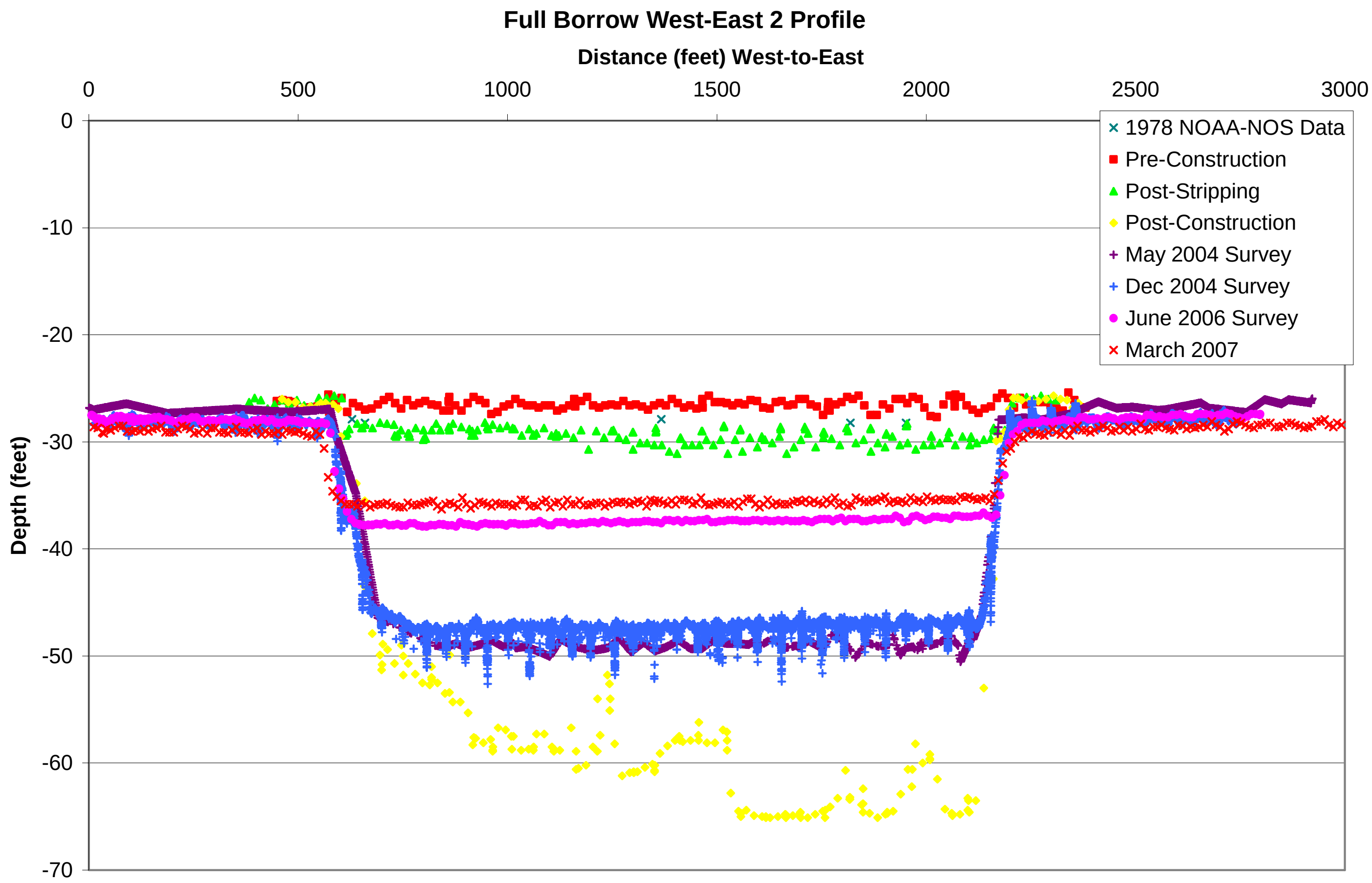

Figure 3.12 Full West-East Pit Transect with All 8 Time Periods

The March 2007 survey shows this continued infilling pattern, with the pit floor about 2 ft (0.6 m) higher (more shallow) than compared to 9 months earlier.

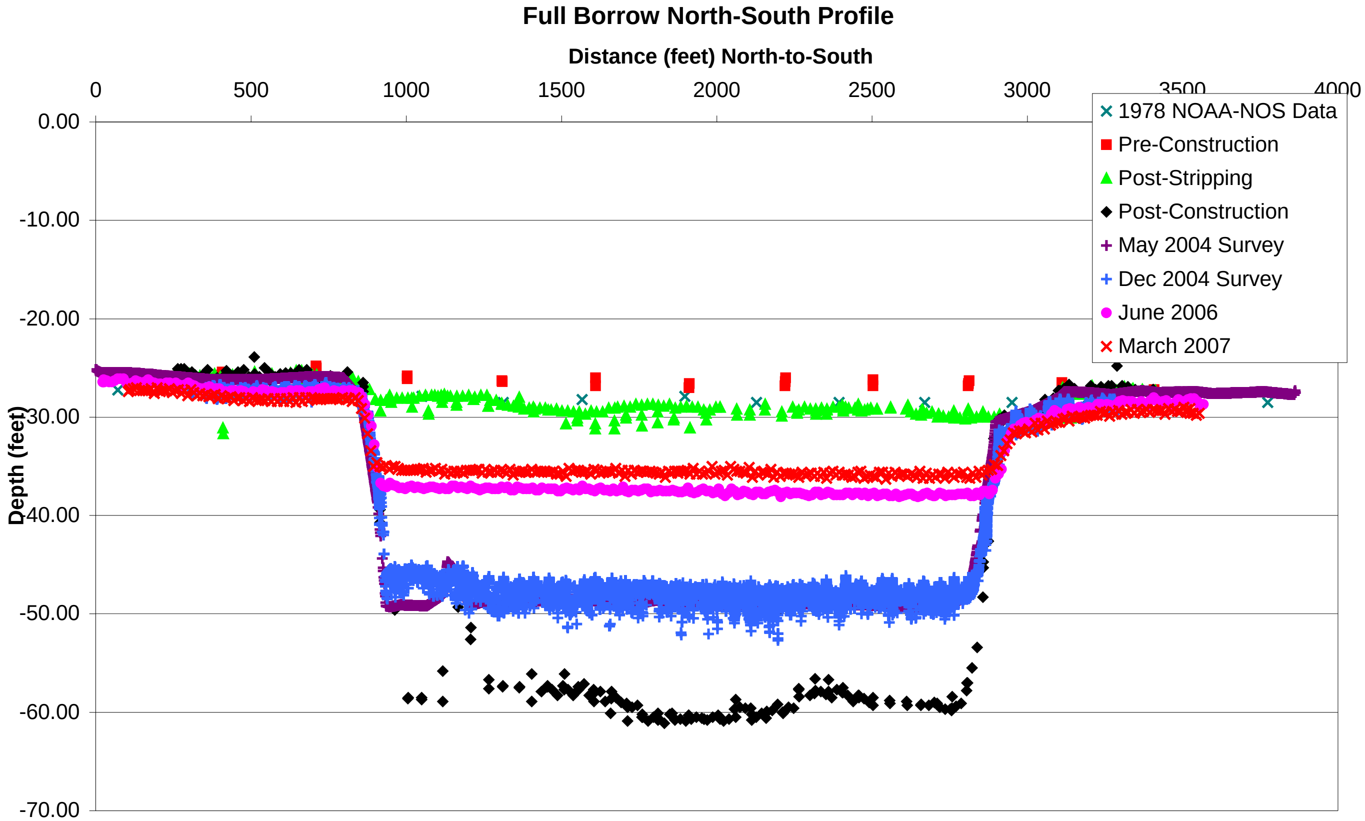

Figure 3.13 Full North-South Pit Transect with All 8 Time Periods

In summary, there are two distinct modes of pit slope evolution around the edges of the Holly Beach Dredge Pit. In areas where the surface sediment beyond the edge of the pit is muddy, the pit slope has changed little, if any. Approximately 1 to 2 ft (0.3 to 0.6 m) of vertical erosion has occurred in the pit margin region for distances of at least 150 to 120 m. Where surface sediment was sandy, the pit margin erosion covered a much smaller distance beyond the original edge of the pit and there was slope flattening.

Continual pit infilling, although at a slowing pace, has occurred since dredging of the pit in April 2003. In the initial 20 months the infilling rates were as high as 0.9 ft (27 cm)/month, for the next 18 months infilling occurred at about 0.6 ft (18 cm)/month and over the last 9 months the infilling has been at a rate of approximately 0.3 ft (9 cm)/month.

3.1.2 ADCP Measurements of Currents

The regional current patterns for the Louisiana OCS are discussed in more detail in Nairn *et al.*, (2005) and consist of tidal currents in the range of +/- 1 ft/s (30 cm/s) driven by the dominant diurnal tides of the Gulf of Mexico (i.e. K1 and O1 constituents). The dominant S to SE winds drive a residual westerly directed current through much of the year that is equally important and at times greater than the tide-driven component (Cochrane and Kelly, 1986 and Nowlin *et al.*, 1998).

3.1.2.1 2006 ADCP Measurements

The Acoustic Doppler Current Profile (ADCP) surveys were completed with an RDI 2100 kHz Navigator. The main objective of the survey was to determine the existing current velocities throughout the water column outside of the pit where there is less or no influence of the dredge pit. A bottom-mounted ADCP was deployed at Site 7, which is about 6.2 miles (10 km) away from the pit (see Figure 3.14). The ADCP data was collected by Environmental Resource Information Services (ERIS) of Port Aransas, Texas, between June 12, 2006 at 13:30 Local Daylight savings Time (LDT) and June 14, 2006 at 17:45 LDT. The ADCP was deployed in approximately 27 ft (8.2 m) of water and began recording data at a depth of 5 ft (1.56 m) above the bottom. Subsequent measurements were taken at 3.28 ft (1.0 m) intervals (bins) to a maximum of 10 bins.

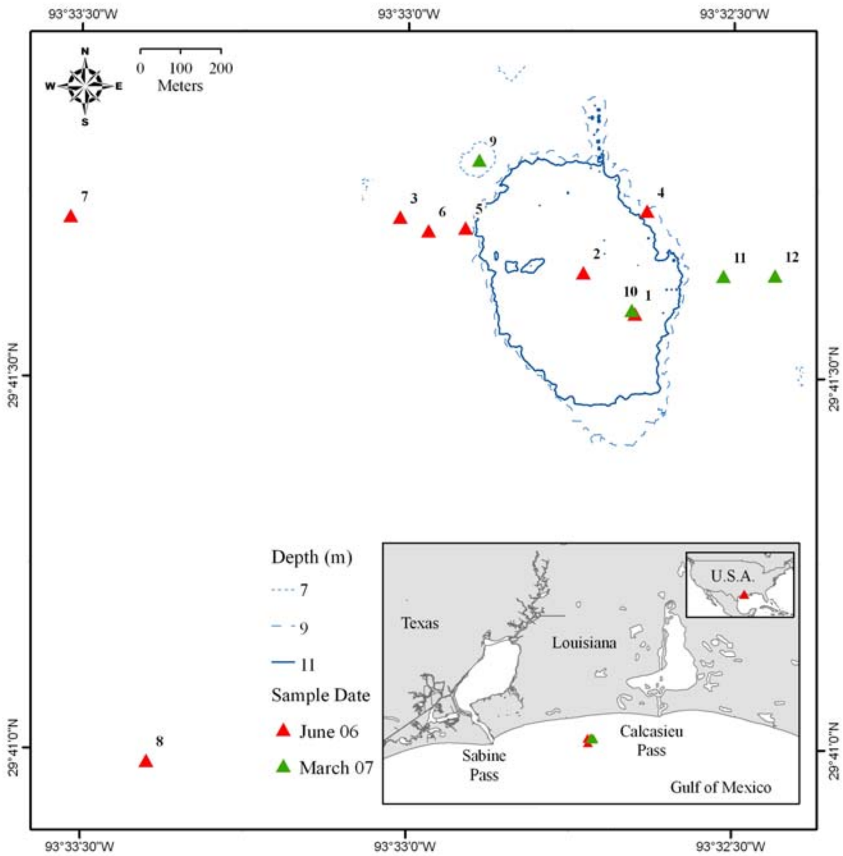

Figure 3.14 The Locations of ADCP Deployment (at Site 7) and Samples

Upon analysis of the ADCP data provided by ERIS, it was determined that near-bottom velocities ranged between 0.0 and 0.5 ft/s (0.0 and 0.15m/s), mid-column velocities were between 0.16 and 1.21 ft/s (0.05 and 0.37m/s) and near-surface velocities ranged from 0.1 to 2.5 ft/s (0.03 and 0.77m/s). Figures 3.15 and 3.16 below show the velocity and direction profiles at the selected time. In order to visualize the reverse flow in the water column, the velocity profiles are plotted as negative values if flow directions are between 180^o and 360^o. The water surface elevation above the seabed measured by the ADCP are also plotted in the figure, which indicated Bins from 1 to 7 were always below the water surface and Bins from 9 to 10 were located above the water surface and should be neglected. Bin 8 was below the water surface at high tide and above the water surface at low tide. Figure 3.16 shows the flow direction profiles at the selected time. These results indicate that reverse flows occurred at the bottom sometimes, which likely results from wind forcing. The currents at the location beyond the influence of the borrow pit are likely a combination of tidal current and wind driven currents; this is later confirmed by the numerical model (see Figures 3.15 and 3.16).

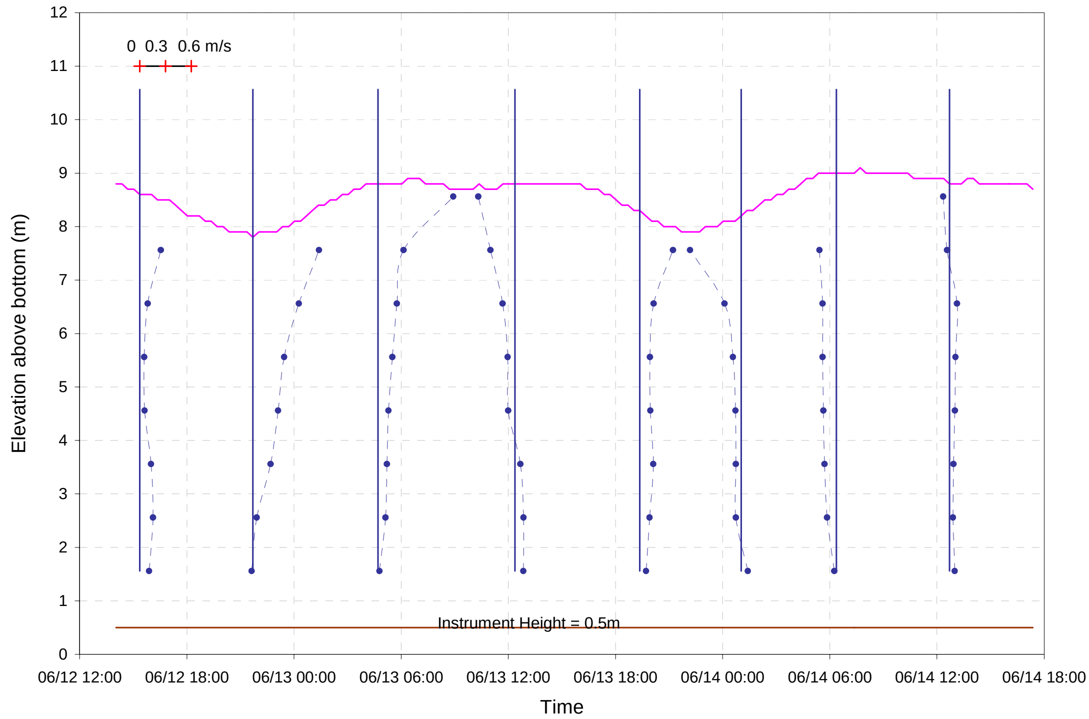

Figure 3.15 Current Velocity Profiles at Site 7 (beyond the area influenced by the pit), June 2006

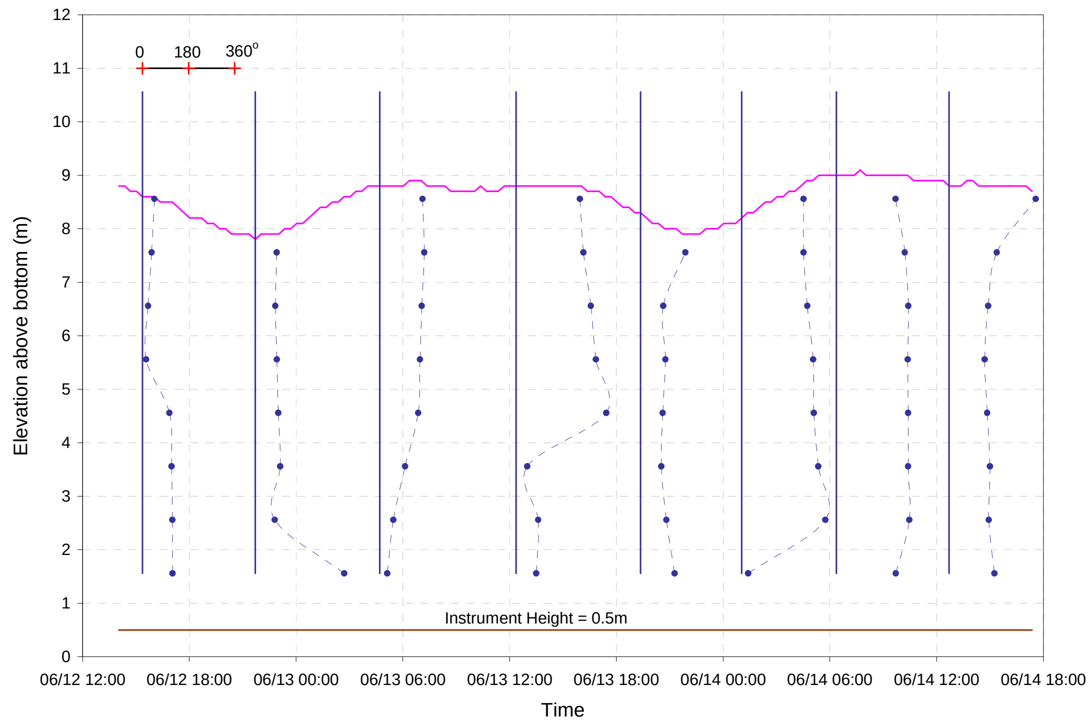

Figure 3.16 Current Direction Profiles for Holly Beach Site 7, June 2006 ("direction to" is plotted)

3.1.2.2 2007 ADCP Measurements

Current velocities were surveyed in March 2007 along pre-defined cross-sections through the pit again using the RDI 1200 kHz Navigator in bottom-tracking (downward-looking) mode for towing. The objective of this survey was to investigate the impacts of the pit dredging on the currents inside the pit and near the edge of the pit. The measurements were carried out using a towed ADCP mounted on a 41-ft (12.5 m) research boat. The flow velocity and direction were measured at 5.3 ft (1.62m) below the water surface and continued in 0.82ft (0.25 m) increments to the ocean bottom. The towed ADCP recorded numerous velocity profiles (ensembles) along preset transect lines, North-South, East-West and Diagonal, with an approximate towing distance of 3300 ft (1000 m) cross the pit (see Figure 3.7). Data was collected between March 5, 2007 at 20:33 LDT and March 6, 2007 at 07:34 LDT. The research vessel conducted four runs along each preset transect line but only one representative run is shown for each transect path in Figures 3.17 to 3.22. In order to visualize the reverse flow at the pit bottom, the velocity profiles are plotted as negative values if flow directions are between approximately 150^{o} and 330^{o}, which was determined from the flow direction at the upper part of the columns (see Figures 3.17 to 3.22). The entire set of current velocity and direction results are included in Appendix B.2.

The ADCP data shown in Figures 3.17 to 3.22 indicates current velocity reverses at a depth of approximately 16.4 ft (5 m) below the water surface. Near-bottom velocities in the pit range between –0.17 to 0.0 ft/s (-0.06 to 0.0 m/s) while near-bottom velocities outside of the pit range from –0.72 to 0.2 ft/s (–0.22 to 0.06 m/s). Mid-column velocities over the pit and outside the pit are approximately –0.5 ft/s (–0.15m/s) but change to 0.46 ft/s (0.14m/s) between a depth of 16.4 to 19.7 ft (5 to 6 m) below the water surface. Near-surface velocities over the pit and outside the pit range between 0.5 to 1.0 ft/s (0.15 and 0.30 m/s). The measured profiles are typical of flow velocity profiles driven by winds. The reduction of flow speed in the pit bottom is clearly visible. Figures 3.23 to 3.25 show the depth-averaged flow velocity changes along the cross-section and again these show a clear reduction in overall flow speed over the pit, particularly for the East-West line.

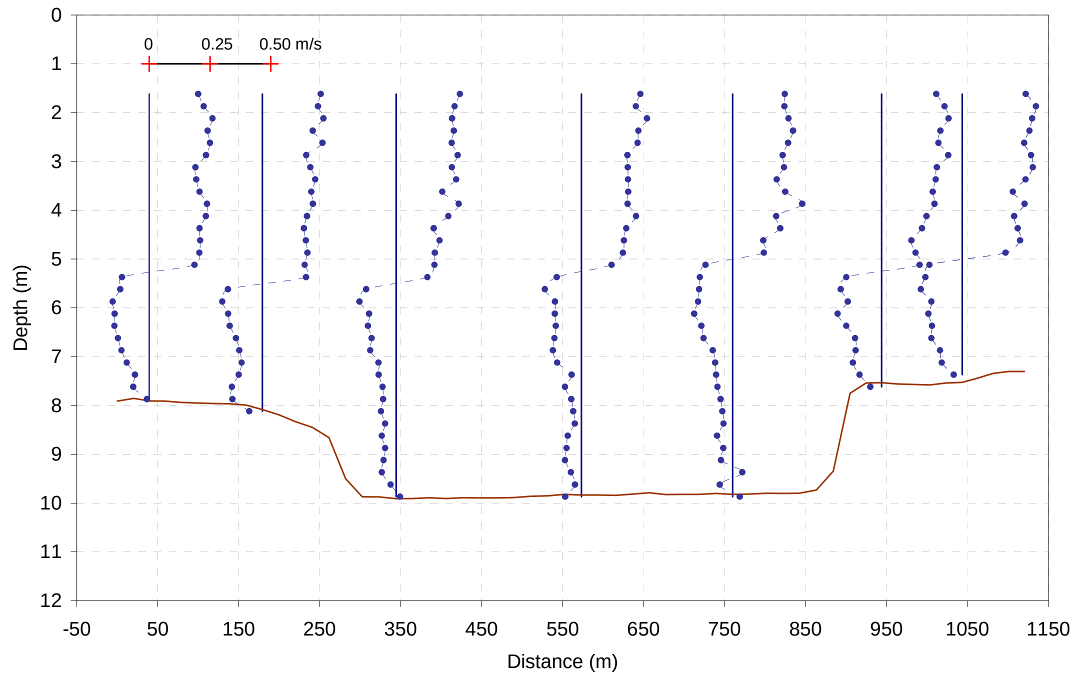

Figure 3.17 Representative Velocity Profiles for North-South Transect Line (05-Mar-2007 22:51-22:58 CST)

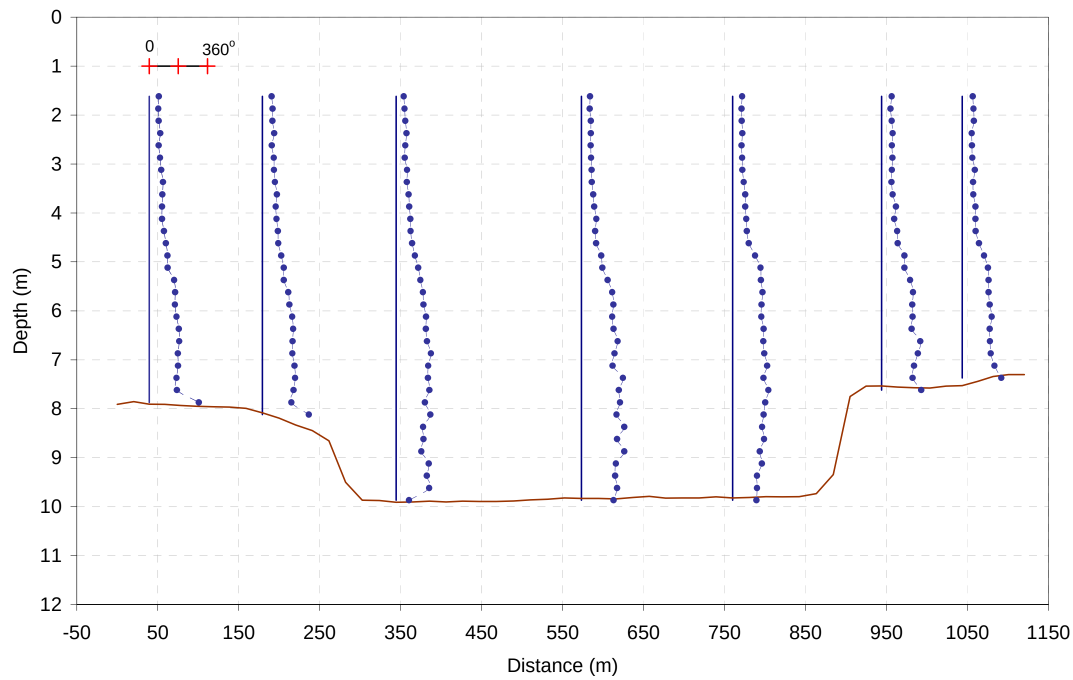

Figure 3.18 Representative Direction Profiles for North-South Transect Line (05-Mar-2007 22:51-22:58 CST) ("direction to" is plotted)

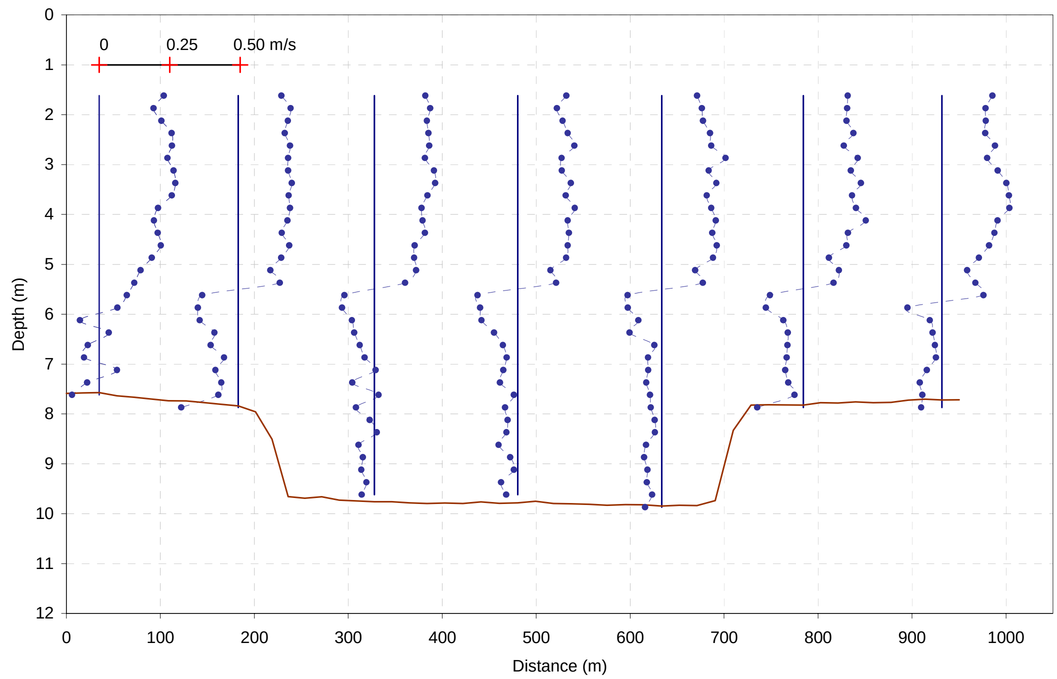

Figure 3.19 Representative Velocity Profiles for East-West Transect Line (05-Mar-2007 20:33-20:40 CST)

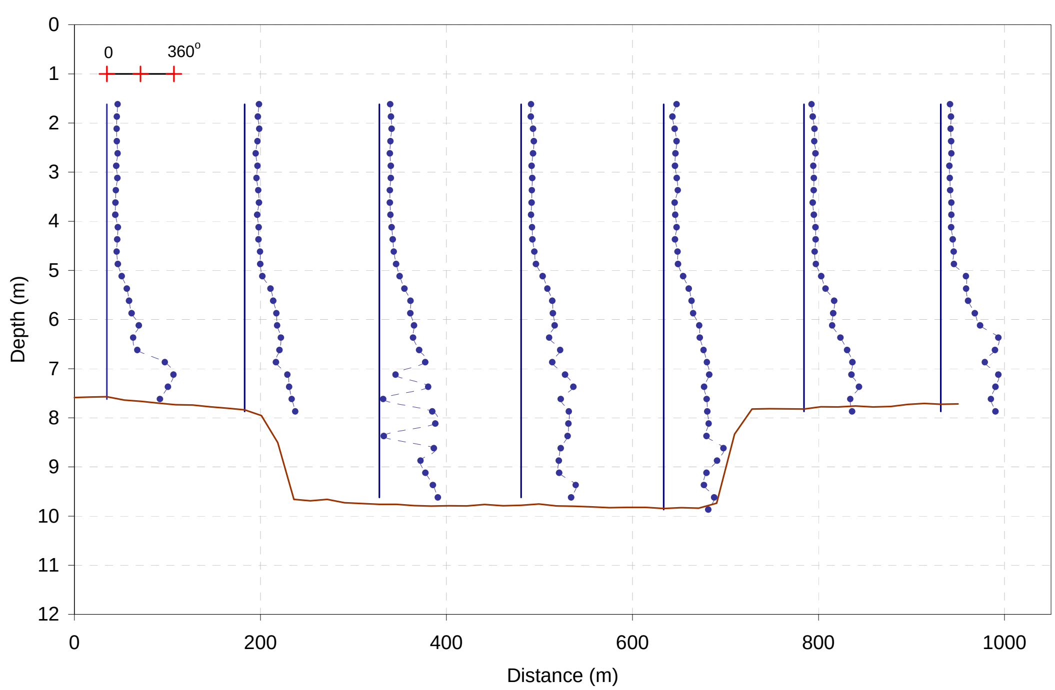

Figure 3.20 Representative Direction Profiles for East-West Transect Line (05-Mar-2007 20:33-20:40 CST) ("direction to" is plotted)

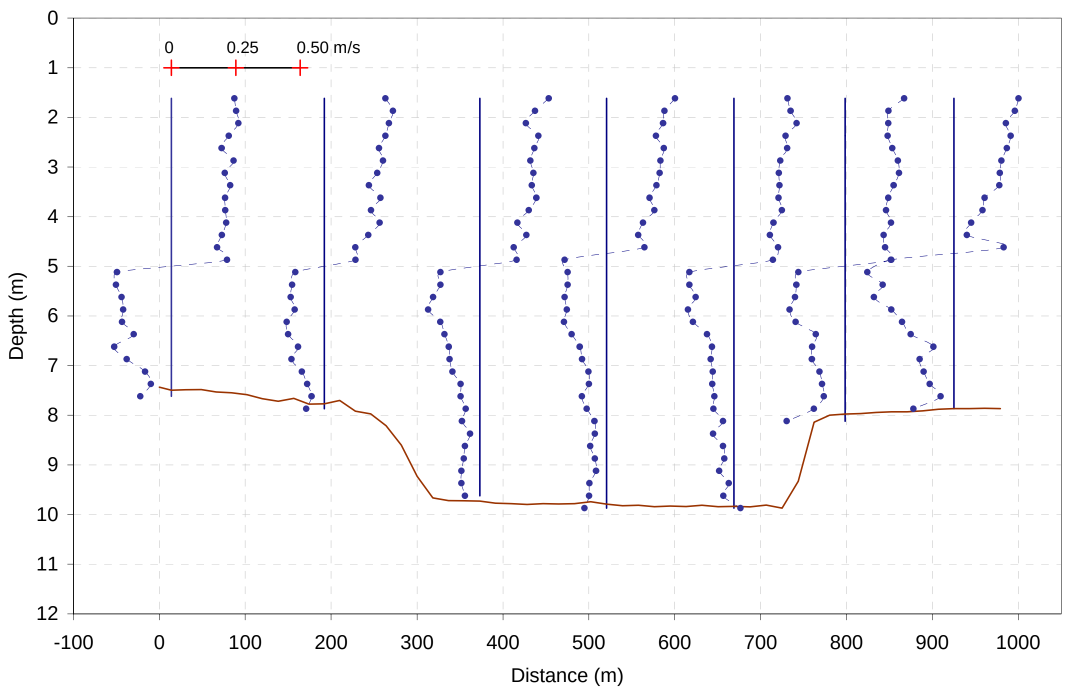

Figure 3.21 Representative Velocity Profiles for Diagonal Transect Line (05-Mar-2007 23:04-23:11 CST)

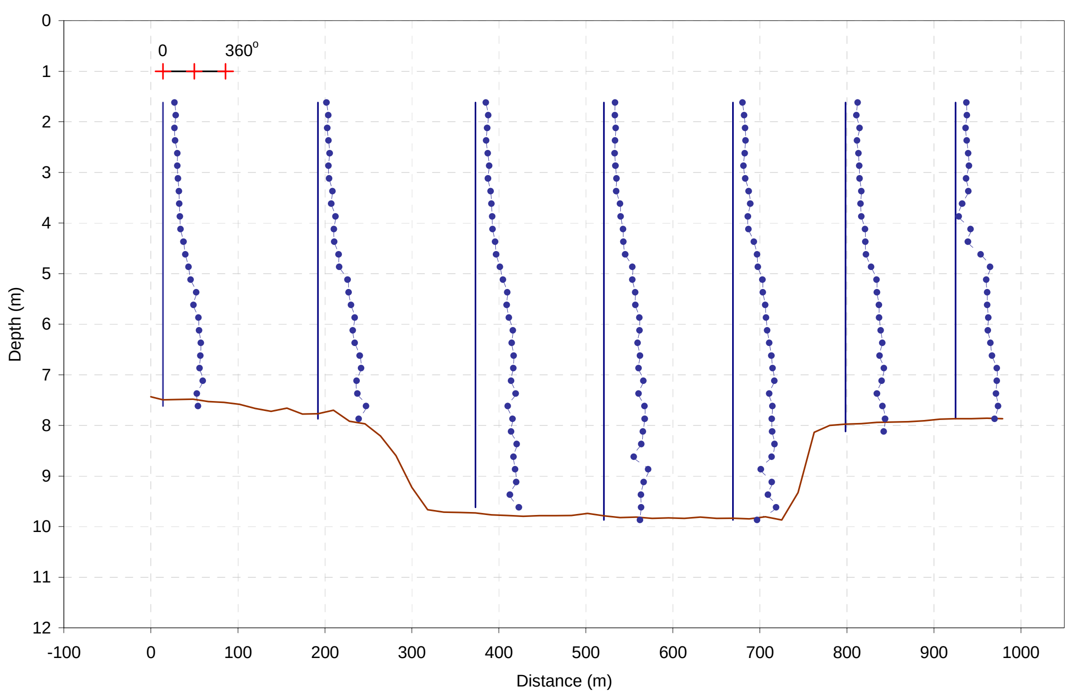

Figure 3.22 Representative Direction Profiles for Diagonal Transect Line (05-Mar-2007 23:04-23:11 CST) ("direction to" is plotted)

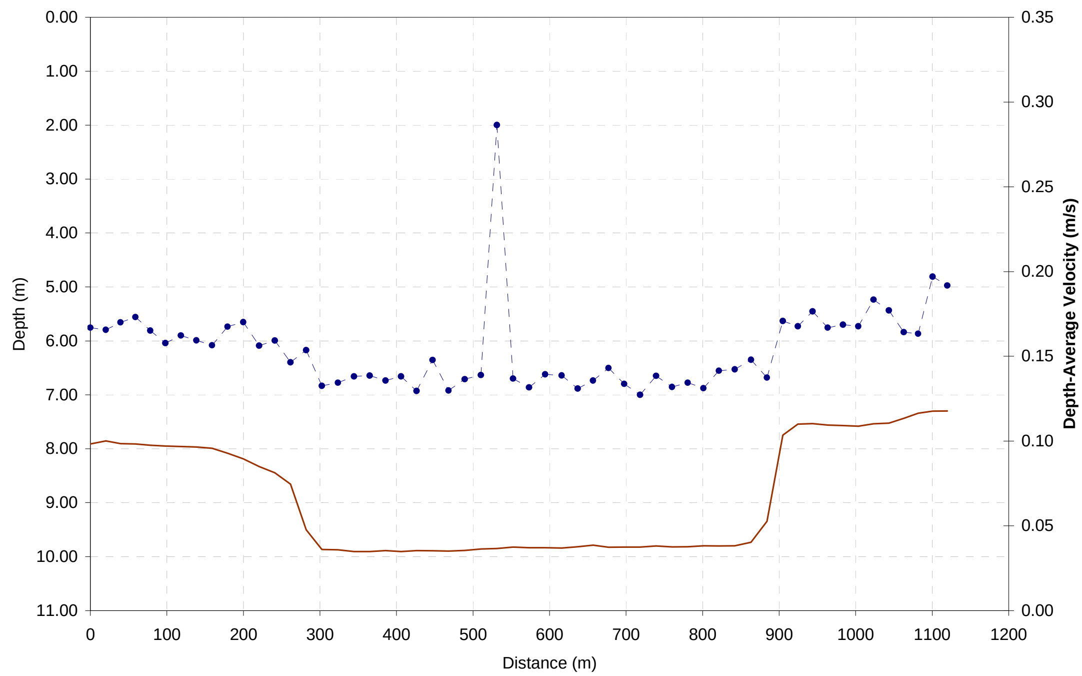

Figure 3.23 Depth-Average Flow Velocity Change Across North-South Cross-Section (05-Mar-2007 22:51-22:58 CST)

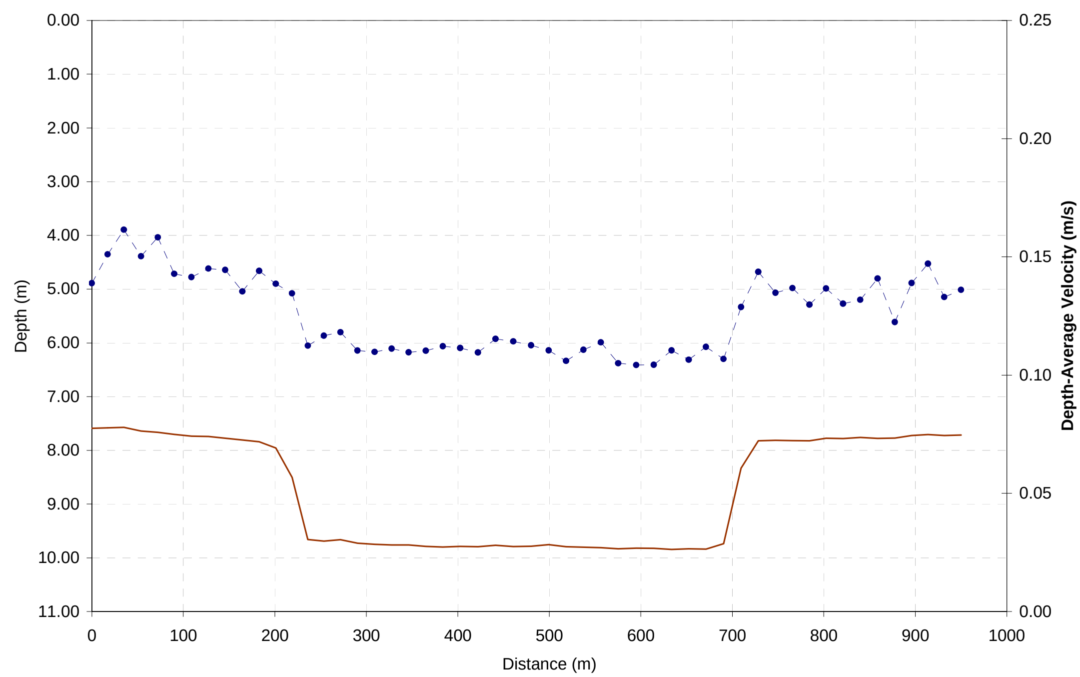

Figure 3.24 Depth-Average Flow Velocity Change Across East-West Cross-Section (05-Mar-2007 20:33-20:40 CST)

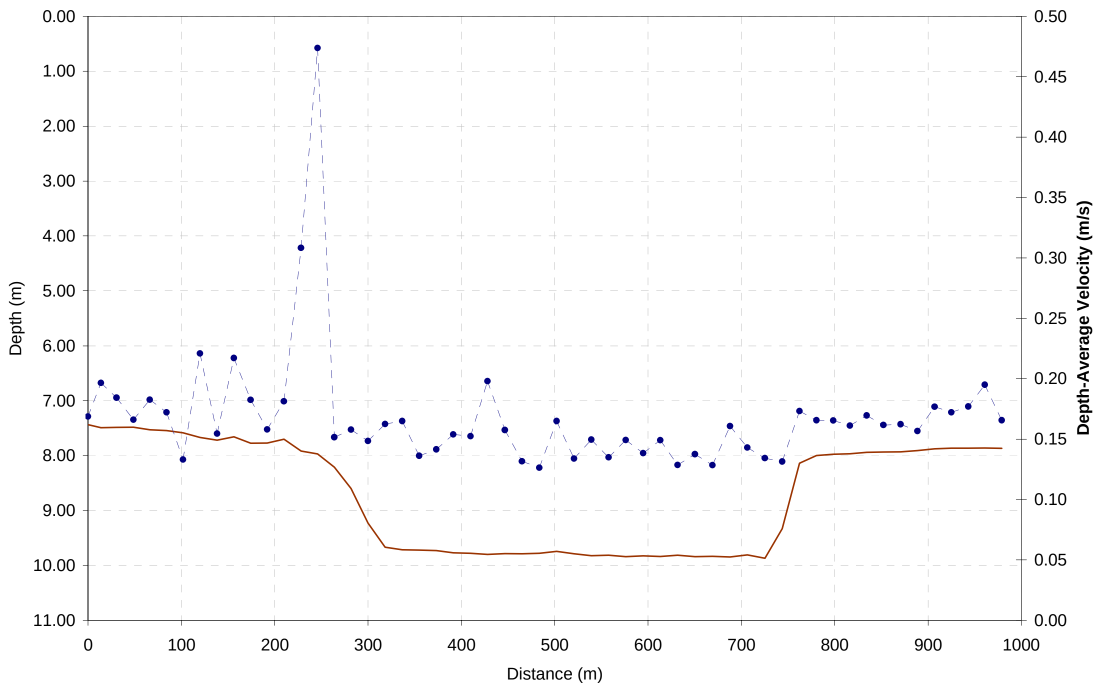

Figure 3.25 Depth-Average Flow Velocity Change Across Diagonal Cross-Section (05-Mar-2007 23:04-23:11 CST)

3.1.3 Water Quality Measurements

The background conditions for water quality at the Holly Beach Dredge Pit site are discussed in more detail in Nairn *et al.,* (2005). The site is beyond the direct influence of the Atchafalaya River plume under most conditions. Therefore, suspended sediment concentration is primarily related to local and regional re-suspension of fine sediment from the seabed by the combined influence of waves and currents. Based on a consideration of local measurements, Nairn *et al.,* (2005) estimated an average annual suspended sediment concentration of 70 to 80 mg/l. The values measured in this investigation were generally lower that this estimated average annual background range for suspended sediment, although this is expected considering the surveys must be completed during relatively calm wave conditions.

A review of the regional dissolved oxygen conditions is provided in Section 2.5.3 of this report.

Water quality data was recorded at two locations in the Holly Beach area over a twelve-hour period on June 13, 2006. ERIS performed the surveys at Site 2 within the pit and at Site 7 beyond the influence of the pit (see Figure 3.14) using an YSI model no. 6920 monitoring instrument. Measurements of turbidity, dissolved oxygen and temperature were taken at the water surface and at 0.66 ft (0.2 m) intervals to the ocean bottom. The results of turbidity, dissolved oxygen, and temperature monitoring at Site 2, which is inside the pit, are shown in Figures 3.26 to 3.28, respectively. The recorded turbidity units (NTU) were converted to concentration units (mg/L) using the following approximation: $\sqrt[3]{C} = 1.71\sqrt[3]{T} - 1.62$, where C represents mg/L and T represents NTU. The resulting estimated total suspended solid concentration levels are zero in the upper part of the water column near the surface and between 15.0 and 30.0 mg/L near the bottom. Figure 3.29 displays the variation of bottom sediment concentration over the twelve-hour period. Dissolved oxygen (DO) measurements are constant over time with values of approximately 7.2 mg/L near the surface and 3.0 mg/L near the bottom. The reduction in DO in the lower part of the water column is not related to the presence of the pit as will be evident in the Site 7 results presented next. Temperature results are steady at 82^{o}F (27.8^{o}C) near the bottom but deviate near the surface to values ranging between 84.6 ^{o}F (29.2^{o}C) to 86.9 ^{o}F (30.5^{o}C). Figure 3.30 shows the differences in surface temperature throughout the twelve-hour period.

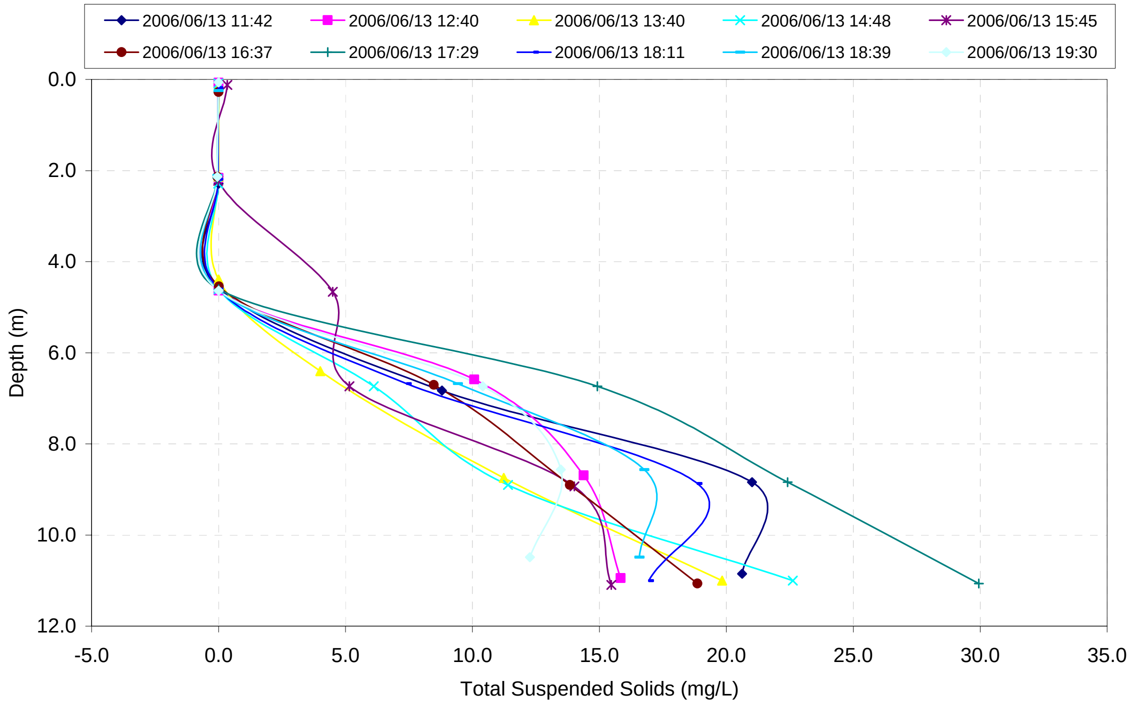

Figure 3.26 Site 2 Turbidity Results Throughout Water Column

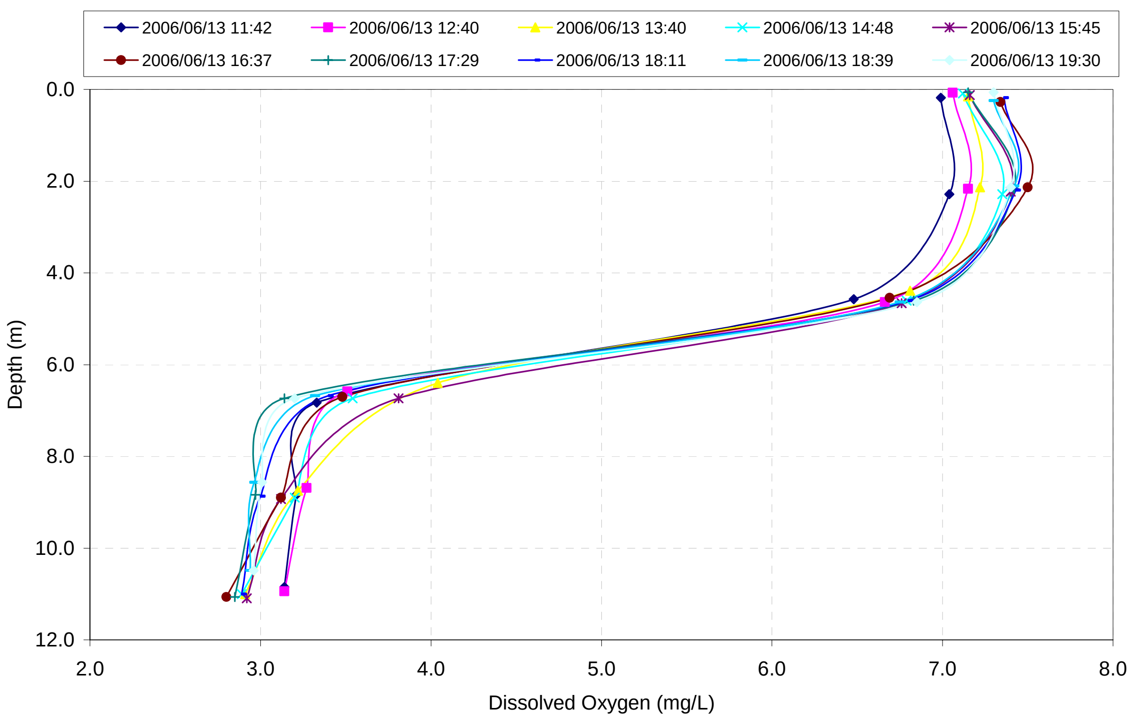

Figure 3.27 Site 2 Dissolved Oxygen Results Throughout Water Column

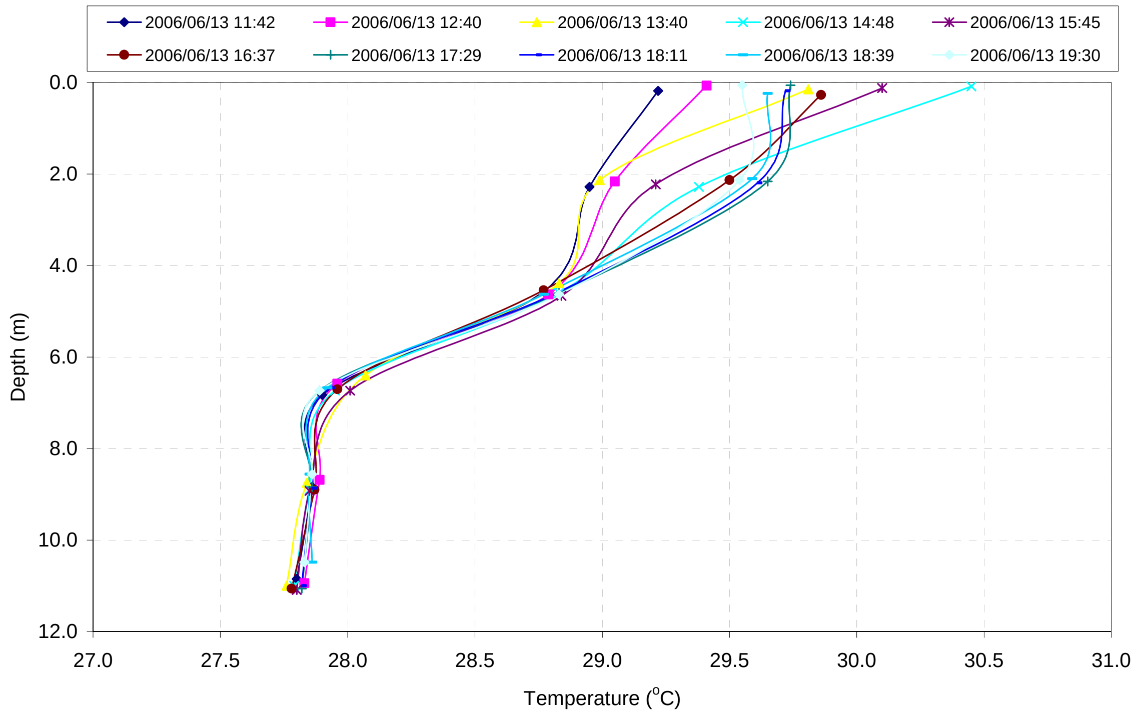

Figure 3.28 Site 2 Temperature Results Throughout Water Column

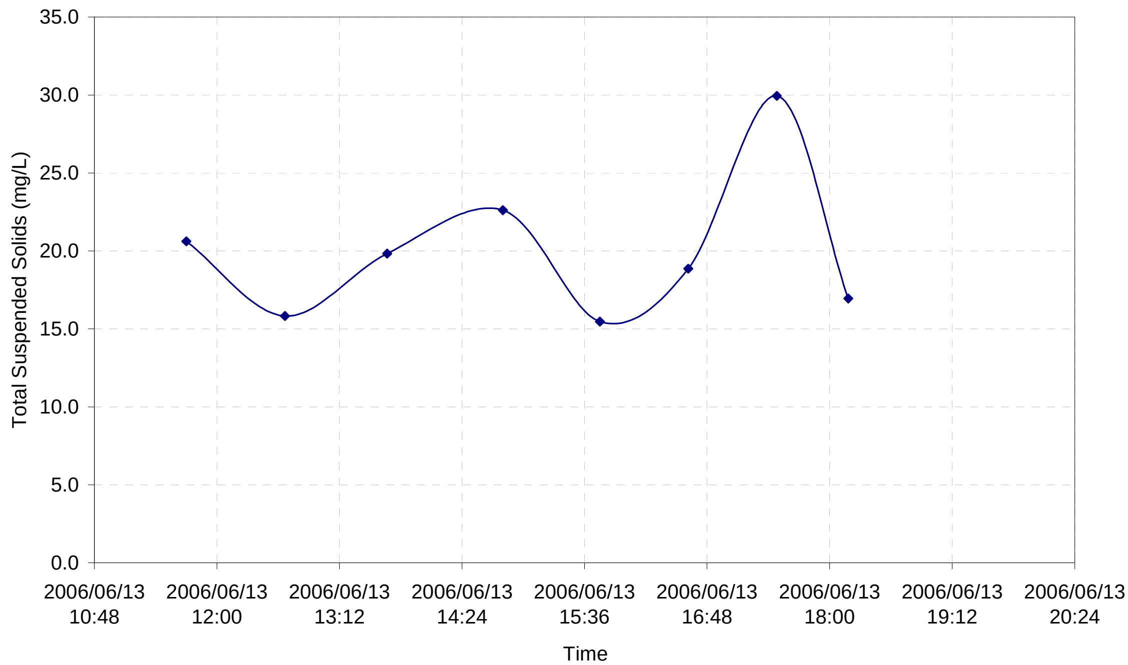

Figure 3.29 Site 2 Variations in Bottom Turbidity Over Time

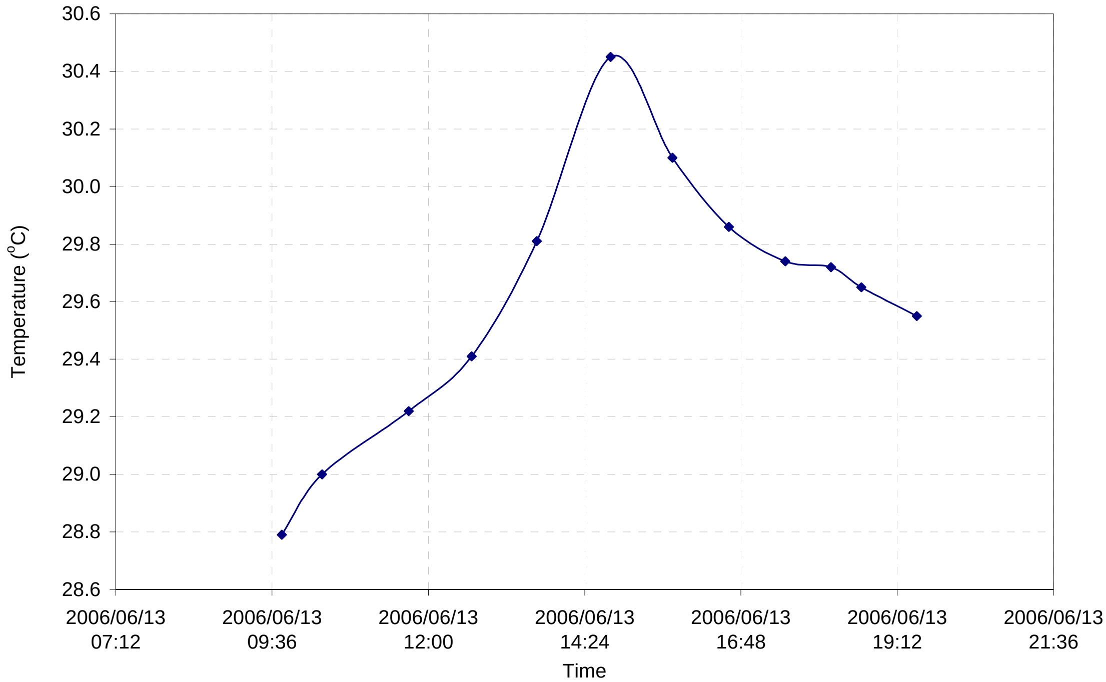

Figure 3.30 Site 2 Variations in Temperature Over Time

The measurements of turbidity, dissolved oxygen and temperature monitoring at Site 7 beyond the influence zone of the pit are shown in Figures 3.31 to 3.33, respectively. Suspended solids concentrations at Site 7 are constant at 0.0 mg/L near the water surface but increase with depth to values ranging from 35.0 mg/L to 60.0 mg/L near the bed. The variations in bottom solids concentration throughout the twelve-hour sampling period are presented in Figure 3.34. Dissolved oxygen measurements are consistent over time with near-surface results of 7.5 mg/L and near-bottom values of approximately 3.0 mg/L (with a similar profile to the measurements over the pit at Site 2). Therefore, the dissolved oxygen stratification is a regional phenomenon and is not related to the presence of the pit. The stratification in dissolved oxygen is likely due to thermocline, which suppresses vertical mixing and prevents oxygen diffusion across density gradient. The dissolved oxygen profile at 18:24 is not consistent with the other results. This data may be omitted for further analyses. Site 7 temperature measurements are steady at 82.4^{o}F (27.8^{o}C) near the bottom and diverge to values ranging from 83.6 ^{o}F (28.7^{o}C) to 86.7 ^{o}F (30.4^{o}C) near the surface. Figure 3.35 shows the differences in surface temperature throughout the twelve-hour period.

Comparing the solids concentrations at the Sites 2 and 7, the concentrations near the bottom of the pit are about two times smaller than the near bed turbidity at the location well beyond the influences of the pit. The reduction of turbidity within the pit likely results from sedimentation in the pit, in turn related to the lower flow speeds over the pit.

Additional discussion of water quality results and the influence on benthic communities is presented in Section 3.2.3.1.2.

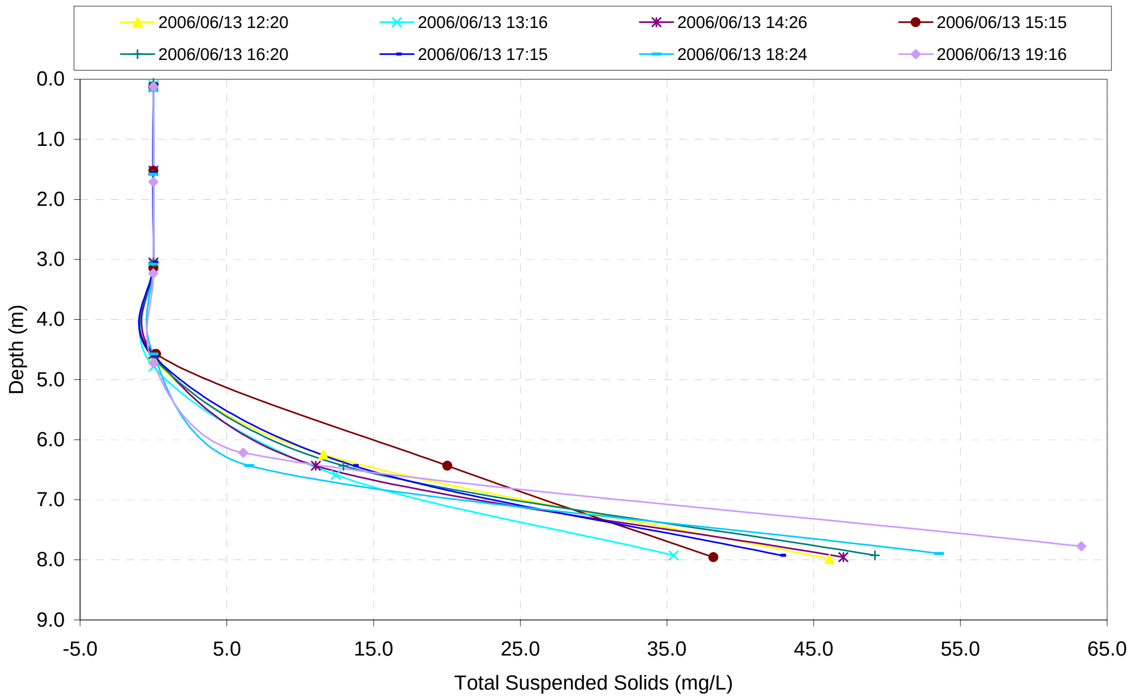

Figure 3.31 Site 7 Turbidity Results Throughout Water Column

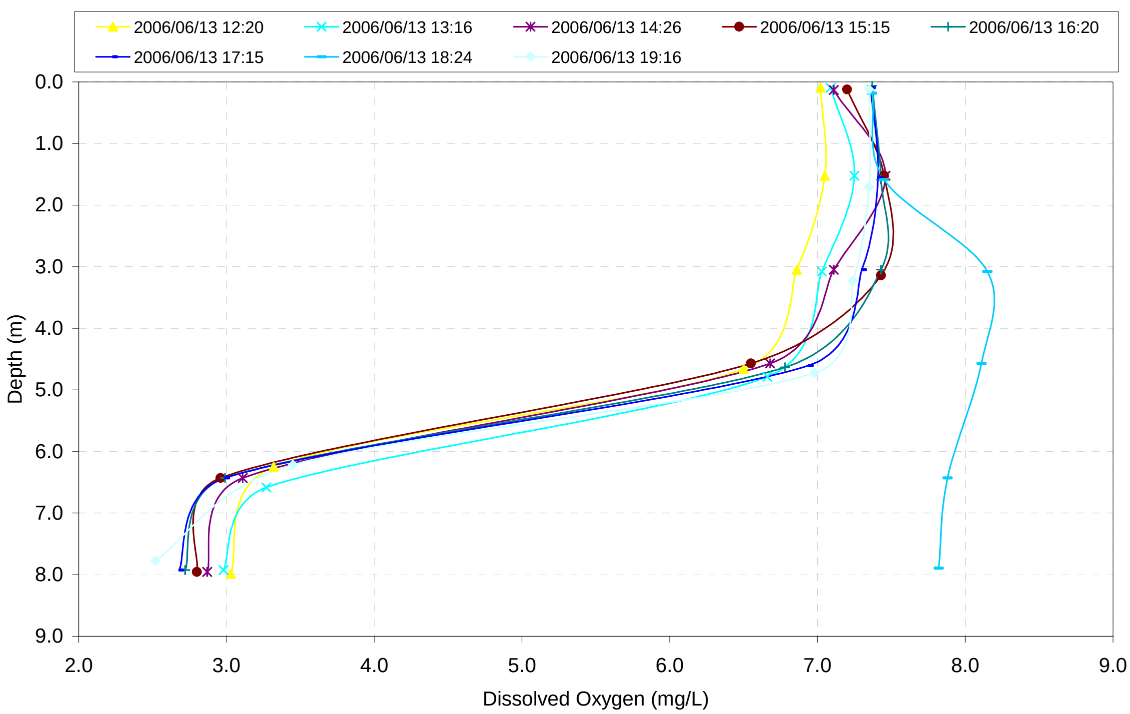

Figure 3.32 Site 7 Dissolved Oxygen Results Throughout Water Column

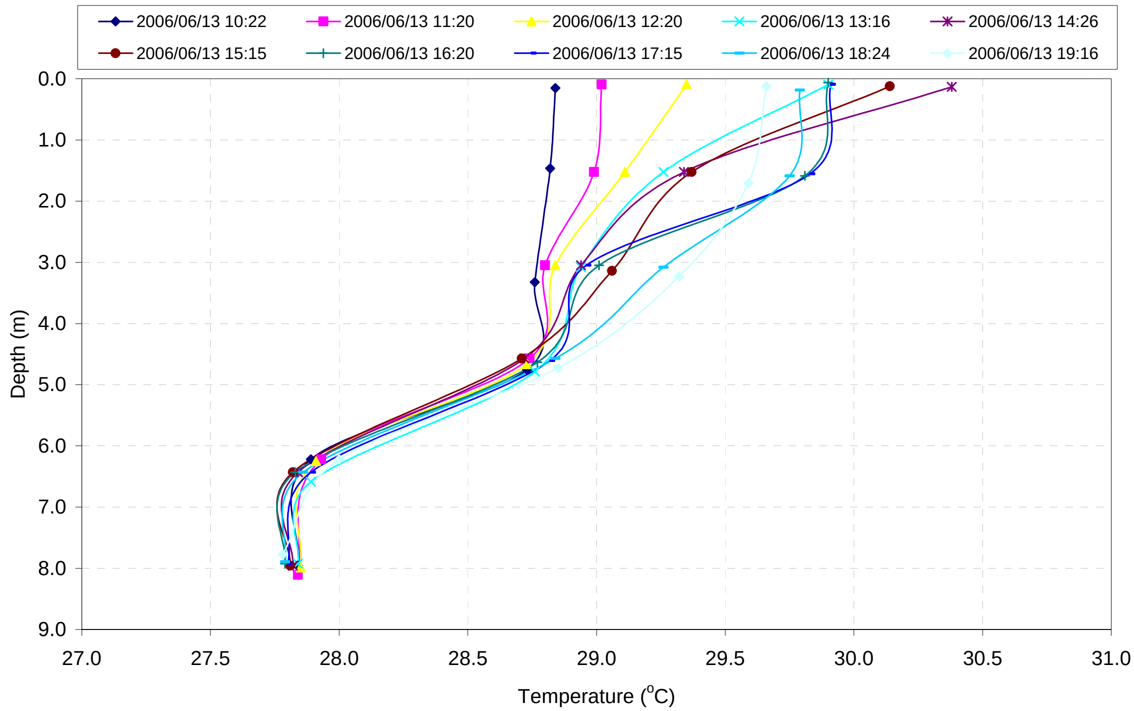

Figure 3.33 Site 7 Temperature Results Throughout Water Column

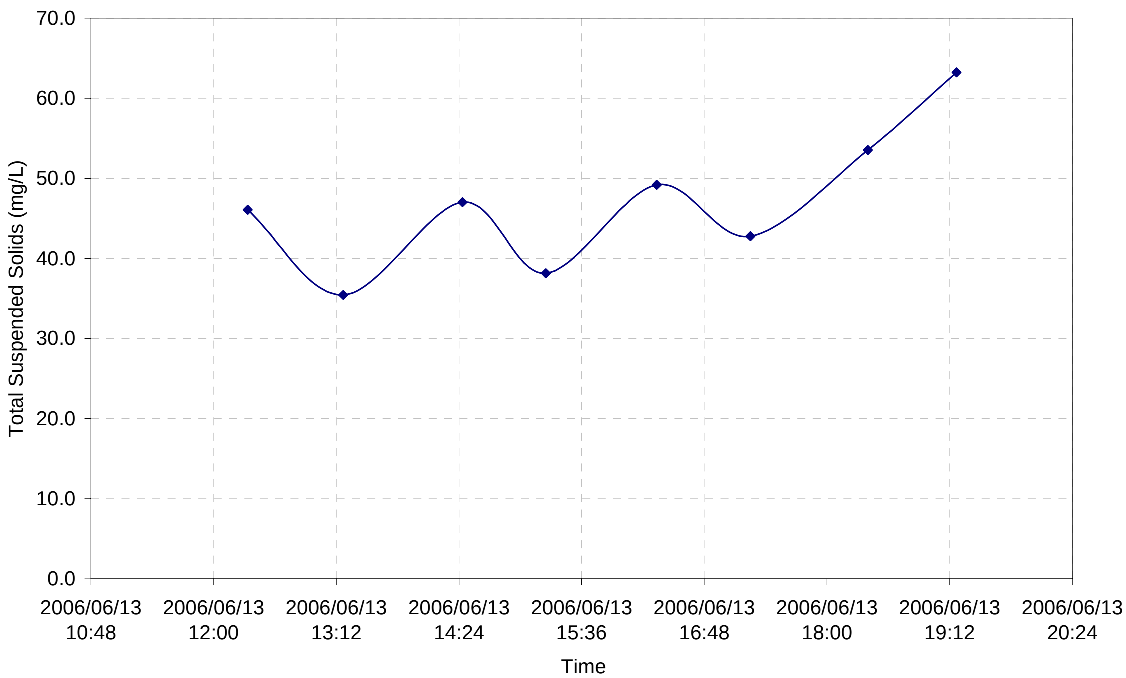

Figure 3.34 Site 7 Variations of Bottom Turbidity Over Time

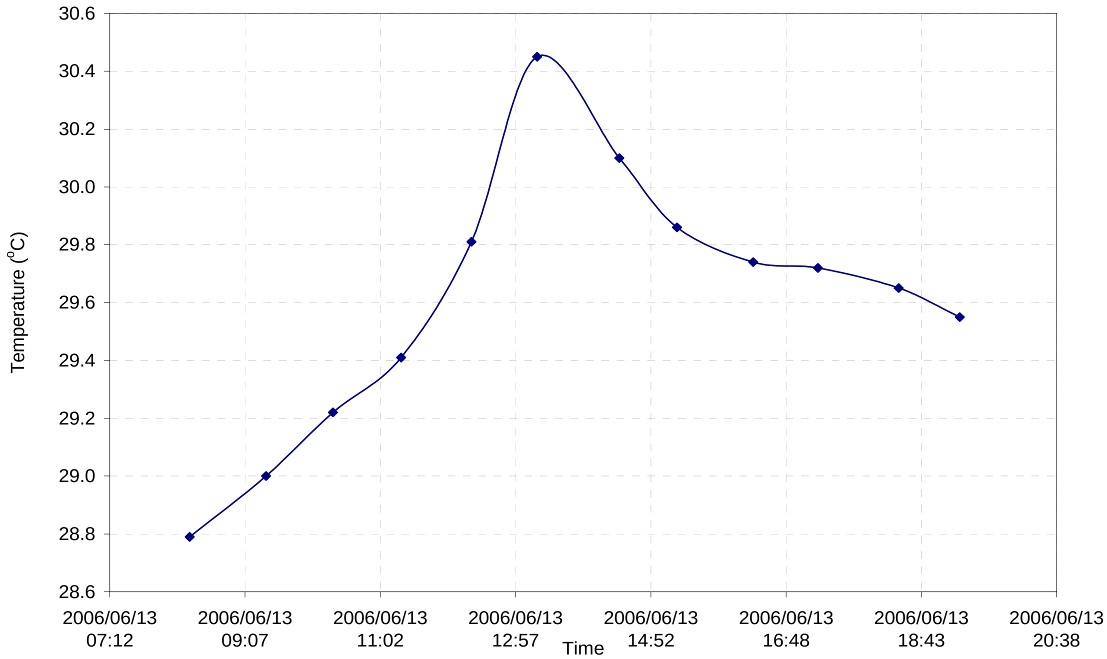

Figure 3.35 Site 7 Variations of Surface Temperature Over Time

3.1.4 Benthic and Sediment Samples

3.1.4.1 Study Design

This study is located in and around a dredge excavation pit located 7 km (4 mi) south of Holly Beach, Louisiana and 28 km (17 mi) east of the Texas-Louisiana border (Figure 3.36). The original pre-dredging depth was 8 m. The pit was excavated in April 2003. A total of eight stations were sampled between 10 - 11 June 2006, over 3 years after excavation (Table 3.1, Figure 3.36). Two sampling stations were located within the pit (Stations 1 and 2), one station on the pit edge (Station 4), one 20 m from the pit edge (Station 5), one 100 m away from the pit edge (Station 6), one 200 m from the pit edge (Station 3), and two at least 0.6 mile (1 km) from the edge of the pit (Stations 7 and 8). A further four new stations were sampled on 4 March 2007 to complement the samples taken in June 2006 (Table 3.1, Figure 3.36). Of these more recently sampled stations, three were situated outside and one inside the excavation pit. One of these stations was 230 ft (70 m) from the pit edge on a dredge disposal mound and the two other stations were located 330 – 720 ft (100 - 220 m) away from the pit, presumably in less disturbed conditions. The only station sampled inside the pit (Station 10) was approximately 33 ft (10 m) from a station sampled in June 2006 (Station 1). Macrobenthic samples were taken at each station, along with hydrographic measurements in the water column and sediment samples.

Table 3.1 Station Locations in State Plane Projected Coordinate System (Louisiana South, feet) and Geographic Coordinate System (North American datum 1983, decimal degrees)

		State Plane		Geographic	
Station	**Description**	**Northing**	**Easting**	**Latitude**	**Longitude**
1	Inside the pit - SW portion	440657	2578919	29.69310	93.54418
2	Inside the pit - center	441475	2577027	29.69540	93.54387
3	180 m west of pit edge	437083	2574897	29.69402	93.54551
4	on pit edge on northeast side	441000	2578505	29.69501	93.54852
5	20 m from pit edge on west side	441493	2579033	29.68306	93.55663
6	100 m west of pit edge	441528	2574351	29.69525	93.55862
7	1000 m west of pit edge	441361	2577256	29.69494	93.54947
8	1400 m southwest of pit edge	441378	2577555	29.69525	93.55019
9	70 m northwest of pit edge	441929	2577676	29.69653	93.54818
10	Inside the pit - SW portion	440687	2578895	29.69318	93.54426
11	100 m east of pit edge	440954	2579645	29.69395	93.54192
12	200 m east of pit edge	440952	2580065	29.69397	93.54059

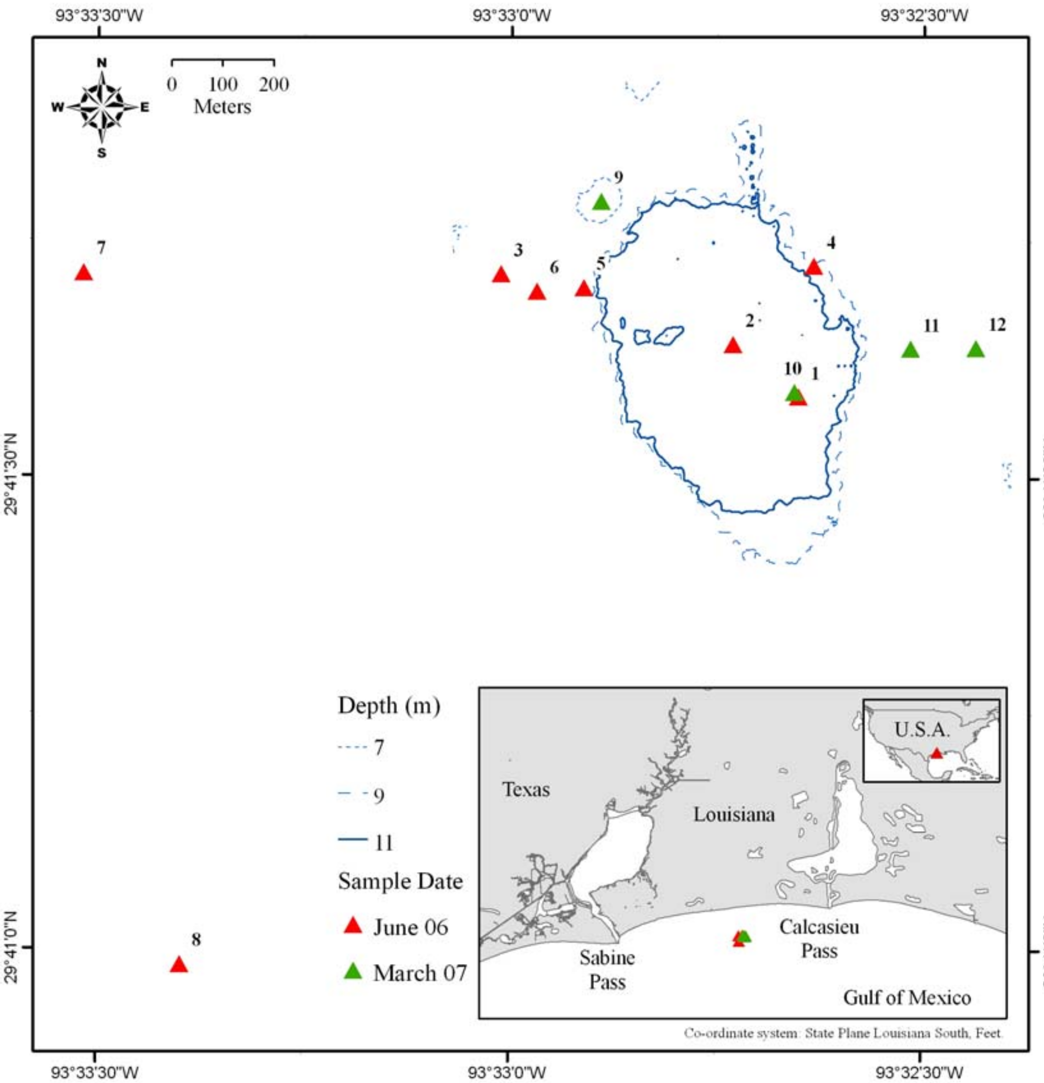

Figure 3.36 Locations of Sampling Stations
(Bathymetry is derived from a June 2006 survey)

3.1.4.2 Water Quality Measurements

Vertical water quality profiles of the water column were taken at each station that was sampled in June 2006. Measurements were taken at six evenly spaced depth intervals (bottom, surface and 20, 40, 60, 80 % of the total depth) in each profile. Only a mid-depth measurement was taken at the stations that were sampled in March 2007. A multiparameter YSI 600XLM datasonde was used to measure temperature (°C), turbidity (NTU), and dissolved oxygen (mg l^{-1}) at each station. The results were presented in Section 3.1.3

3.1.4.3 Macrofauna

Macrofauna samples were collected using SCUBA. Macrofauna were sampled with 2.6 in (6.7-cm) diameter core tubes and sectioned at depth intervals of 0 - 1.1 in (0 - 3 cm) and 1.1 – 3.9 in (3 - 10 cm). Photos of the testing and analysis are provided in Appendix C. Samples were preserved with 5 % buffered formalin. Five samples were taken at each of the eight stations that were sampled in June 2006; however, only four samples were taken at each of the four stations that were sampled in March 2007. In the laboratory, macrofauna were sorted on 0.2 in (0.5-mm) sieves and sorted from sediments using a dissecting microscope. Organisms were identified to the lowest taxonomic level possible, usually the species level. Organisms from each sample were pooled into higher taxonomical categories (Crustacea, Mollusca, Polychaeta, and Others) and dried for 24 h at 131 ^{o}F (55 ^{o}C) to determine dry weight biomass. The dried categories were then weighed to the nearest 0.01 mg. Mollusks were placed in 1 N HCl from a few minutes to an hour until carbonate shells were dissolved, and washed before drying.

3.1.4.4 Sediment Size Analysis

Sediment samples were collected with 2.6 in (6.7-cm) diameter core tubes and sectioned at depth intervals of 0 - 1.1 in (0 - 3 cm) and 1.1 – 3.9 in (3 - 10 cm). Photos of the testing and analysis are provided in Appendix C. Percent contribution by weight was measured for four size classes: rubble and coarse sand (>125 µm), fine sand (125 - 62.5 µm), silt (62.5 – 3.9 µm), and clay (<3.9 µm). To determine grain size, a 1.2-in^3 (20-cm$^{3)}$ sediment sample was mixed with 0.05 qt (50 ml) of hydrogen peroxide and 0.07 qt (75 ml) of deionized water to digest organic material in the sample. The sample was wet sieved through a 62-µm mesh stainless steel screen using a vacuum pump and a Millipore Hydrosol SST filter holder to separate rubble and sand from silt and clay. After drying, the rubble and sand were separated on a 125-µm screen. In this study rubble is defined as sediment over 125-µm in diameter and is usually composed of shells, gravel, debris and coarse to medium sand. The silt and clay fractions were measured using pipette analysis. The sediment size analysis follows the methods in Folk (1964).

3.1.4.5 Statistical Analysis

Species diversity was calculated using Hill's number one (N1) diversity index, which is the exponential form of the Shannon HN diversity index (Hill, 1973). Hill's N1 was used because it has units of number of dominant species, and is more interpretable than most other diversity indices (Ludwig and Reynolds, 1988).

A one-way analysis of variance (ANOVA) was used to test for differences in macrofauna abundance, biomass and Hill's N1 diversity between stations. Calculations were made after pooling all sections and are reported to a depth of 0.3 ft (10 cm). Abundance and biomass were log transformed (log(x+1)) prior to analysis. Where significant differences were detected, Tukey multiple comparison tests were used to find which means were different from one another. The experimentwise error rate for the Tukey tests was maintained at 0.05. Tukey tests were also conducted on log-transformed data. All univariate analyses were performed using SAS software (SAS Institute Inc. 1999).

Community structure of infaunal species was analyzed by non-metric multi-dimensional scaling (MDS). MDS is a multivariate statistical tool that can be used to compare many variables from many stations simultaneously. In this study, MDS was used to examine community structure by comparing numbers of individuals of each species at each station. MDS was also used to compare the biomass of each major taxa at each station. The distance between stations in an MDS plot can be related to community similarities or differences between stations. Differences and similarities among communities were highlighted using cluster analysis using the group average cluster mode. The significance that the clustering structure was not a result of randomization was tested using a similarity profile (SIMPROF) test with a significance level of 5 %. Species abundance data was log transformed prior to analysis and used a Bray-Curtis similarity matrix to create the MDS plot. MDS was performed using Primer software (Clarke and Gorley 2006).

Principal Component Analysis (PCA), a parametric multivariate method, was used to assess relationships between physical variables (sediment grain size, bottom depth, and hydrographic measurements) characteristic of stations. Water quality variables were log-transformed prior to analysis. Sediment sizes were averaged for the two vertical sections, and arcsine root transformed because they were in percentage form. Results are presented in bivariate plots as station scores and as variable loads. The plot of variable loads allow for visualization of the importance of variables in contributing to the loading scores. The PCA station score plots allow for visualization of relationships among the sampling stations. PCA analyses were performed using a rotated covariance model with SAS software (SAS Institute Inc., 1999).

Relationships between macrofauna communities and environmental factors were investigated using the Biota-Environment (BIO-ENV) procedure. The BIO-ENV procedure is a multivariate method that matches biotic (i.e., macrofauna community structure) with environmental variables (Clarke and Warwick, 2001). This is carried out by calculating weighted Spearman rank correlations (Δ_w) between sample ordinations from all of the environmental variables and an ordination of biotic variables (Clarke and Ainsworth, 1993). Correlations are then compared to determine the best match. The BIO-ENV procedure uses different numbers of abiotic sample variables in calculating correlations to investigate the different levels of environmental complexity. For this study, the macrofauna species abundance MDS ordination was compared with all physical variables. The significance of relationships were tested using RELATE, a non-parametric form of the mantel test. The BIO-ENV and RELATE procedures were calculated with Primer software (Clarke and Gorley 2006).

Relationships between physical and macrofaunal characteristics were also determined by correlating the first two principal components from PCA with macrofaunal abundance, biomass and diversity (N1) using regression analysis. An individual principal component represents a calculated amount of variability within a multivariate dataset and in effect represents a combination of physical variables rather than just one. In this study, if a principal component was found to represent a combination of water quality variables, a linear regression line was used. A Gaussian 3-parameter curve was used in the case that either of the principal components represented only sediment size variables. The peaked curve was used because abundance, biomass and diversity were predicted to peak at minimum disturbance intensities, which was hypothesized to co-occur with relatively moderate grain sizes. Disturbance by accretion was predicted to result in sediment dominated by fines inside the pit, whereas erosion on the dredge disposal mound and pit margin erosion was predicted to leave the sediment dominated by larger grain sizes. Regression analysis was implemented using Sigmaplot software (Systat Software, 2006).

A discussion of results is presented in Section 3.2.3.

3.2 Analysis of Holly Beach Dredge Pit Evolution and Impacts

3.2.1 Morphological Modeling of Dredge Pit Evolution

The work completed by Nairn *et al.* (2005) on numerical modeling of morphologic evolution of the Holly Beach Dredge Pit in support of the assessment of the impact of pits on adjacent infrastructure, was extended for this study to further test the capability to predict morphologic change of dredge pits. The other objective of the morphologic modeling was to improve the simple techniques for estimating the infilling rate for future pits based on local information, again building on the methods presented in Nairn *et al.* (2005).

The Baird in-house hydrodynamic, sediment transport and morphologic model MISED was used to simulate the morphological changes of the Holly Beach Dredge Pit. Two model applications were performed. The first consisted of a full three-dimensional (3D) model setting and the second consisted of a vertical two-dimensional (2DV) model simulation (i.e. where only a vertical slice through the pit is simulated, assuming a pit with infinite width). Since the computational time for the modeling with full 3D configuration was much longer than the model for the simplified 2DV configuration, the 2DV model was primarily used to simulate the long-term morphological change of the pit. The 3D model application was used primarily to evaluate whether the 2DV model was sufficient to simulate pit evolution or not and to understand the impacts of the dredge pit on the hydrodynamics over and in the vicinity of the pit. Section 3.2.1.1 describes the model setup, calibration and simulations of pit evolution.

Section 3.2.1.2 provides a description of a new simple technique for estimating the rate of pit infilling.

3.2.1.1 Numerical Modeling of Dredge Pit Evolution

3.2.1.1.1 Model Setup

MISED used 9-nodal quadrilateral elements to discretize the model domain. The grid for the 3D model is shown in Figure 3.37. The grid size was refined to 246 ft (75 m) in the vicinity of the pit. The three open boundaries (west, east, and south boundaries) were controlled by tide levels. As explained in Section 3.1.2, the ADCP data showed that the measured currents in the vicinity of the pit were likely a combination of both tide- and wind-driven currents. The variation in flow direction through the water column is compatible with currents driven by wind. (i.e. the current direction at the bottom opposite to the current direction at the surface). Therefore, wind-driven currents were considered as input to this 3D model application. In addition, the influence of waves is also likely to be an important factor for sediment re-suspension and this process was also included in the model.

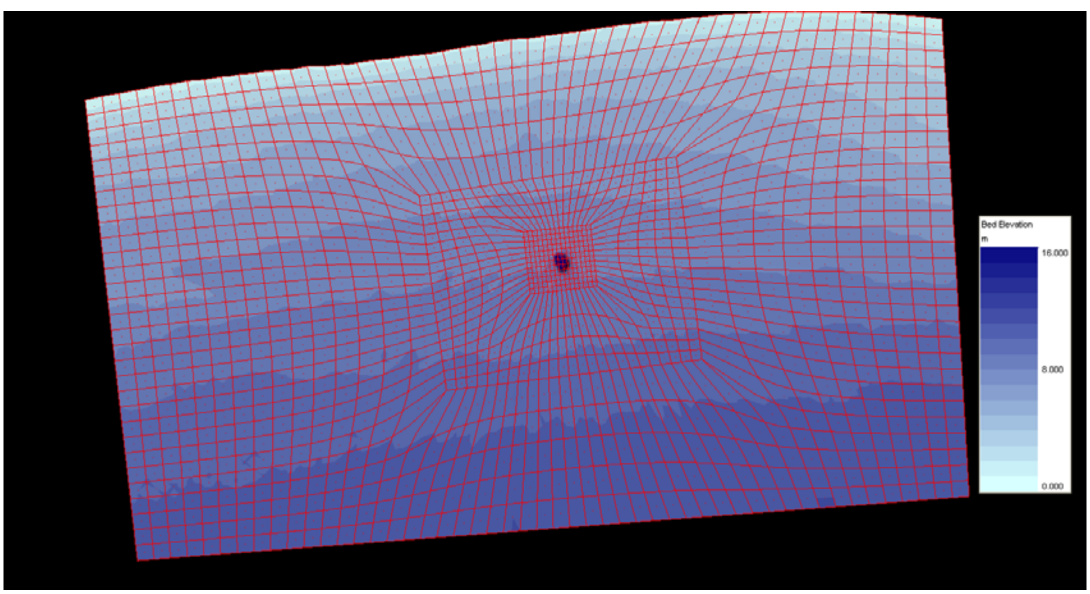

Figure 3.37 Grid Used for 3D Morphological Modeling

The tide levels on the model open boundaries were calculated by using the eight main tidal constituents extracted from the ADCIRC model provided to Baird (personal communication, Mitch Brown, U.S. Army Corps of Engineers, Engineering Research and Development Center). The dominant tides in the Gulf of Mexico are K1 and O1. Both are diurnal tides. M2 is a secondary tide in the Gulf of Mexico. The water levels on all three boundaries are tilted by calculating from the water levels at the two ends of each boundary. Figure 3.38 shows the tide used in the model calibration.

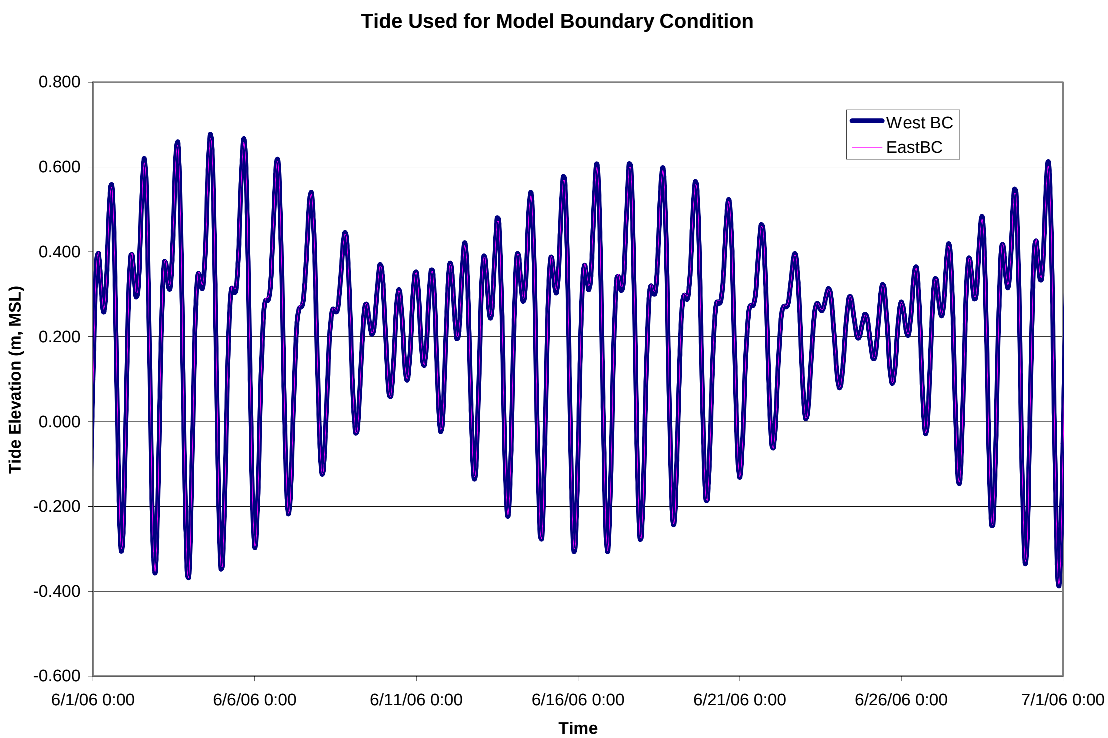

Figure 3.38 Tide Levels Used in the Model Calibration

There are two buoy stations near the pit (see Figure 3.39 for the locations). NDBC Buoy 42053 has wind and wave data from 2003 to present while Station SRST2 at the coast near the border of Louisiana and Texas has only wind data. The wind speeds recorded at the two stations are quite different and the choice of the wind data is a part of the model calibration process (see Figure 3.40). The rose plots for wind data at the two stations for the period from 2003 to 2006 are shown in Figures 3.41 and 3.42. For both stations the dominant winds are from the south to southeast sectors.

Figure 3.39 Wind Station Locations Relative to the Holly Beach Dredge Pit

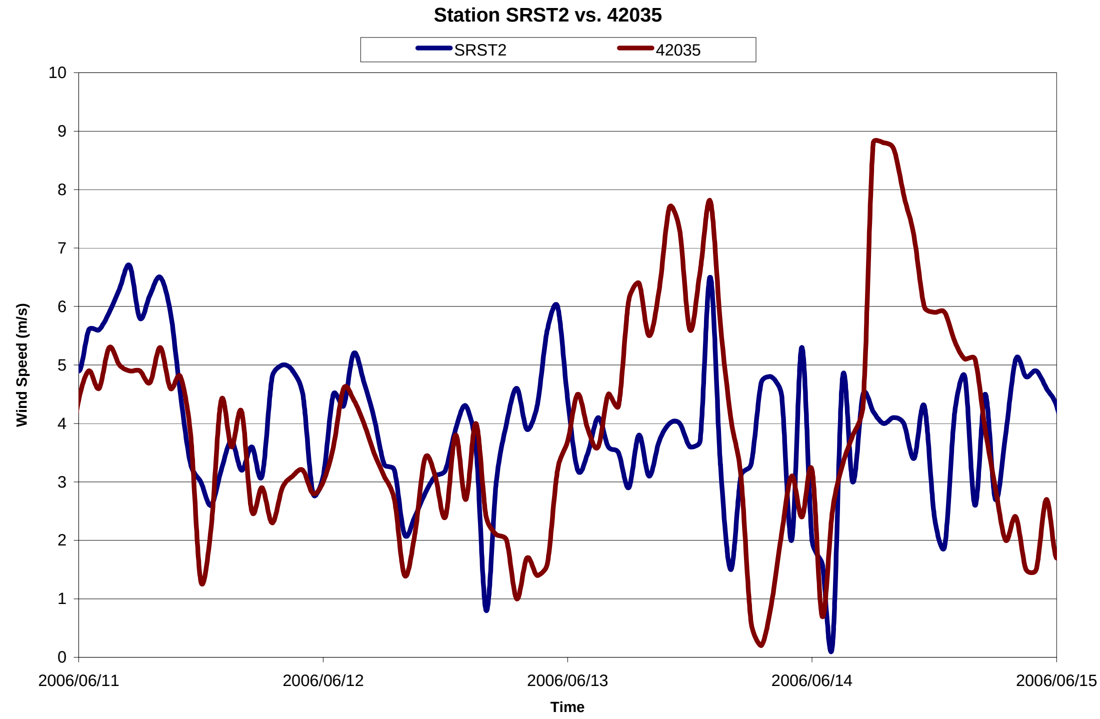

Figure 3.40 Wind Data Recorded at the Two Stations During the Period of Model Calibration

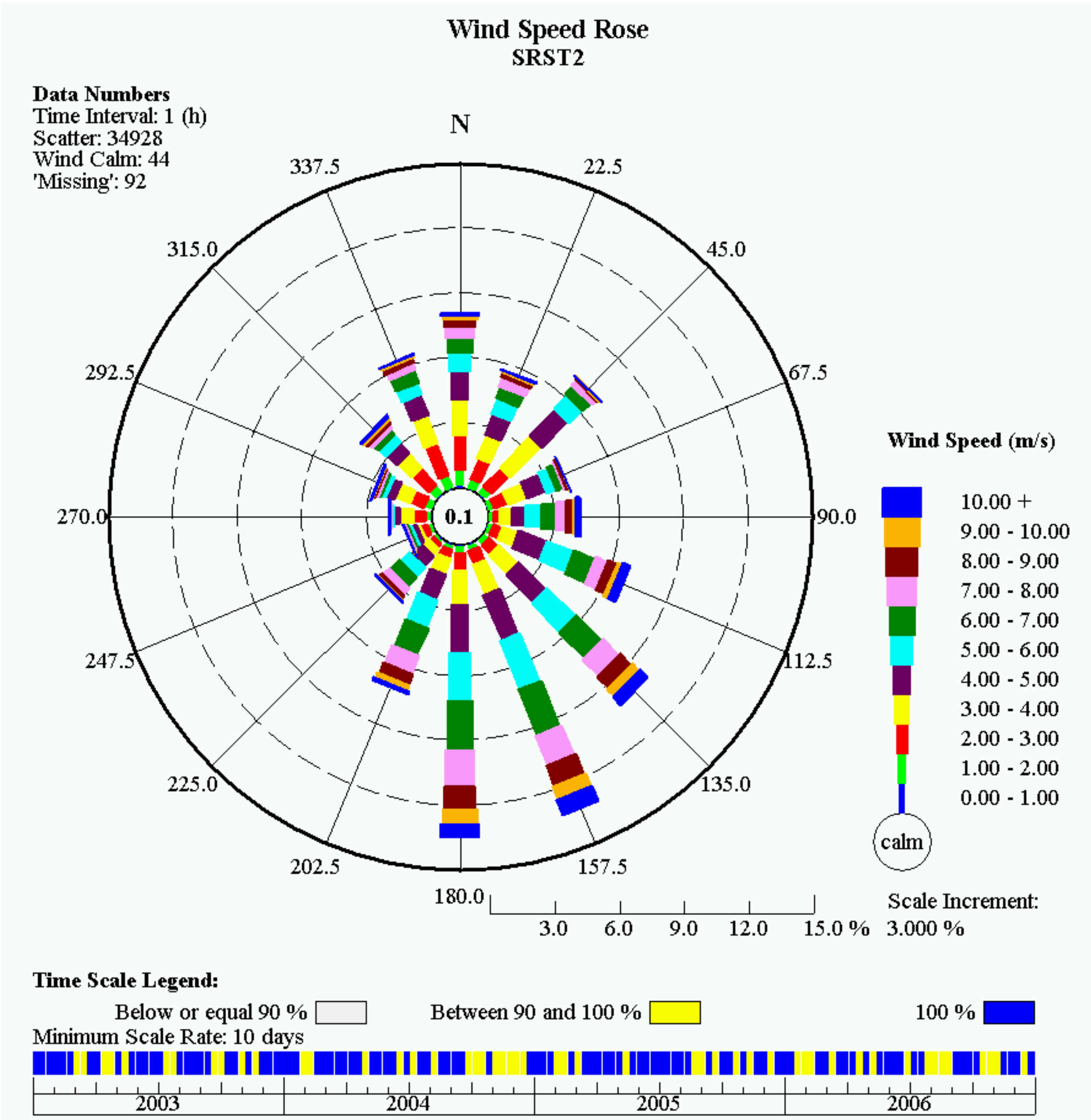

Figure 3.41 Wind Rose for Station SRST2 (2003 to 2006)

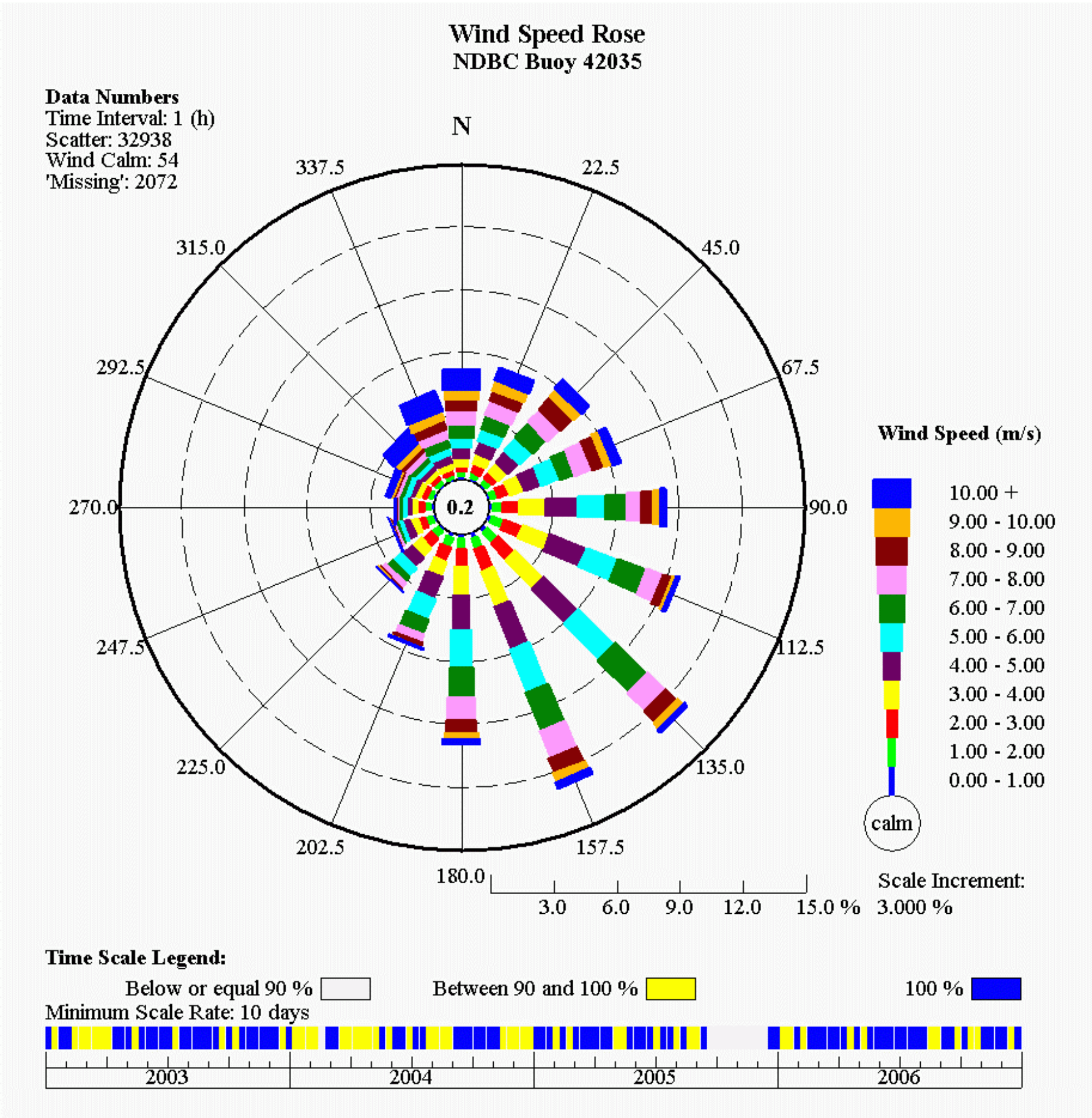

Figure 3.42 Wind Rose for Station NDBC42035 (2003 to 2006)

Waves are an important factor for sediment re-suspension in the coastal area. The MISED model has the capability to import wave information from the other models or from recorded observations. The nearest station with wave data is the NDBC42035 and therefore, wave data from this buoy was used to estimate sediment re-suspension. Station NDBC 42035 is located 62 miles (100 km) southwest of the Holly Beach Borrow Area, and the water depth at the station is 45 ft (13.7 m). The rose plot for the wave data from this station is shown in Figure 3.43. The most frequent sectors of wave direction are from south to southeast. Large waves occur from south-southwest to east.

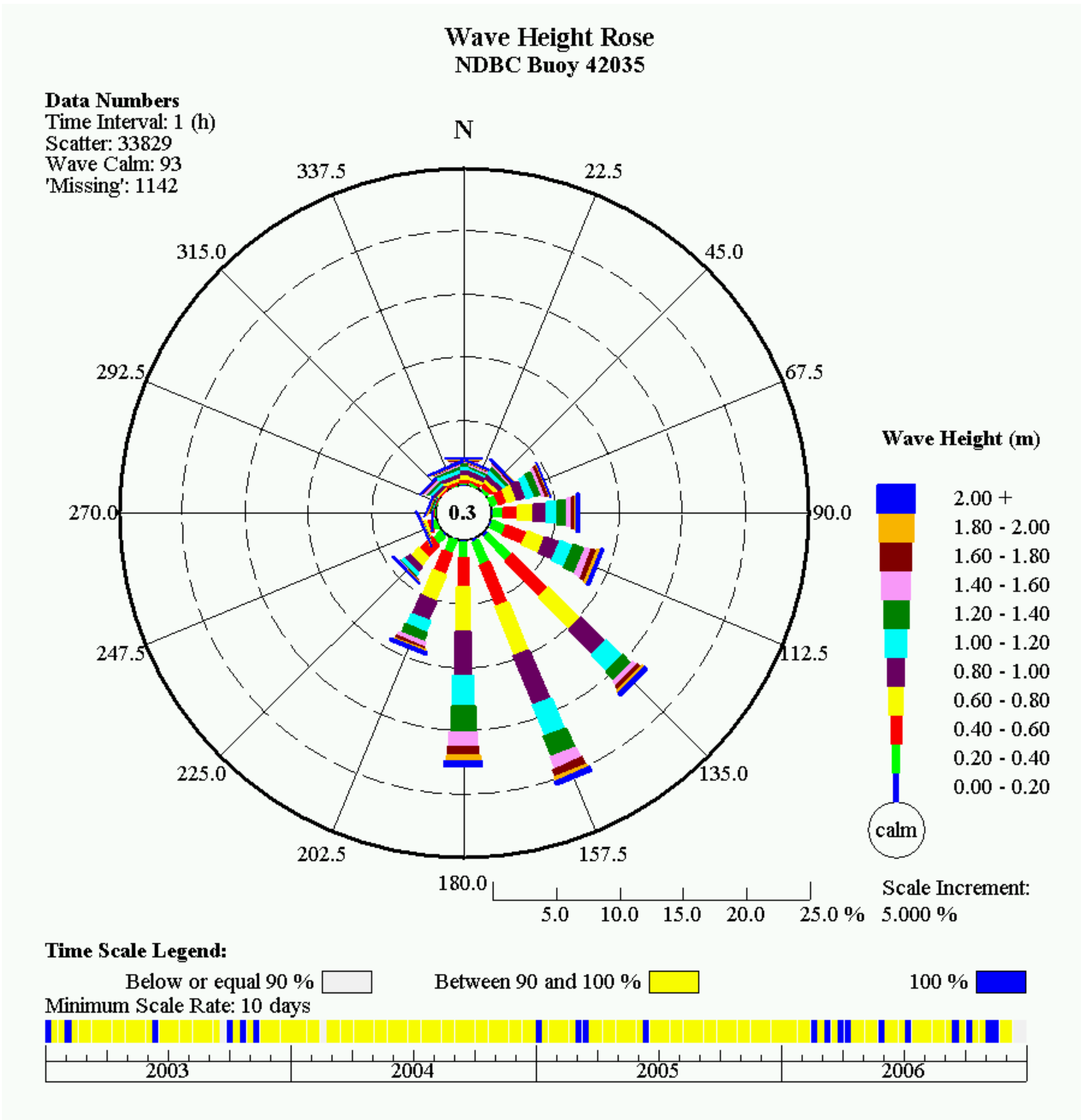

Figure 3.43 Wave Rose for Station NDBC42035 (2003 to 2006)

The MISED model used the van Rijn (200 formulae to calculate the bed shear stress produced by both current and wave. The combined bed shear stress is calculated by the following equation:

$$\left|\tau_{b,cw}\right| = \alpha_r \tau_{b,c} + \left|\tau_{b,w}\right| \tag{3.1}$$

where

$\tau_{b,cw}$ is the combined bed shear stress (N/m^2)

$\tau_{b,c}$ is the current-related bed shear stress (N/m^2)

$\tau_{b,w}$ is the wave-related bed shear stress (N/m^2)

α_r is bed-shear stress reduction factor

The current-related bed shear stress is calculated by the following equation:

$$\tau_{b,c} = \frac{\rho \kappa^2 \bar{v}_R^{\,2}}{\left[-1 + \ln\left(30h / k_s\right)\right]^2} \tag{3.2}$$

where

ρ is the water density (kg/m^3)

$\bar{v}_R$ is depth-averaged velocity magnitude (m/s)

κ is Kerman's coefficient (=0.4)

h is water depth (m)

k_s is bed roughness (m)

The wave-related bed shear stress is calculated by the following equation:

$$\tau_{b,w} = \tfrac{1}{4} \rho f_w \hat{U}_\delta^2 \tag{3.3}$$

where

$\tau_{b,w}$ is time averaged (over half a wave cycle) bed shear stress (N/m^2)

f_w is friction coefficient

$\hat{U}_\delta$ is peak value of the orbital velocity ($\hat{U}_\delta = \omega \hat{A}_\delta = \dfrac{\pi H}{T \sinh(kh)}$)

$\hat{A}_\delta$ is the peak value of the orbital excursion ($\hat{A}_\delta = \dfrac{H}{2\sinh(kh)}$)

ω is angular velocity (s^{-1})

k is wave number (m^{-1})

H is wave height (m)

T is wave period (s)

The current-related bed-shear reduction factor due to the present of wave is calculated by

$$\alpha_r = \left[\frac{\ln(30\delta / k_a)}{\ln(30\delta / k_s)}\right]^2 \left[\frac{-1+\ln(30h / k_s)}{-1+\ln(30h / k_a)}\right]^2 \qquad (3.4)$$

where

k_a is apparent bed roughness (m) ($k_a = \exp\left(\gamma \hat{U}_\delta / \bar{v}_R\right) k_s$)

γ is the coefficient (0.75 ~ 2.1) ($\gamma = 0.8 + \phi - 0.3\phi^2$)

$\bar{v}_R$ is depth-averaged velocity magnitude (m/s)

ϕ is angle between current and wave direction (in radians between 0 and π)

3.2.1.1.2 Model Calibration and Validation

The model was calibrated by comparing the model results with the measured ADCP data and suspended sediment data. The currents predicted with the model using the wind data from Station 42053 did not well agree with the ADCP data at the Site 7 well beyond the edge of the pit (see Figure 3.14 of Section 3.1.2.1 for the location of Site 7). However, the calculated flow velocities predicted with the MISED model agree well with the ADCP data using the wind data recorded at the station SRST2 for model input, as shown in Figure 3.44.

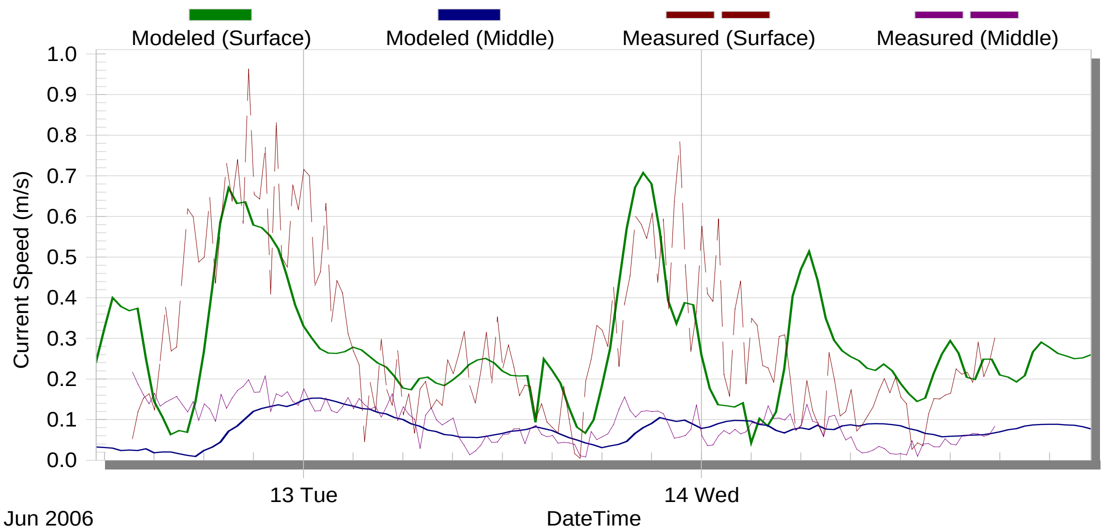

Figure 3.44 The Comparison of the Model Predicted Flow Speed with the ADCP Measured Data at the Surface and at Mid-depth

The sediment concentration calculated by the model was compared with data measured at Site 2 within the pit and Site 7 located well beyond the edge of the pit (see Figure 3.45 for the results and Figure 3.14 of Section 3.1.2.1 for the location of the two measurement sites). The estimated concentrations match fairly well with the sample data measured at the site HB7 (i.e. Site 7). It is important to note from the model results that when compared with the concentration outside the pit, there is a delay in the concentration change inside the pit near the bed. This indicates that the suspended sediment inside the pit was mainly brought by currents from the outside (i.e. advection) and through diffusion. There will be little or no sediment re-suspension inside the pit. As noted in Section 3.1.3, water samples were taken after a strong wind event. Therefore, the sample data did not capture the high suspended sediment levels that the model predicted for the strong wind events, which reached almost 0.8 kg/m^3. The peak concentration inside the pit (about 0.2 kg/m^3) is much less than the peak concentration well outside the pit, as a result of sediment deposition in the pit (and thus a loss of sediment from the water column above the pit). This is reflected in both the predicted and measured suspended sediment levels. The reduction in the measured suspended sediment levels from outside to inside the pit is significant, even though it does not appear so due to the scaling of Figure 3.45.

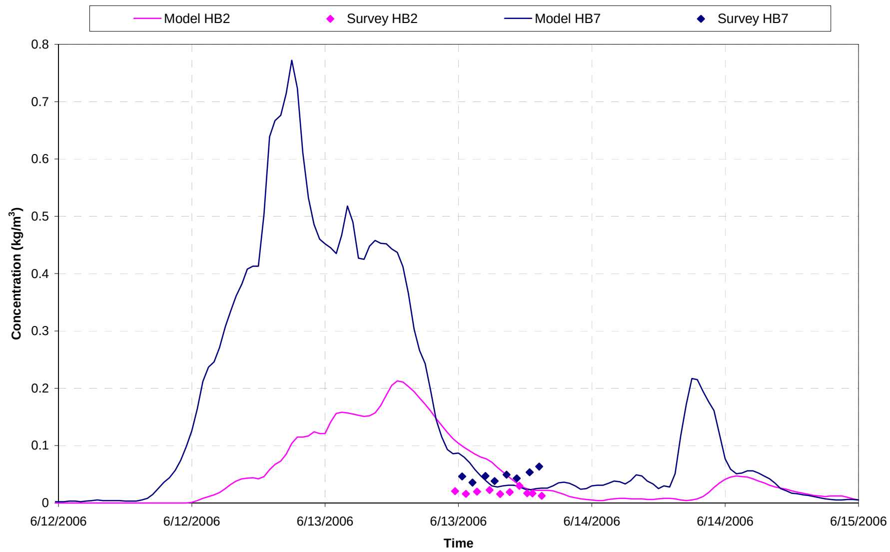

Figure 3.45 Measured and Predicted Suspended Sediment Concentrations for Site 2 (HB2) Inside the Pit and Site 7 (HB7) Well Beyond the Edge of the Pit

The morphological change calculated by the model was compared with the survey data and the model results calculated by the 2DV model conducted in the previous phase. The morphological simulation using the 3D model was started on April 1, 2003, just after the pit was constructed. The comparison of the model results with survey data are shown in Figures 3.46a and 3.46b. The pit infilling calculated by the 3D model agrees well with the results calculated by the 2DV model result, which also match well with the surveyed data. Note that the bed elevation in June 2006 and March 2007 were measured after the 2DV model run (refer to Figure 3.23 of Nairn *et al.* (2005)). This indicates that the prediction of the pit infilling from the 2DV MISED model is quite accurate. Since the 2DV model does not consider extreme wind and wave conditions generated by extra-tropical storms and hurricanes, the discrepancy between the surveyed bed elevation and the modeled bed elevation on June 2006 may be caused by the influence of storm events, and particularly, Hurricane Rita in September 2005. As described in Table 2.1 in Section 2.2, the significant wave heights during Rita at the Holly Beach Dredge Pit location were predicted to exceed 4 m for a period of 23 hours and to have reached a maximum of 5 m with a period of 16 s. Nevertheless, considering how good the model prediction is using average wave conditions (i.e. ignoring the influence of Hurricane Rita) hurricanes do not appear to have an important influence on long-term morphological change of the dredge pit. This is probably explained by a combination of three factors: 1) the duration of a hurricane event is relatively short (about 24 hours) compared to the period of infilling over many months; 2) the background suspended sediment concentrations are already high and are likely not more than doubled to quadrupled during a hurricane event; and 3) the re-suspension potential may be suppressed as a result of armoring that may develop through winnowing fine sediment from the surface of the sea bed. This finding is important because it indicates that predictions of the morphologic charge of pits can be made with averaged conditions (i.e., with considering individual storm events).

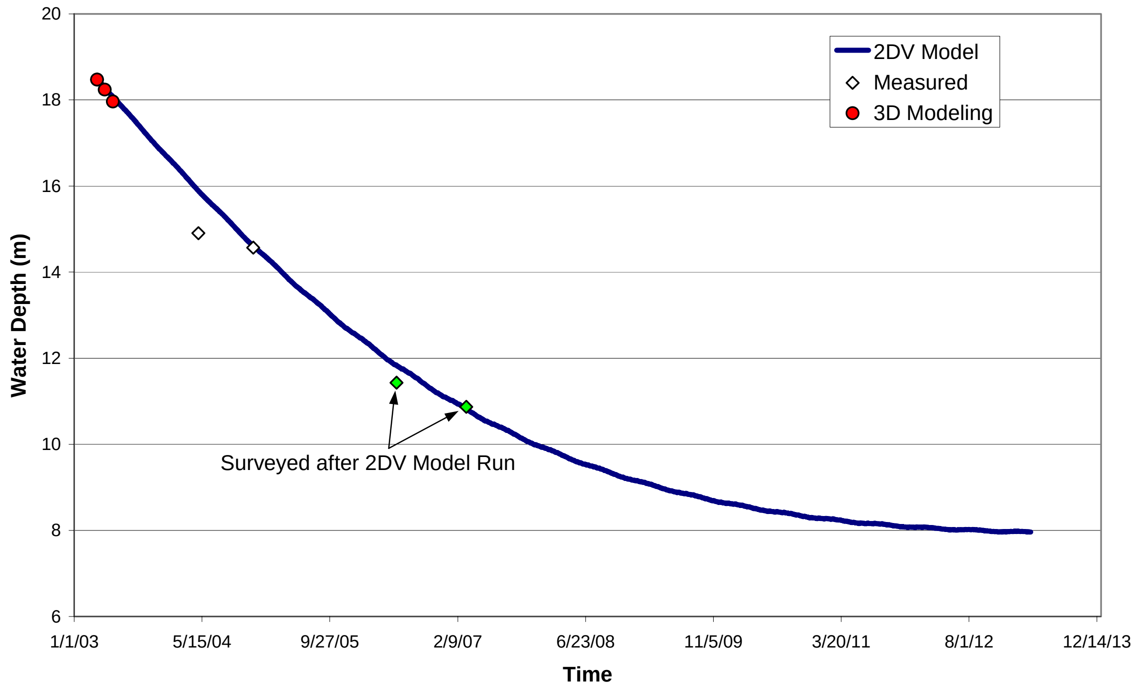

Figure 3.46a Measured and Predicted Water Depth within the Holly Beach Dredge Pit Showing the Rate of Pit Infilling

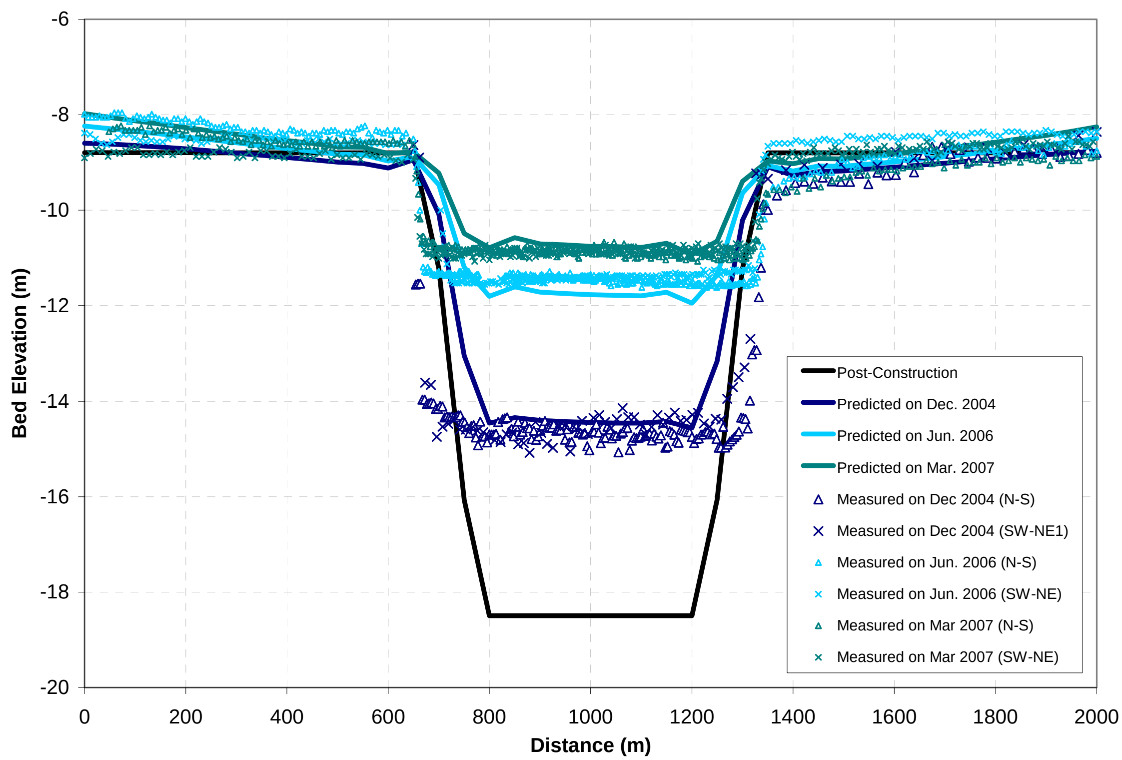

Figure 3.46b Measured and Predicted (2DV Model) Pit Infilling and Pit Margin Erosion for the Holly Beach Dredge Pit

Figure 3.46b shows that the model predicts the reversal from erosion to accretion in the pit margin erosion zone. This reversal is in fact over-predicted in the model and this finding was discussed in Nairn *et al.,* (2005), it is likely a result of over-prediction of the background suspended sediment concentration. The reversal from pit margin erosion to accretion results from the fact that the pit is now shallow and the driving forces for erosion have been reversed and the entire area is now infilling.

The 3D model was run with a time step of 60 seconds for a year from April 1, 2003 to March 31, 2004. Using a PC with an Intel Pentium IV, the model run took about 300 hours for the one-year simulation. It may not be computationally feasible to use a 3D model to predict long-term morphological change in a pit over periods of 5 to 10 years. Considering that the 2DV model did has done well in predicting the change over the last four years, it may be sufficient to apply the 2DV model for longer term predictions. Nevertheless, the 3D model was definitely useful in developing an understanding of the hydrodynamic and morphological responses associated with the presence of the pit, and these are described in the next section.

3.2.1.1.3 Understanding Pit Margin Erosion

It was explained in Nairn *et al.* (2005) and has been shown in the bathymetry measurements presented in Section 3.1.1, that the other primary morphologic response associated with dredge pits in muddy settings is pit margin erosion. In Section 3.2.1.1.2 above the lower suspended sediment concentrations over the pit, compared to areas well away from the pit, was noted in both the measurements and predictions. The numerical modeling showed that this was a result of higher deposition within the pit resulting from the lower flow speeds over the pit. The gradient in suspended sediment concentration between the pit and the adjacent areas was shown theoretically, and through the use of the 2DV model in Nairn *et al.* (2005), to result in erosion of the sea bed around the pit. This pit margin erosion was found to extend to distances of more than 492 ft (150 m) from the edge of the pit ranging from 0.9 m at the edge of the pit.

The 3D model simulations completed as part of this investigation elucidated another factor explaining the reason for pit margin erosion and this related to the influence of the pit on the flow field. It was determined that the flow speed and the resulting bed shear stress increases over the pit margin on the upstream side of the flow and is both increased (directly in the lee of the pit) and decreased along two lobes off the downstream edge of the pit. This is known as a “flow attraction” effect of pits and has been described in Van Rijn *et al.,* (2005). Flow attraction results from the greater potential for total flow over the pit pulling water towards the pit in the direction of flow on the upstream side; this effect also explains the increase in flow speed (and shear stress) on the central area immediately downstream side of the pit and the two lobes of reduced shear stress extending away from either corner of the pit.

Figures 3.47 and Figure 3.48 show the 3D model result for two different and typical flow conditions during the model simulation period. Figure 3.47 corresponds to a low wind speed and average tide resulting in westward directed currents. Figure 3.48 shows the results for an average tidal condition and a higher wind speed causing stronger westerly directed currents. For each of the model results three figures are presented as follows: the first two (a and b) show the flow vectors near the bed overlaid on the color mapping of bed shear stress for (a) a view of the overall model domain, and (b) a close up. The third figure (c) shows the suspended sediment concentration.

For these test cases there is no reverse flow at the bottom. The increased bed shear stress over the upstream margin of the pit is evident in the figures, as is the narrow area of increase on the downstream side bracketed by two areas of reduced shear stress. The lateral extent of the zone of elevated shear stresses ranges from about 655 to 1312 ft (200 m to 400 m) for the low to high wind condition examples. The lower flow condition is more representative of average conditions and the 655 ft (200 m) extent of increased shear stresses compares well to the 492 to 655 ft (150 to 200 m) of pit margin erosion observed from the analysis of the bathymetry data in Section 3.1.1.

The suspended sediment concentration is lower on the downstream side due to the deposition that occurs over the pit (see Figures 3.47c and 3.48c).

Figures 3.49a and 3.49b show the bed shears around the pit with the combined conditions of wave, wind-driven, and tidal currents. The bottom reverse flow is generally found in the strong wind-driven currents. The reduction of bed stress around the pit was obviously seen in the figures.

The bathymetry comparisons showed that the pit margin erosion was most pronounced in the period from April 2003 to December 2004. On the east and west edge of the pit there was little or no pit margin erosion for the period from December 2004 to June 2006. On the north and south margin of the pit accretion occurred, as shown in Figure 3.46b. The limited cross-section available from the March 2007 survey suggest that pit margin erosion was re-activated on the east and west side of the pit in this latter period or the erosion in this period was a more regional process occurring everywhere. However, on the north and south side, accretion continued in the former pit margin erosion zone, as shown in Figure 3.46b. In general it would be expected based on the understanding of the processes that pit margin erosion will reduce and eventually reverse to pit margin accretion with the infilling of the pit due to: 1) a reduction in the change in suspended sediment concentration from over to beyond the pit; and 2) a reduction in the flow attraction effect over the pit. Also the pit margin erosion zone itself will begin to be influenced by the adjacent areas, just as the pit margin was influenced by the pit.

3.2.1.1.4 Morphologic Evolution of Dredge Disposal Mounds.

The bathymetry surveys and sediment sampling provided information that indicated that the erosion of the primary dredge disposal mound located immediately northwest of the borrow deposit was slow and limited. The slow morphologic response was explained by the fact that the mound was capped and effectively armored with sandy sediment, likely derived from the final clearing of the mud cap and removal of some of the underlying sand. Recommendations have been included in the proposed guidelines to avoid this unintended armoring of the dredge disposal mound that prevents the mound from being eroded to fill the adjacent pit. Accelerated filling of the dredge pit is a desired outcome to accelerate physical and biological recovery. Modeling of this condition would therefore not have yielded any useful information to the investigation and development of guidelines.

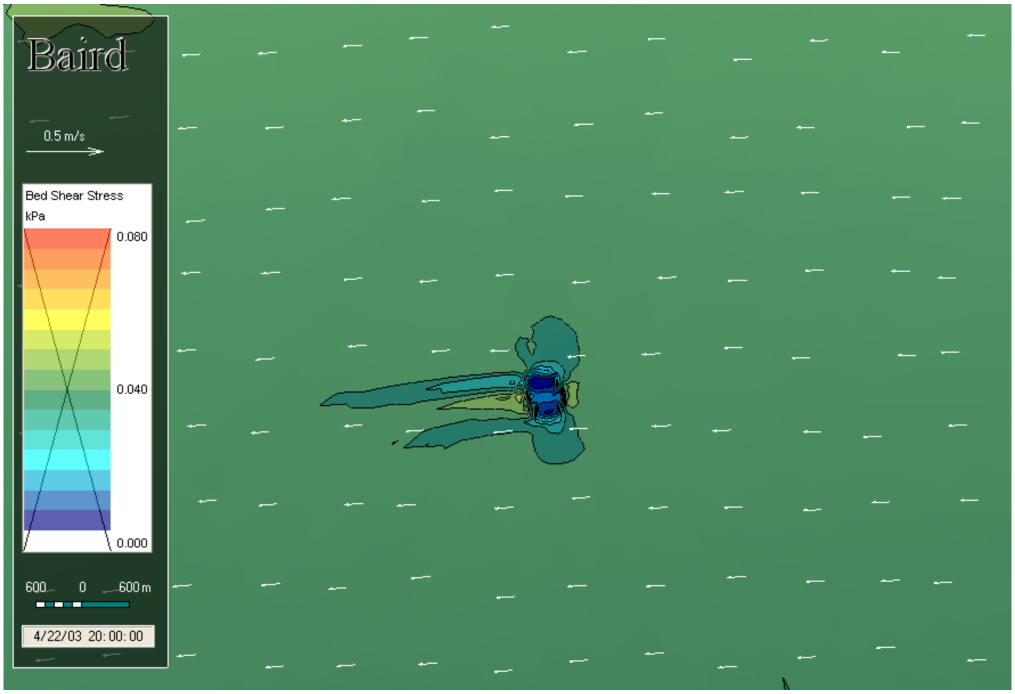

Figure 3.47a Near Bed Flow Vectors Overlaid on the Bed Shears Stress Map for the Full Model Domain and the Lower Flow Condition

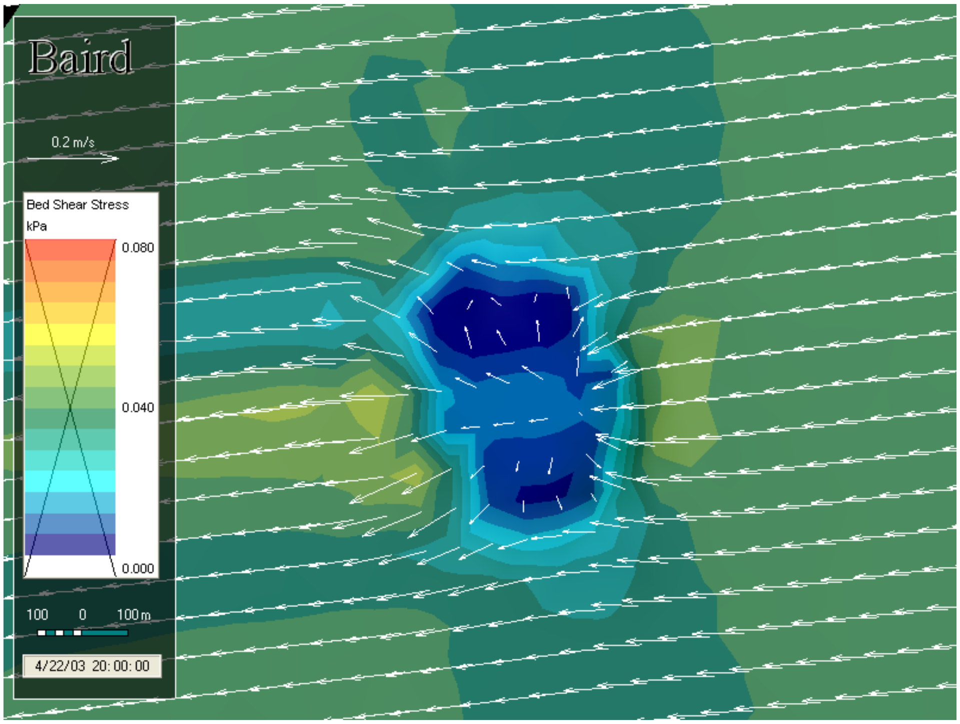

Figure 3.47b First Close-up of the Near Bed Flow Vectors Overlaid on the Bed Shears Stress Map for the Lower Flow Condition

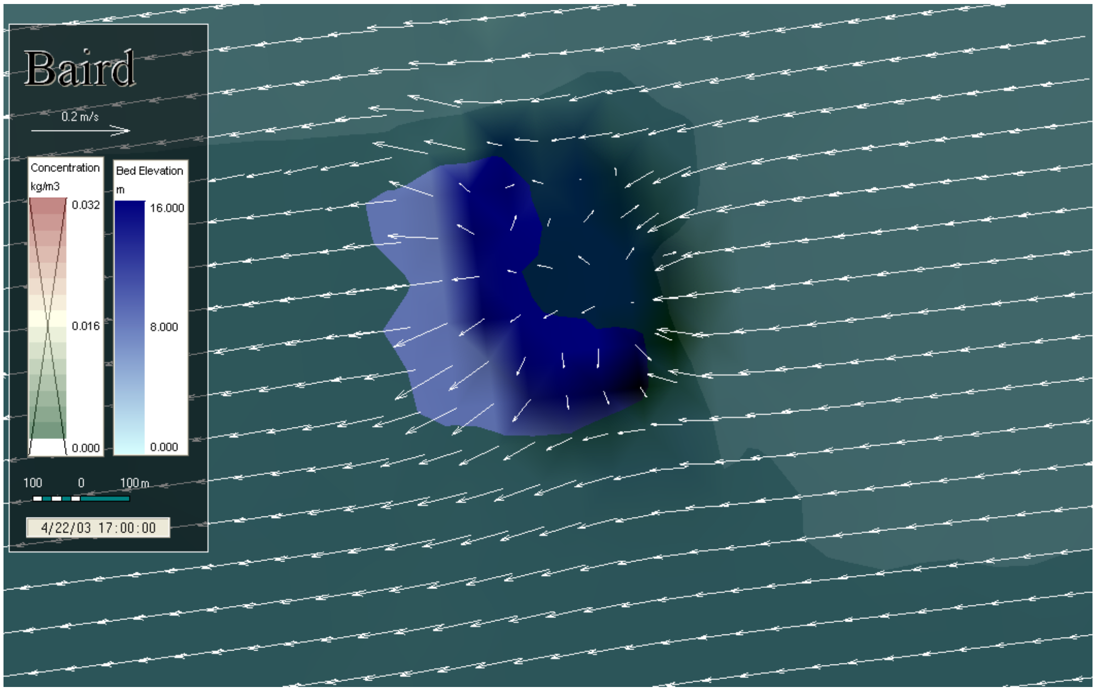

Figure 3.47c First Close-up of the Near Bed Flow Vectors Overlaid on the Suspended Sediment Concentration Map and Bed Elevation for the Lower Flow Condition

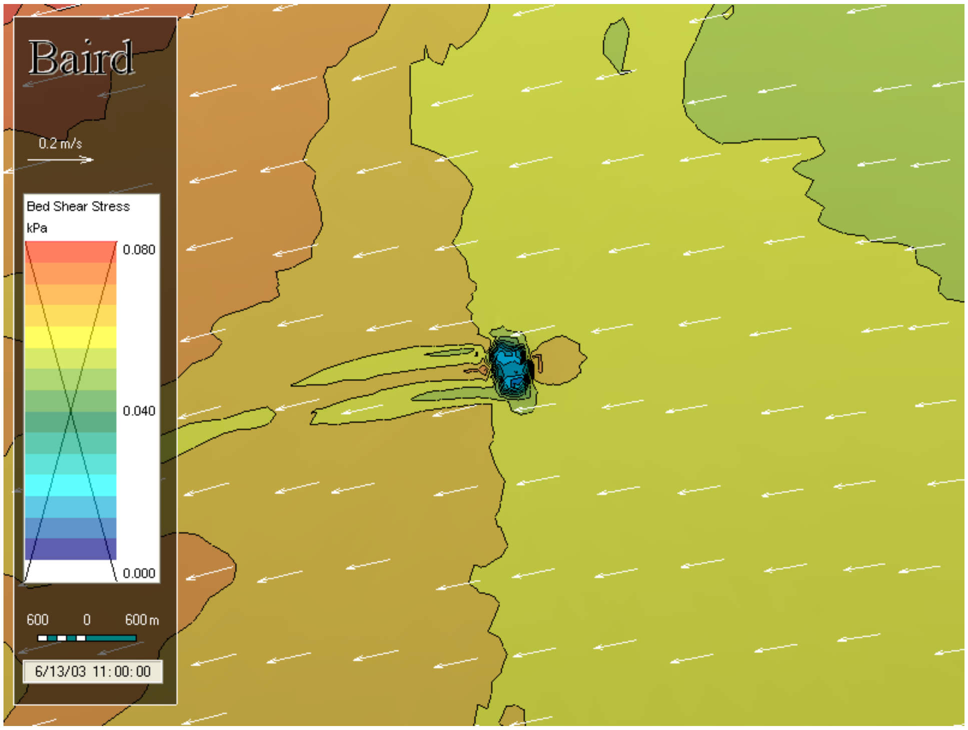

Figure 3.48a Near Bed Flow Vectors Overlaid on the Bed Shears Stress Map for the Full Model Domain and the Higher Flow Condition

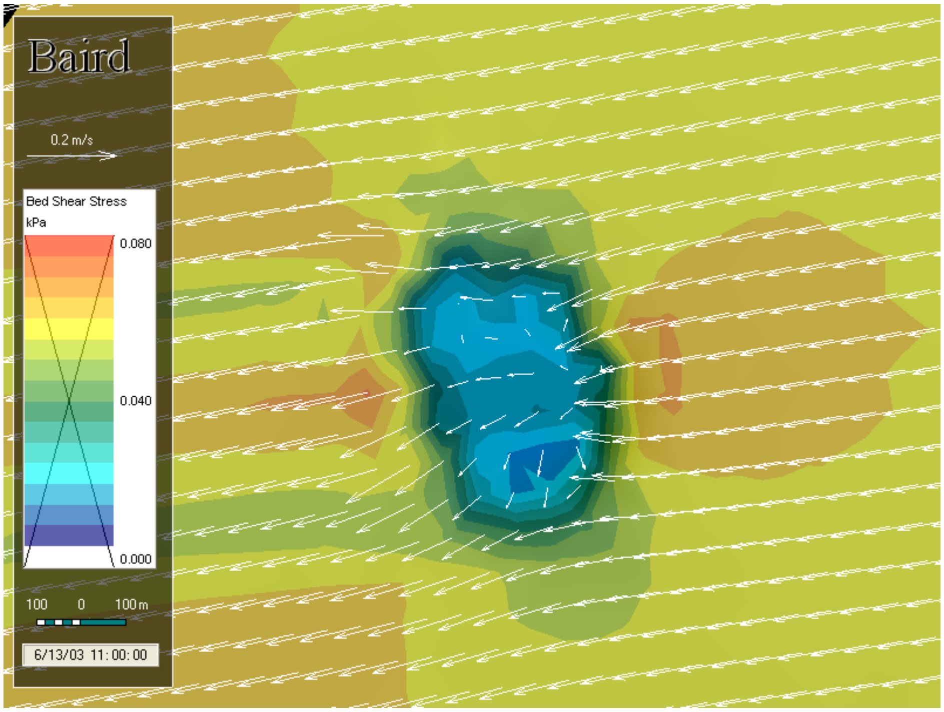

Figure 3.48b First Close-up of the Near Bed Flow Vectors Overlaid on the Bed Shears Stress Map for the Higher Flow Condition

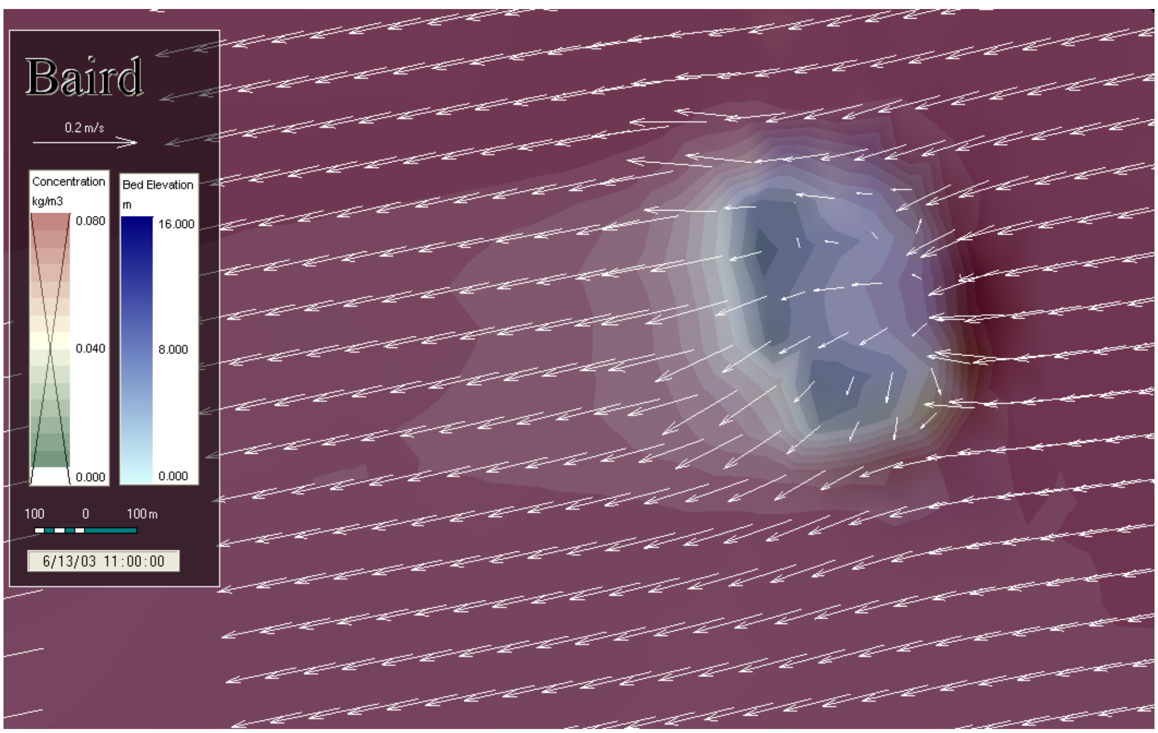

Figure 3.48c First Close-up of the Near Bed Flow Vectors Overlaid on the Suspended Sediment Concentration Map for the Higher Flow Condition

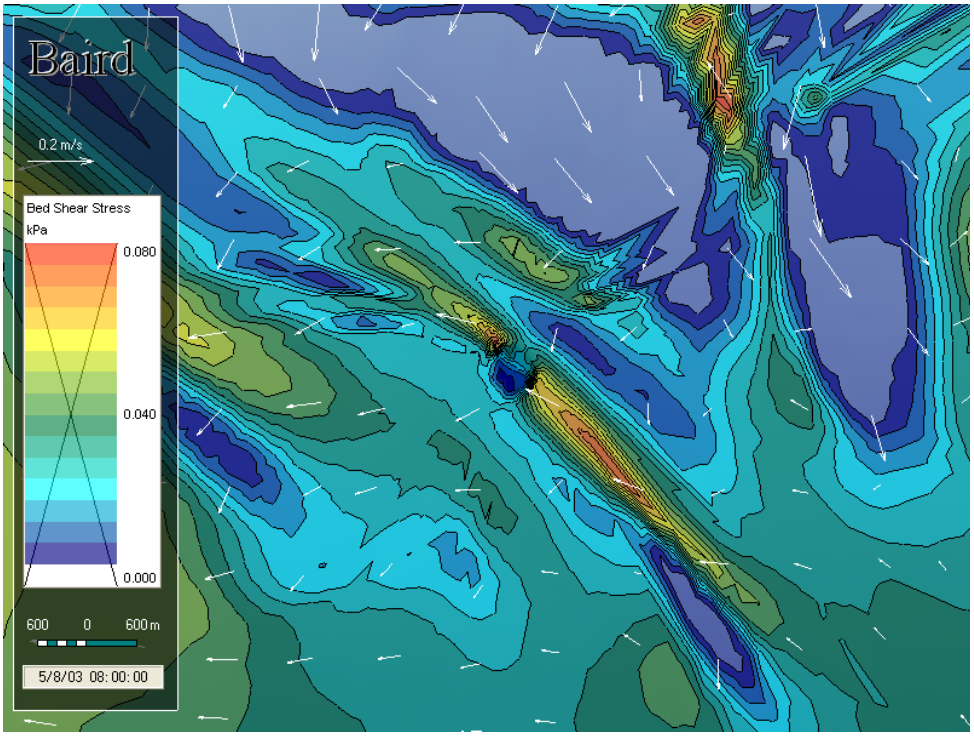

Figure 3.49a Near Bed Flow Vectors Overlaid on the Bed Shears Stress Map for the Full Model Domain and Complicated Combined Condition

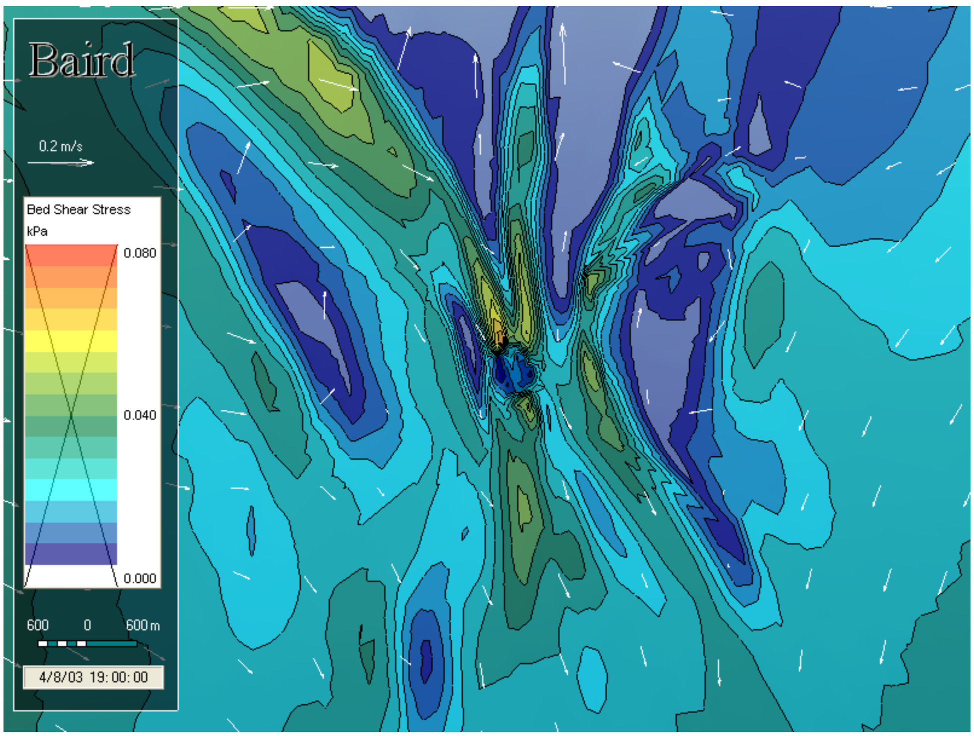

Figure 3.49b Near Bed Flow Vectors Overlaid on the Bed Shears Stress Map for the Full Model Domain and Complicated Combined Condition

3.2.1.2 A Simple Technique for Estimating the Rate of Pit Infilling

Section 3.1.2 of Nairn *et al.* (2005) presented a simple technique for estimating pit infilling based on a spreadsheet solution of the equations for pit sedimentation. This section extends the previous work to provide an even simpler approach for estimating pit infilling rate.

3.2.1.2.1 Infilling Rate Formulation

The equation for the pit infilling is derived on the basis of the empirical equations developed by Jiaju Liu (Liu and Zhang, 1992) for sedimentation of dredged channels with fine sediment in the previous report (Nairn *et al.*, 2005)

$$\Delta Z_b = k_1 C_0 \omega_s T \frac{1}{\rho_{dry}} \left[1 - \left(\frac{h_0}{h_1} \right)^3 \right] \qquad (3.5)$$

where ΔZ_b is total siltation thickness per tide (m);

C_0 is background concentration outside the dredged channel, which is generally determined by using the tide-mean and depth-averaged sediment concentration for the surrounding area (kg/m^3 or mg/l);

k_1 is empirical coefficients (k_1=0.35);

ω_s is settling velocity of mud, which may include the acceleration effects of cohesive sediment flocculation (m/s);

T is tidal period (s);

h_0 is water depth above the natural bed outside the channel or pit (m);

h_1 is water depth of the dredge pit (m);

ρ_{dry} is dry bulk density (kg/m^3); and,

Obviously, the infilling rate is a function of the water depth in the pit; the shallower the pit, the lower the sedimentation and the infilling rate. By using y as water depth in the pit rewritten as $y = z_0 - z_b$ in which z_0 is mean sea level, the above equation can be rewritten in the form of the following differential equation:

$$\frac{dy}{dt} + \frac{k_1 C_0 \omega_s}{\rho_{dry}} \left[1 - \left(\frac{h_0}{y} \right)^3 \right] = 0 \qquad (3.6)$$

where t is the time after the dredging. The water depth changed with time can be obtained by solving the above equation, which is described below.

3.2.1.2.2 Analytical Solution

The analytical solution for above equation is

$$y = h_1 - \frac{k_1 C_0 \omega_s}{\rho_{dry}} t + \frac{h_0}{6} \log\left[\frac{y^2 + h_0 y + h_0^2}{h_1^2 + h_0 h_1 + h_0^2} \cdot \left(\frac{h_1 - h_0}{y - h_0} \right)^2 \right] + \frac{h_0}{\sqrt{3}} \arctan\left[\frac{\sqrt{3} h_0 (y - h_1)}{2 y h_1 + 2 h_0^2 + h_0 (y + h_1)} \right] \tag{3.7}$$

Unfortunately, the above equation is implicit and must be solved by using an iterative method. In order to calculate the time of pit infilling in terms of percent full, the above equation can be rewritten in the following explicit form:

$$t = \frac{\rho_{dry}(h_1 - h_0)}{k_1 C_0 \omega_s} \left\{ 1 - r + \frac{r_0}{6} \log\left[\frac{1 + 3(1 + r_0/r) r_0/r}{1 + 3 r_0 r_1} \right] + \frac{r_0}{\sqrt{3}} \arctan\left[\frac{\sqrt{3} r_0 (r - 1)}{3 r_0 r_1 + 3 r_0^2 + 2 r r_1 + r r_0} \right] \right\} \tag{3.8}$$

where t is the time from pit excavation in seconds; r is the infilling rate of depth $= \frac{y - h_0}{h_1 - h_0}$, ranging from 0 (completely full) to 1 (just excavated), $r_0 = \frac{h_0}{h_1 - h_0}$ and $r_1 = \frac{h_1}{h_1 - h_0}$.

Figure 3.51 shows the results of percent full versus time for the Holly Beach Dredge Pit.

3.2.1.2.3 Parameter Determination

The key parameters for the infilling rate calculation are the determination of the background suspended sediment concentration using average significant wave height and average tidal current. Nairn *et al*. (2005) describe how these parameters were estimated for both the Holly Beach Dredge Pit and for the proposed Sandy Point Dredge Pit.

For the Holly Beach Dredge Pit, the following parameters were used: average significant wave height of 1 ft (0.3 m), average tidal current flow speed of 0.3 m/s and an annual average background concentration of 70 to 80 mg/l. The background concentration was determined as follows using the approach of Liu and Zhang (1992):

$$C_0 = 0.0273 * \rho_s \frac{(U_c + U_w)^2}{gh} \tag{3.9}$$

where ρ_s is sediment density (=2650 kg/m3), U_c is the average current speed, U_w is the orbital velocity calculated using the average wave height; h is water depth, and g is gravitational acceleration (=9.8 m/s^2).

Average settling velocity is also required for the calculation. The flocculation of cohesive sediment is the main factor determining settling velocity, and this process depends on salinity and concentration. The settling velocity increases as salinity increases up to 15 ppt and as concentration increases up to 1,000 mg/l. On the basis of physical measurements and laboratory tests (see Van Rijn, 1998), the mean settling velocity is in the range of 0.0005 m/s to 0.003 m/s, depending on cohesiveness of sediment, salinity, and concentration. A settling velocity of 0.0015 m/s was used in this calculation based on our experience.

The dry density of deposited mud is very dependent on the degree of consolidation that increases with time after deposition. There are three stages of consolidation: initial (days), intermediate (weeks), and final (years). Dry density of highly consolidated sediment (about 1 year old) ranges from 400 to 550 kg/m^3 (corresponding to wet density in the range of 1,250 to 1,350 kg/m^3). A mean depth-averaged dry density of 450 kg/m^3 was used for this calculation (this considers that sediment has been accumulating at the base of the pit for 48 months since initial dredging). The variation of dry density within a reasonable range of values does not have a significant impact on the predicted infilling rate. The parameters used in the calculation are listed in Table 3.2. Note that the background concentration was slightly smaller than that in previous theoretical analysis but all other parameters are the same.

Table 3.2 Parameters Required for the Analytical Estimate of Pit Infilling Rate

Parameters	Values
K_1	0.35
Background concentration (C_0)	0.075 kg/m^3
Settling velocity (ω_s)	0.0015 m/s
Dry density (ρ_{dry})	450 kg/m^3
Undredged water depth (h_0)	8.8 m
Initially dredged water depth (h_1)	18.5m

Figure 3.50 shows that the results of the water depth change in the pit using Equation 3.7 agree well with the measurements. Figure 3.51 shows the percentage of pit infilling with time. It is estimated that 95 % of the pit will be filled by the end of 2008.

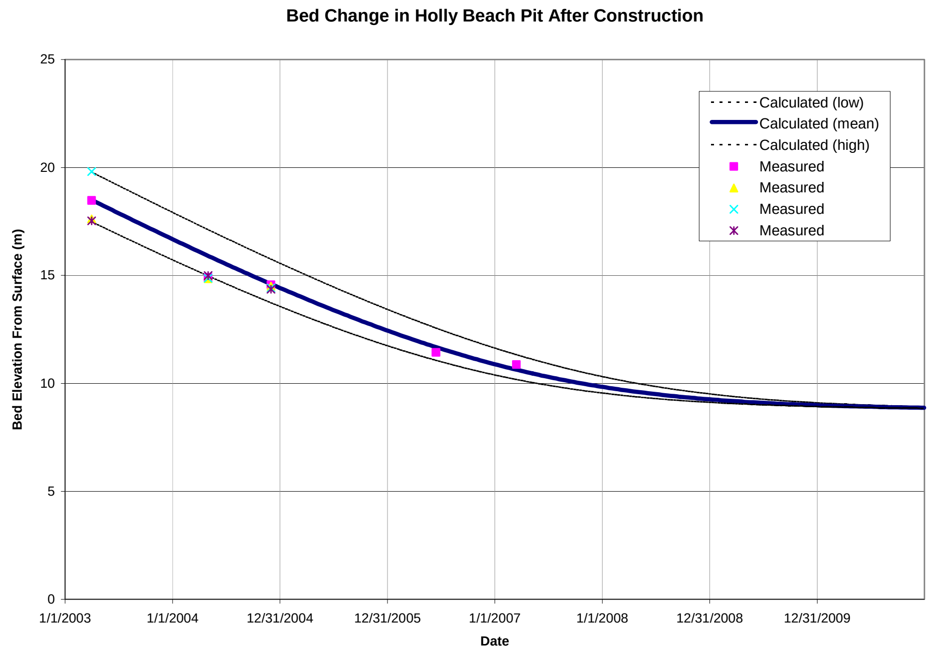

Figure 3.50 The Estimated Water Depth in the Pit Using the Analytical Solution (Equation 3.7)

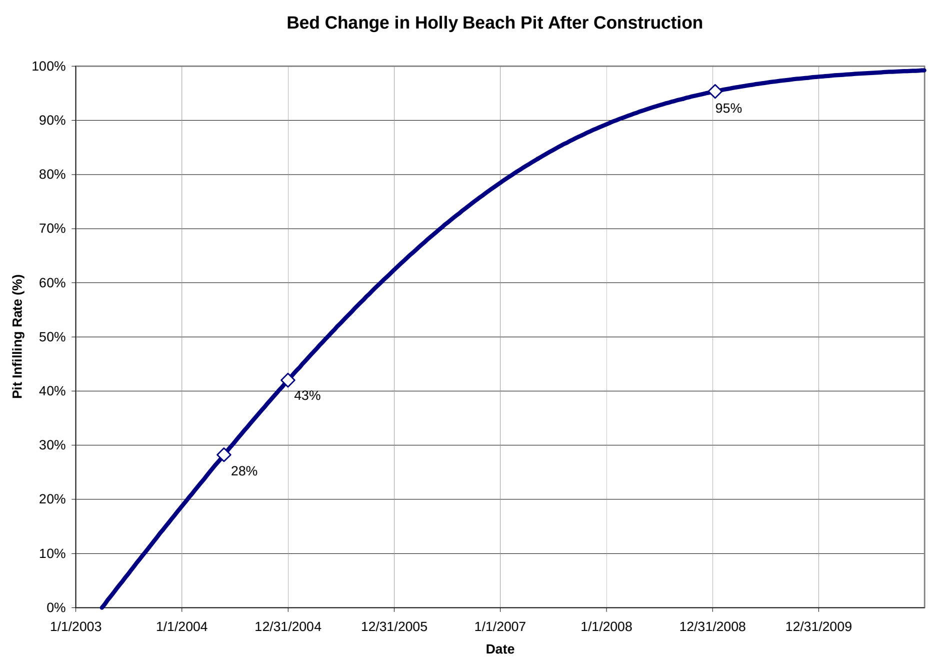

Figure 3.51 Predicted Infilling of the Pit in Terms of Percent Full Using the Analytical Solution (Equation 3.8)

3.2.2 Impact of Dredge Pits on Wave Transformation

Simulation of morphodynamics and evolution of dredge pits under wave and current action requires accurate modeling of the near field waves around the feature under consideration. In this study an inter-comparison of several numerical wave models was conducted to evaluate their performance and possibly recommend the most suitable model(s).

The key objectives of this investigation were to:

1. Evaluate the relative importance of different wave transformation processes (refraction, diffraction and reflection) for impacts associated with dredge pits using the Boussineq model as the base for comparison (given it is most likely to reproduce actual conditions); and

2. Evaluate the performance of various models being applied by MMS contractors in terms of simulating the key processes associated with impacts of dredge pits.

Four spectral wave transformation models were considered for this purpose. These are STWAVE, WABED, SWAN and *HYDROSED*; a brief description of each model is given in the following sections. Important wave-related processes over a dredge pit are wave refraction, shoaling, diffraction and reflection off the steep pit slopes. Borrow pits are normally well outside of the nearshore zone in depths where wave breaking is not an issue. The performance of the above spectral wave models was therefore evaluated against results obtained from solving the Boussinesq wave (BW) equations and the BW module of the MIKE21 package was used for this purpose. The Boussinesq model is currently the most state of the art wave transformation model, and includes several processes of interest in the present problem such as refraction, shoaling, diffraction and reflection off the steep pit slopes. However, direct application of BW model to long-term morphology change simulations requires intensive computational time and is not practical at present. Spectral wave transformation models, on the other hand, do not involve intensive calculations and are more suitable for practical applications.

The dredge pit considered for the present comparison is called “Holly Pit” and is located 4 miles (7 km) off the Louisiana coast in about 30 ft (9 m) of water. The pit has been dredged to –60 ft (18 m) and has a dimension of about 0.3 mile (0.5 km) (E-W) by 0.4 miles (0.7 km) (N-S). Using the available bathymetry data, a 619×718 mesh (1.9 miles (3.1 km) cross-shore × 202 miles (3.6 km) alongshore) was generated with grid size of 16 ft (5 m) for calculations. The depth at the offshore boundary of the calculation domain was approximately 28 ft (8.8 m). The offshore boundary had a 492 ft (150 m) wide zone with constant depth of 28 ft (8.8 m) as a requirement by the BW model. Figure 3.52 shows an oblique view of the calculation domain.

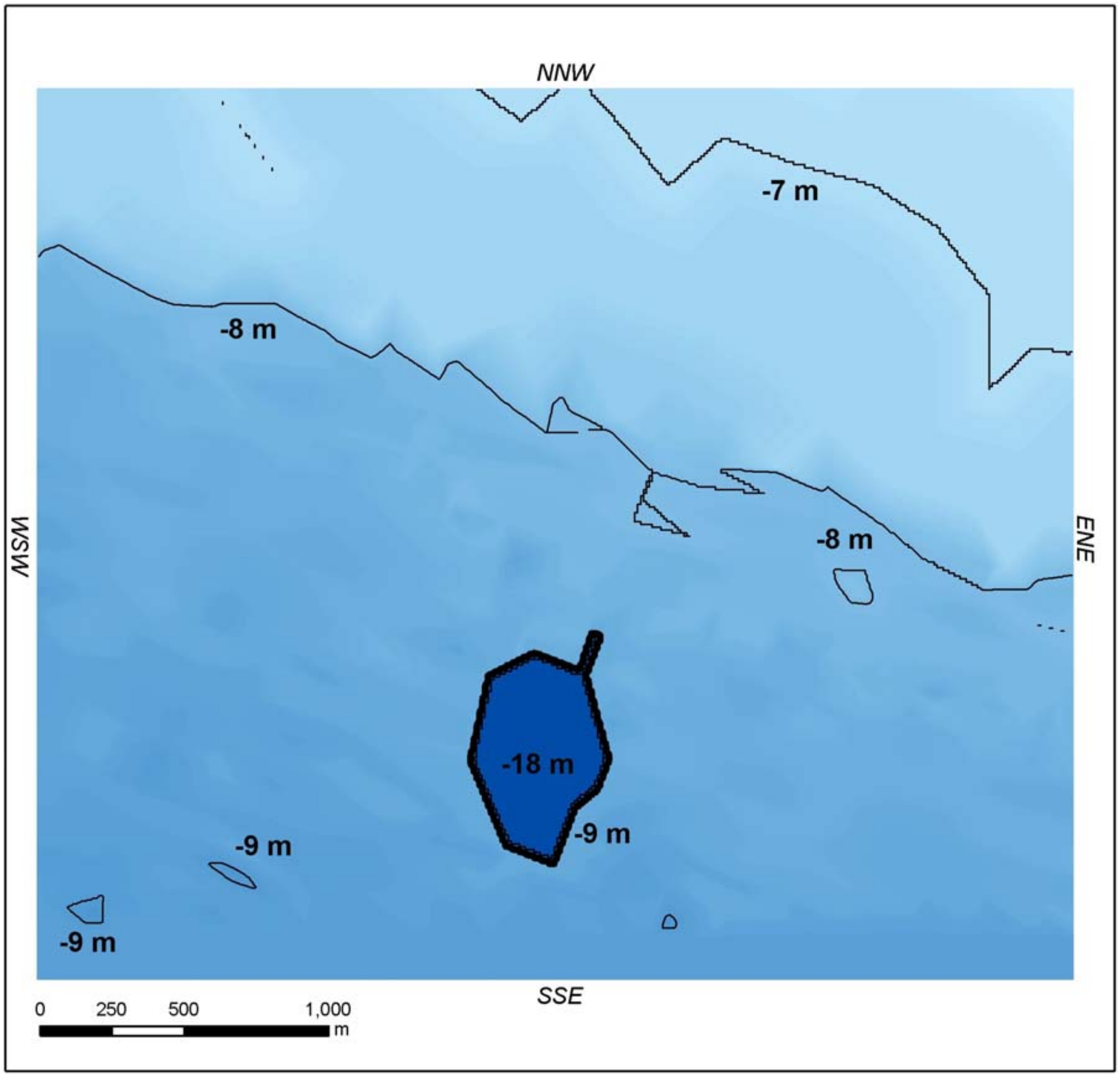

Figure 3.52 Oblique View of the Calculation Domain

The prepared grid is in SSE-NNW direction, which is the direction of predominant waves in the area. Input waves will therefore arrive normal to the grid. Upon their arrival at the pit, waves would go under considerable refraction (because of the sudden increase in depth) and be diverted towards the two sides of the pit. Because of the non-symmetric shape of the pit, more refraction is expected towards the right (east) edge of the pit. This would result in a reduction of wave height over the dredged area. On the other hand, the refracted waves will shoal over the side edges of the pit and then interact with incoming waves outside of the pit. This will create areas of increased wave height on both sides of the pit. The wave height distribution will then be somewhat modified through diffraction processes which is the transfer of wave energy from higher wave energy zones to lower energy areas. Some reflection may also occur along the pit boundaries. The effect of dredge pit on the wave field would extend to a certain distance inshore of the pit (in the wave propagation direction). The wave field is expected to gradually recover moving away from the pit towards the shore.

3.2.2.1 Boussinesq Wave Model

The MIKE21 Boussinesq Wave (BW) model is a phase-resolving wave model capable of reproducing the combined effects of most wave phenomena of interest in coastal and harbour engineering. Capabilities of the BW model include:

- Wave propagation, shoaling, refraction and diffraction;
- Wave breaking and dissipation;
- Partial or complete reflection;
- Wave-current interaction;
- Propagation over complex bathymetries;
- Wave nonlinearity;
- Diffraction.

MIKE 21 BW includes porosity for the simulation of partial reflection from and transmission through for instance pier structures and breakwaters. Sponge layers are applied when full absorption of wave energy is required for example behind wave generation lines, along open sea boundaries or where very mild sloping highly absorbing shoreline features exist. Wave conditions are defined internally by applying a discharge or flux along the length of the generation line; therefore, in order to maintain a consistent wave signal the depth at the offshore boundary should be constant along the generation line.

The following two wave conditions were simulated using the MIKE21 Boussinesq model:

1. Wave Direction: SSE, H_{mo}= 1 m, Tp = 12s

2. Wave Direction: SSE, H_{mo}= 1 m, Tp = 9s

The offshore wave spectra extracted from the results of these two wave conditions were then used to define the input wave condition for the STWAVE, SWAN, WABED and *HYDROSED* models. Figures 3.53 and 3.54 show the directional and frequency spectrum for both wave conditions.

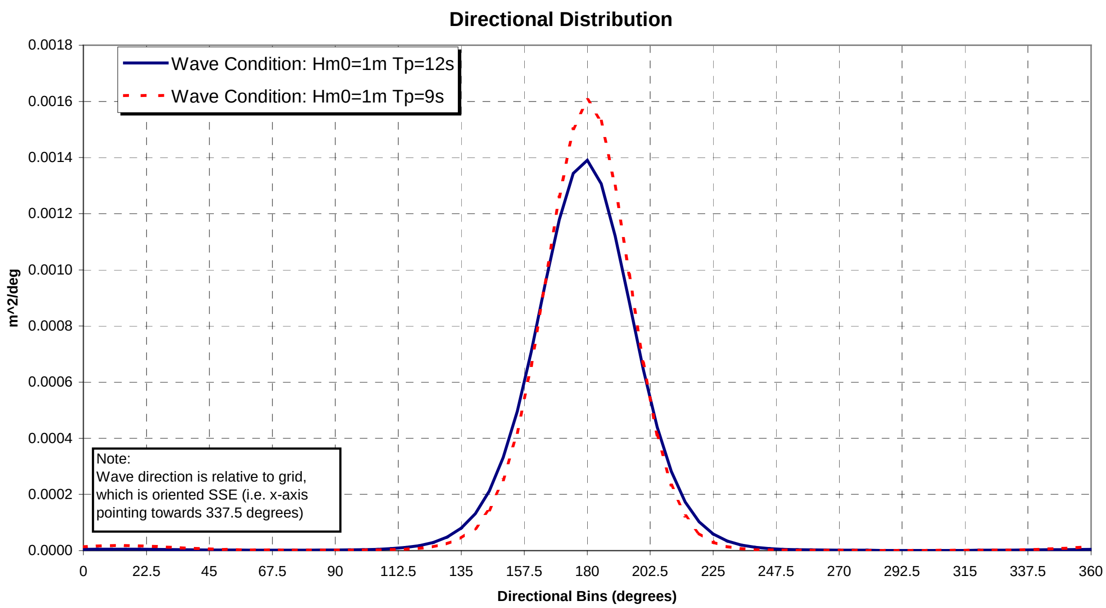

Figure 3.53 Directional Spectra for 9s and 12s Wave Conditions

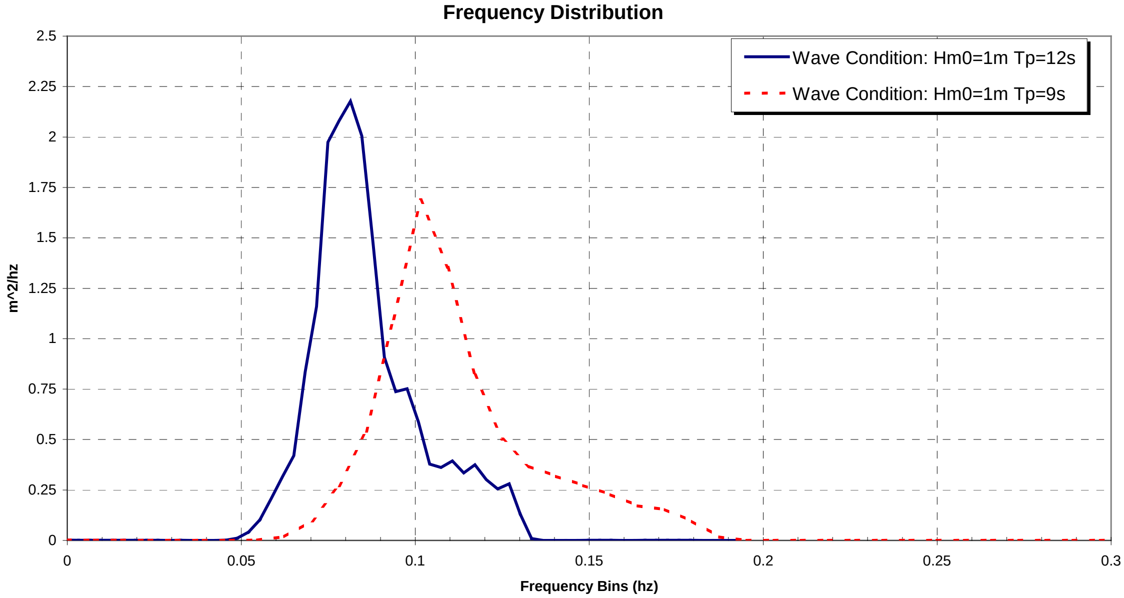

Figure 3.54 Frequency Spectra for 9s and 12s Wave Conditions

The minimum wave periods defined for the 9-second and 12-second wave conditions were 5.25 s and 7.5 s, respectively. In order to simulate a wave period of 5.25 s, deepwater terms were included for the 9 s wave condition. Note that the minimum wave period that can be resolved in a simulation is governed by two criteria: 1) the maximum water depth, and 2) whether the classical form (deepwater terms excluded) or the enhanced form (deepwater terms included) of the Boussinesq equations is solved. For this study, the maximum water depth was 60 ft (18 m); therefore the minimum wave period was determined to be approximately 7.24 s if deepwater terms are excluded and 4.4 s if deepwater terms are included.

The numerical model was setup to simulate the propagation of waves across the model domain for a period of 60 minutes. A 0.3 s time step was used and 20 layers of sponge were applied around the outer edge of the computational domain to absorb wave energy. Wave disturbance coefficients were calculated based on an average of the final 55 minutes of the model run and are presented in Figure 3.55 and 3.56.

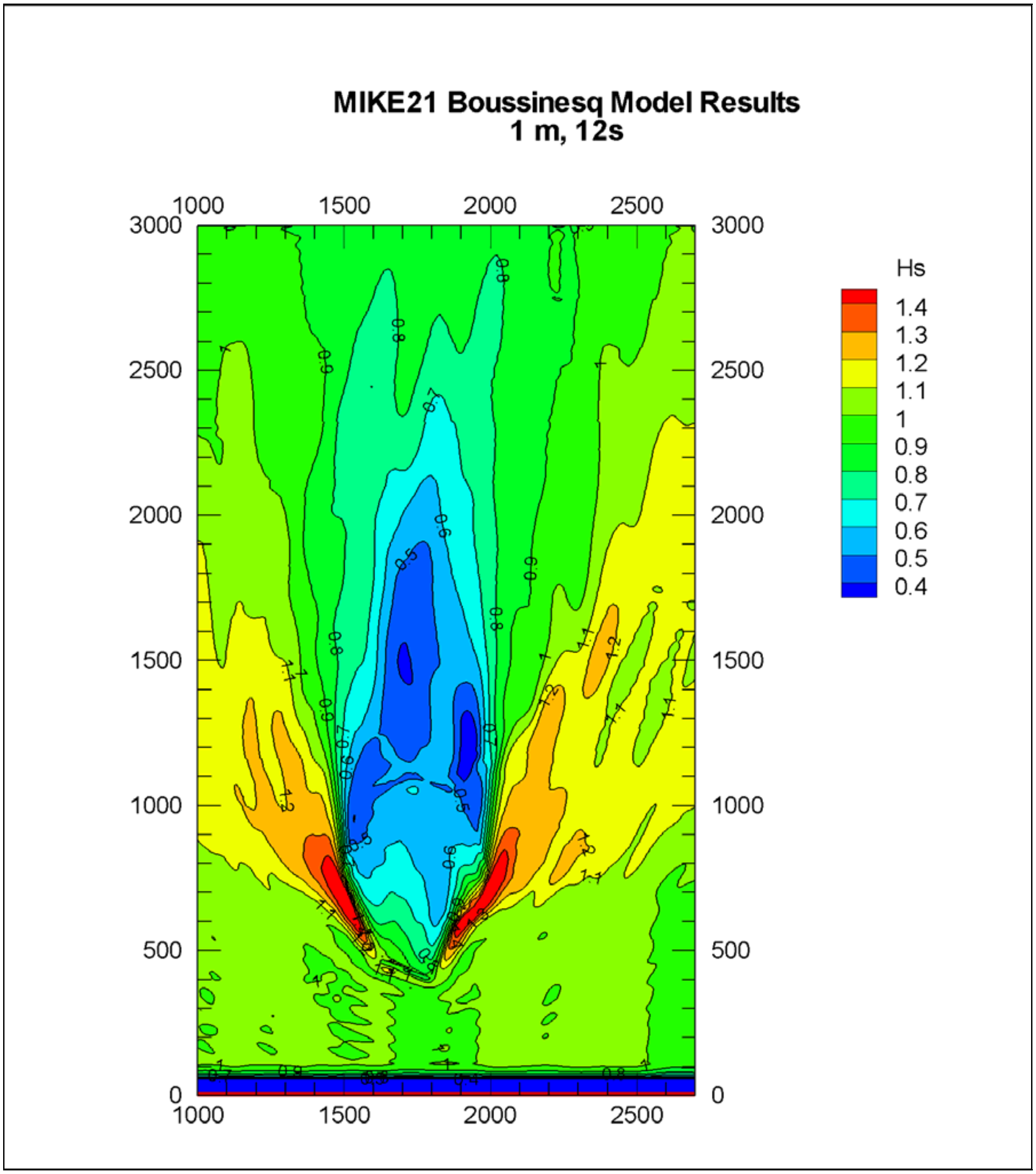

Figure 3.55 2D Map of Significant Wave Height from M21BW Results (Wave Condition: SSE, Hm0=1m, Tp=12s) and (coordinates are in meters)

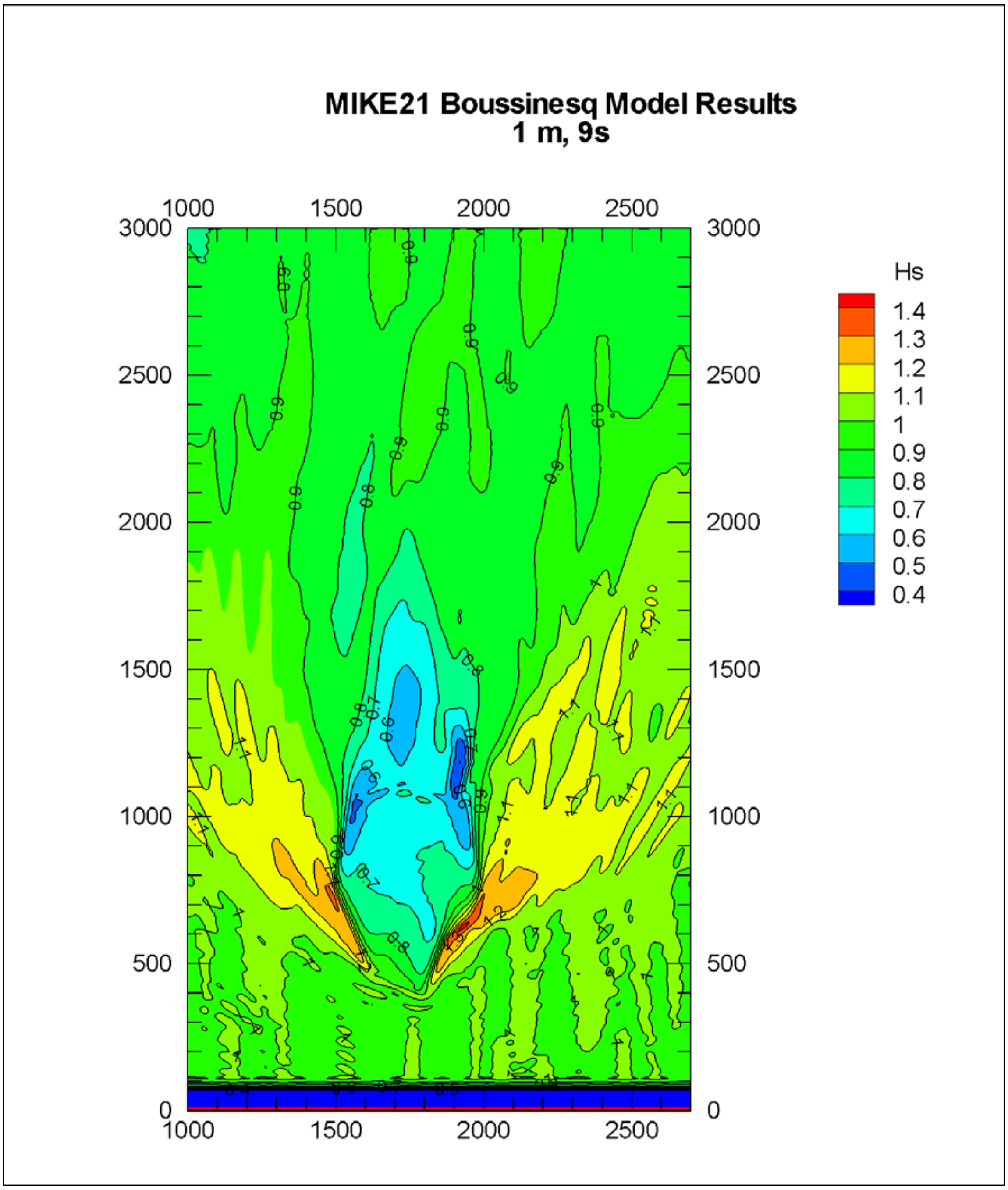

Figure 3.56 2D Map of Significant Wave Height from M21BW Results (Wave Condition: SSE, Hm0=1m, Tp=9s) and (coordinates are in meters)

In general, the trends observed in Figures 3.55 and 3.56 were very similar for both wave conditions. The results from the simulations showed a reduction in wave height in the dredge pit and for a distance shore side of the pit. Increased wave heights were observed along the side edges of the pit due to a combination of processes such as refraction, reflection, diffraction and localized shoaling. The wave heights around the edge of the pit were noticeably higher for the 12 s wave condition as longer period waves would respond to the bathymetric features along the ocean floor more than shorter period waves. It is noted that this wave focusing may also have contributed to pit margin erosion.

3.2.2.2 STWAVE Model

STWAVE model is developed by the US Army Corps of Engineers (Smith *et al.*, 2001). It is a phase-averaged, steady state, half plane, two-dimensional, spectral wave model based on the wave action balance equation. STWAVE is capable of incorporating the following physical processes:

- Wave propagation in time and space, shoaling and refraction;
- Wave generation by wind;
- Triad and quadruplet wave-wave interactions;
- White-capping, bottom friction and depth-induced breaking;
- Propagation at a wide range of possible scales.

For this application for the Holly Beach Dredge Pit, the model was used in Cartesian mode with the identical grid employed for the other wave models. Stationary model simulations were conducted. The input spectra as derived from the MIKE21 Boussinesq model, was applied at the offshore boundary. Most of the model features were used in default mode, including three- and four- way wave interactions and white-capping. Input settings included:

- 10° angular resolution;
- For the 1m – 12 s run total 29 frequencies are used, which are from 0.045573 to 0.136719 Hz with an increment of 0.003255;
- For the 1m – 9 s run total 18 frequencies are used, which are from 0.0625 to 0.1953125 Hz with an increment of 0.007813;
- Simulations are carried out with zero wind conditions;
- Bottom friction was not utilized.

No tuning or adjustment of the model was carried out.

Figures 3.57 and 3.58 provide colour contour plots of significant wave height for the simulations conducted with 12 s and 9 s peak wave period, respectively. STWAVE provided solutions that were similar in structure to the other phase-averaged models such as WABED and *HYDROSED*.

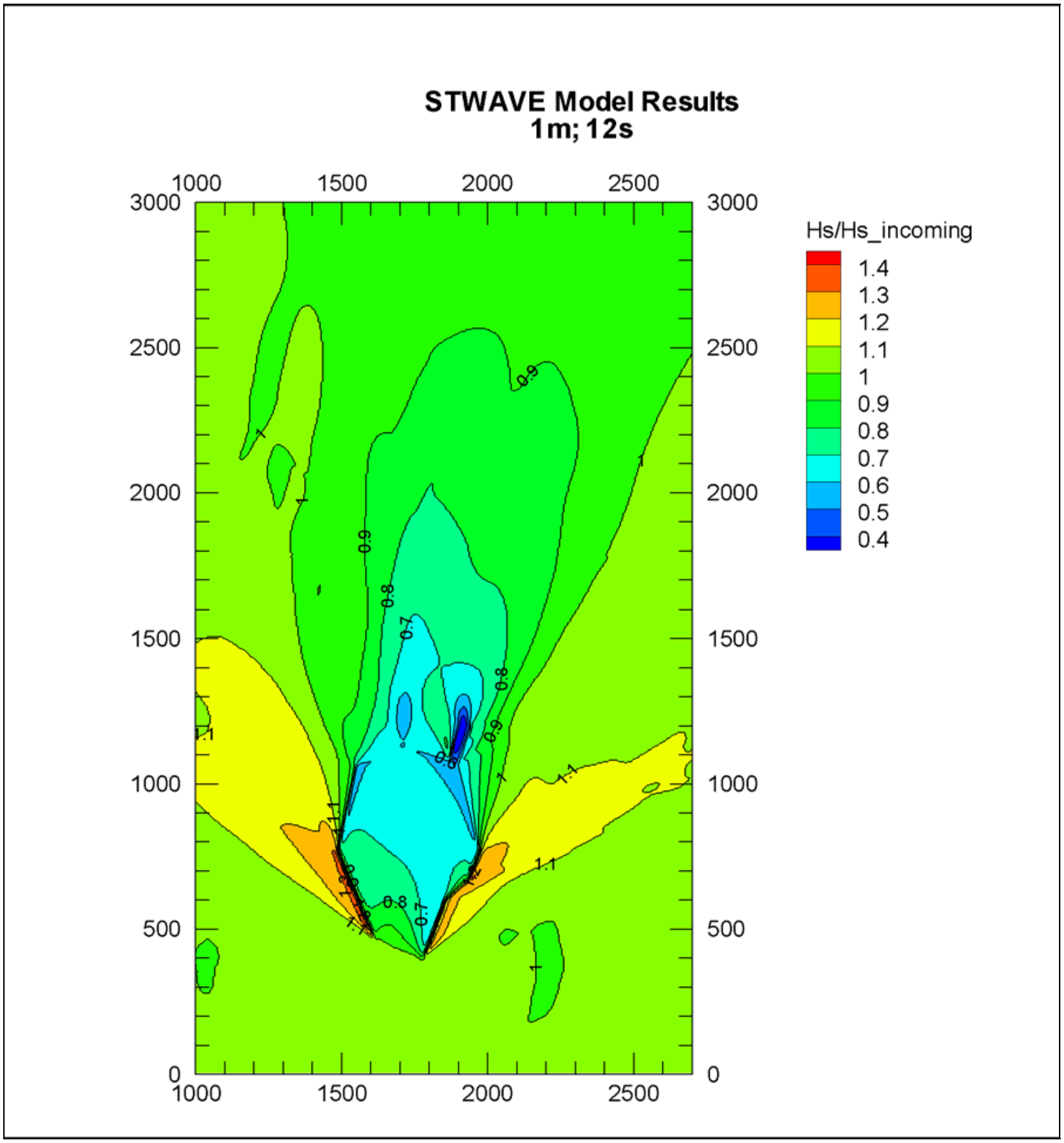

Figure 3.57 Colour Contour Plots of Significant Wave Height for Tp=12s by STWAVE
(coordinates are in meters)

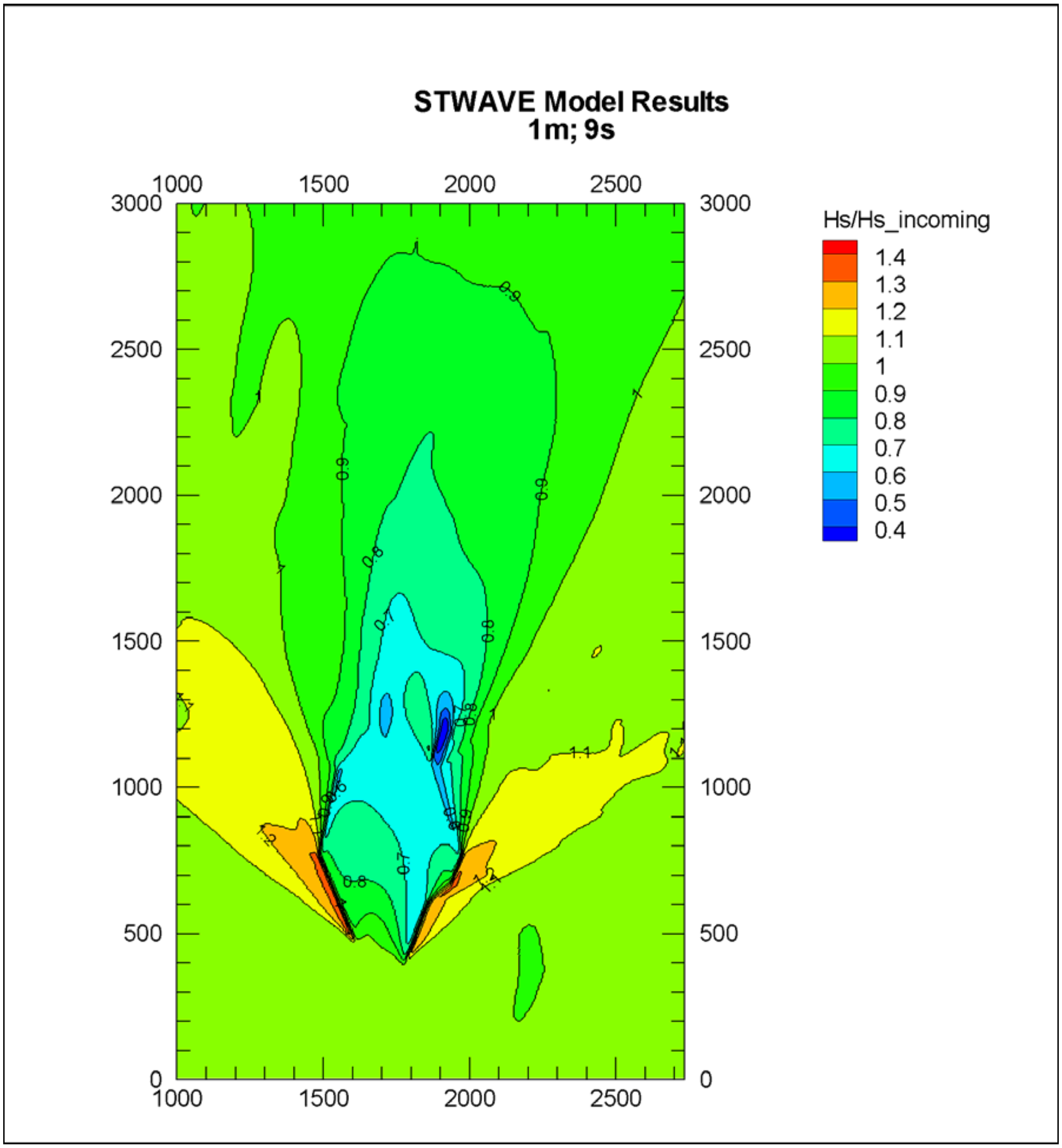

Figure 3.58 Colour Contour Plots of Significant Wave Height for Tp=9s by STWAVE
(coordinates are in meters)

3.2.2.3 SWAN Model

SWAN (**S**imulating **WA**ves **N**earshore) is a third-generation wave model capable of simulating the growth and transformation of waves in nearshore coastal regions. Developed at the Technical University of Delft, SWAN is capable of incorporating the following physical processes:

- Wave propagation in time and space, shoaling, refraction due to current and depth, frequency shifting due to currents and non-stationary depth;
- Wave generation by wind;
- Triad and quadruplet wave-wave interactions;
- White-capping, bottom friction and depth-induced breaking;
- Wave-induced set-up;
- Propagation at a wide range of possible scales;
- Transmission through and reflection (specular and diffuse) against obstacles;
- Diffraction (in a phase-decoupled approach).

SWAN may utilize an input bathymetric grid in either a Cartesian or spherical coordinate system, and stationary or non-stationary simulations may be carried out.

For this application for the Holly Beach Dredge Pit, the model was used in Cartesian mode with the identical grid employed in the other wave models. Stationary model simulations were conducted. The input spectra as derived from the MIKE21 Boussinesq model, was applied at both the offshore and lateral boundaries. Most of the model features were used in default mode, including three- and four- way wave interactions and white-capping. Input settings included:

- 10° angular resolution;
- Thirty-one frequency bins with a logarithmic progression starting at a minimum frequency of 0.0521 Hz;
- Bottom friction was not utilized;
- SORDUP propagation scheme.

Diffraction was not used in the model runs, as a stable solution could not be achieved with this feature turned on. No tuning or adjustment of the model was carried out.

Figures 3.59 and 3.60 provide colour contour plots of significant wave height for the simulations conducted with 12 s and 9 s peak wave period, respectively. SWAN provided solutions that were similar in structure to the other phase-averaged models, such as STWAVE and *HYDROSED*, but with some noted undulations in the wave height alongshore. This might be because SWAN uses a higher order propagation scheme, which is less diffusive than other models.

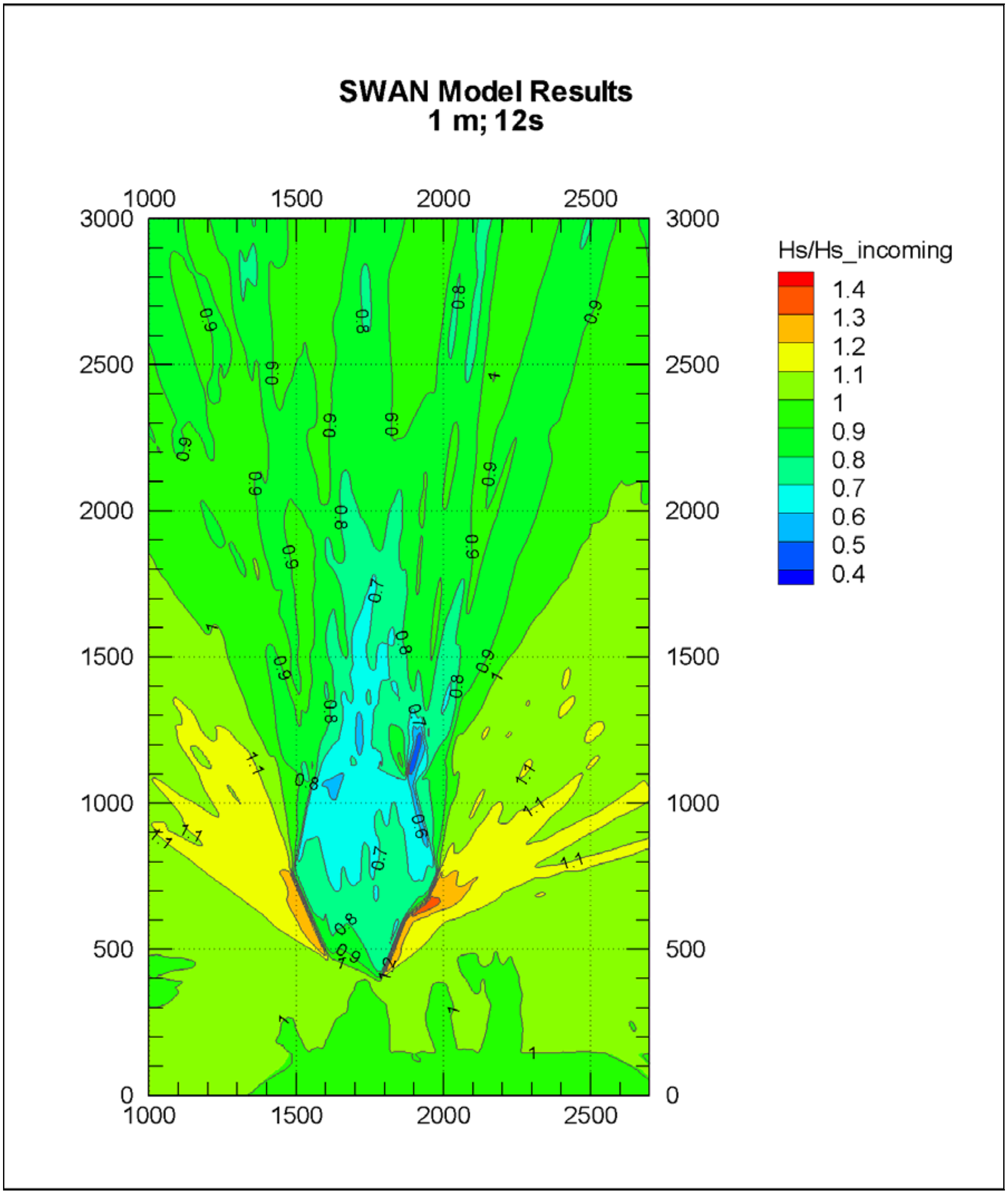

Figure 3.59 Colour Contour Plots of Significant Wave Height for Tp=12s by SWAN (coordinates are in meters)

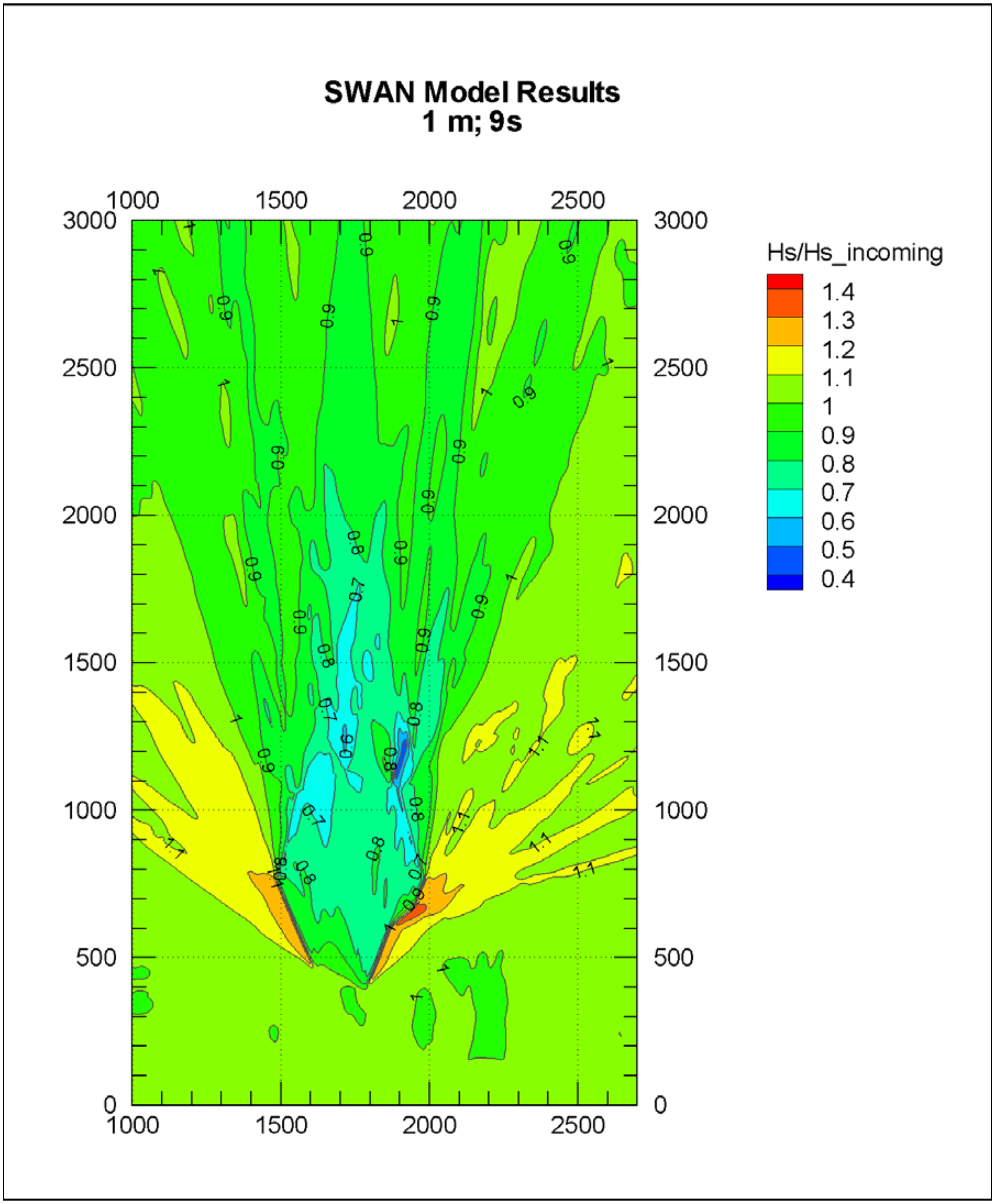

Figure 3.60 Colour Contour Plots of Significant Wave Height for Tp=9s by SWAN (coordinates are in meters)

3.2.2.4 WABED Model

WABED (**W**ave-**A**ction **B**alance **E**quation **D**iffraction) is a 2-D wave spectral transformation (phased-averaged) model and represents changes that occur only in the wave energy (action) density. Phase-averaged energy (action) balance models neglect wave phase and they cannot directly predict wave diffraction and reflection caused by bathymetric features and structures. However, these effects may be incorporated in such models in approximate ways. The WABED model contains theoretically developed approximations for both wave diffraction and reflection and, therefore, is expected to be suitable for conducting wave simulations in situations involving these processes. WABED employs a forward-marching, finite-difference method to solve the wave action conservation equation. Capabilities of the WABED model include:

- Wave propagation, shoaling and refraction;
- Depth-limited breaking and dissipation;
- Wave-current interaction;
- Propagation at a wide range of possible scales;
- Forward reflection;
- Diffraction.

Wave diffraction is implemented by adding a diffraction term derived from the parabolic wave equation to the energy-balance equation. The model operates on a coastal half-plane so primary waves can propagate only from the seaward boundary toward shore. If the seaward reflection option is activated, the model will also perform backward marching for seaward reflection after the forwarding-marching calculation is completed. For further details about WABED model, the reader is referred to Lin and Demirbilek (2005) and Demirbilek, *et al.* (2007).

Inclusion of diffraction is through diffraction coefficient "*akap*" (=0 for no diffraction, =3 for maximum diffraction). WABED input files are similar to those for the spectral model STWAVE. Input settings included:

- 10 ° angular resolution;
- For the 1m – 12s run total 29 frequencies are used, which are from 0.045573 to 0.136719 Hz with an increment of 0.003255;
- For the 1m – 9s run total 18 frequencies are used, which are from 0.0625 to 0.1953125 Hz with an increment of 0.007813;

- Bottom friction was not utilized;
- Simulations were conducted for diffraction coefficients of akap = 0, 1 and 3.

No tuning or adjustment of the model was carried out.

Figures 3.61 to 3.66 provide colour contour plots of significant wave height for the simulations conducted with 12 second and 9 second peak wave period, respectively, with diffraction parameter of *akap* = 0, 1 and 3. WABED provided solutions that were similar in structure to the other phase-averaged models, such as STWAVE and *HYDROSED*. Inclusion of diffraction resulted in smoothing of the wave field with more smoothing observed for *akap* = 3 results. This is expected as wave diffraction works to transfer wave energy from high energy zones to lower energy areas.

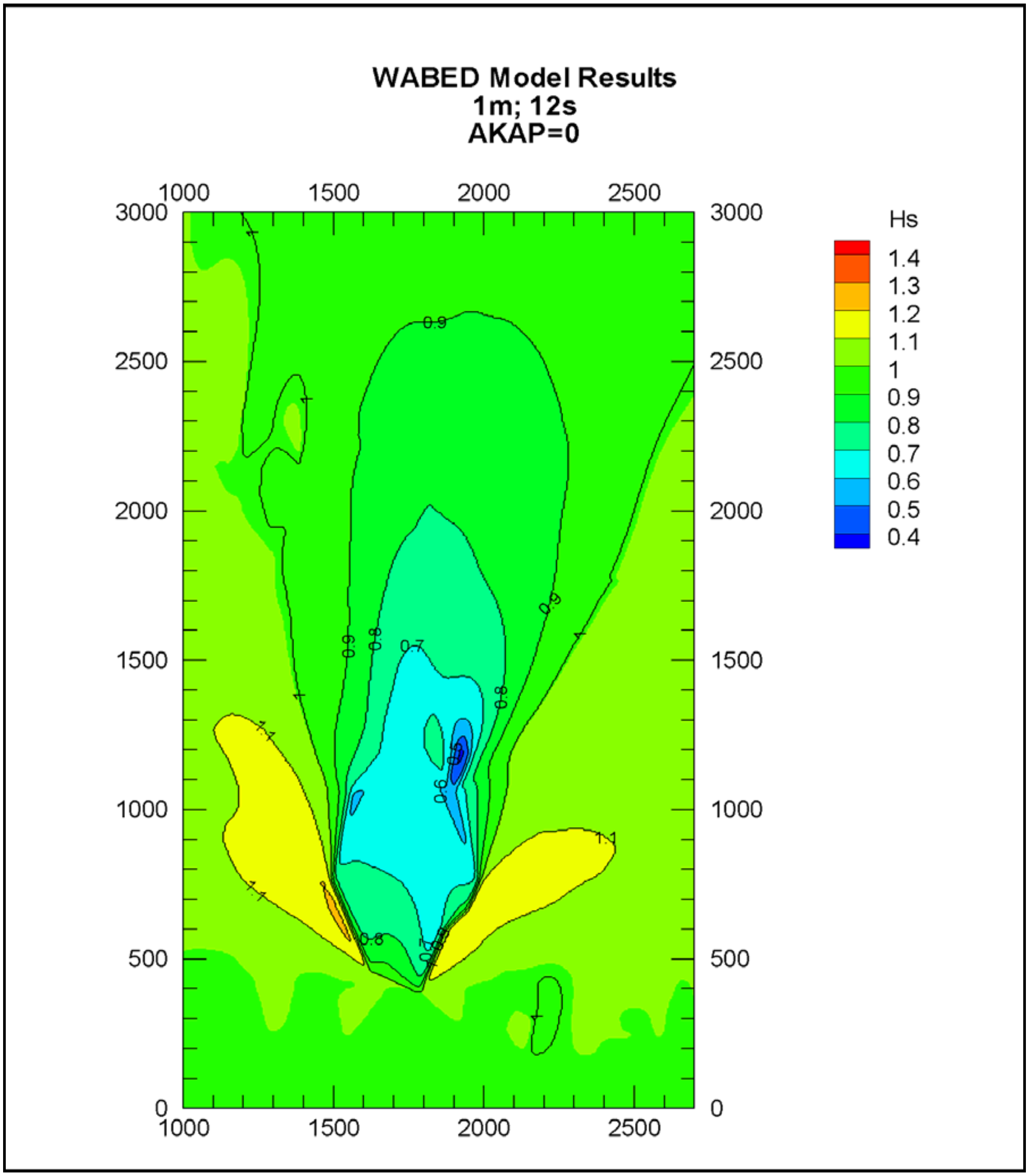

Figure 3.61 Colour Contour Plots of Significant Wave Height for T_p = 12s by WABED with Diffraction Coefficient of *akap* = 0 (coordinates are in meters)

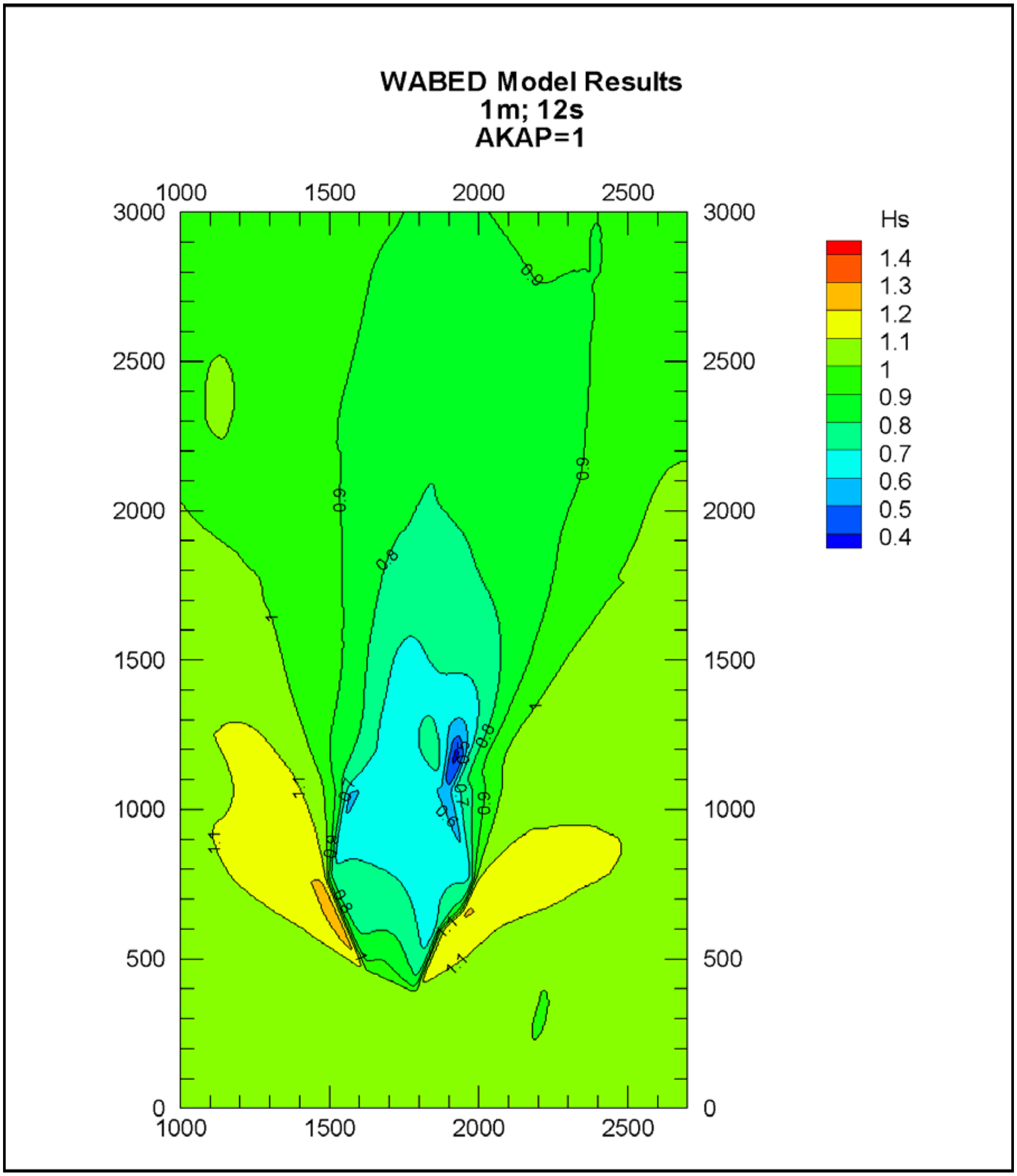

Figure 3.62 Colour Contour Plots of Significant Wave Height for T_p = 12s by WABED with Diffraction Coefficient of *akap* = 1 (coordinates are in meters)

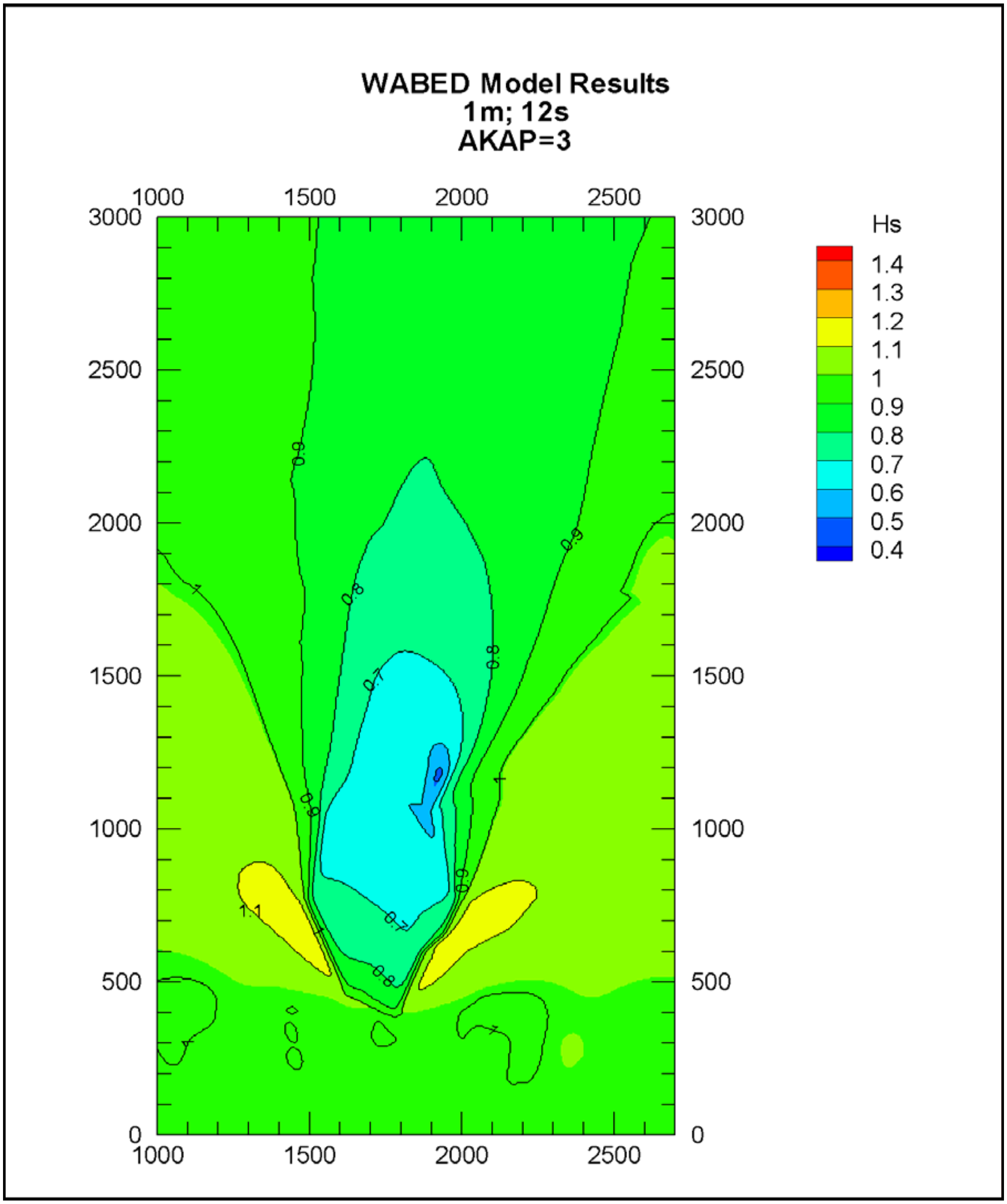

Figure 3.63 Colour Contour Plots of Significant Wave Height for T_p = 12 s by WABED with Diffraction Coefficient of *akap* = 3 (coordinates are in meters)

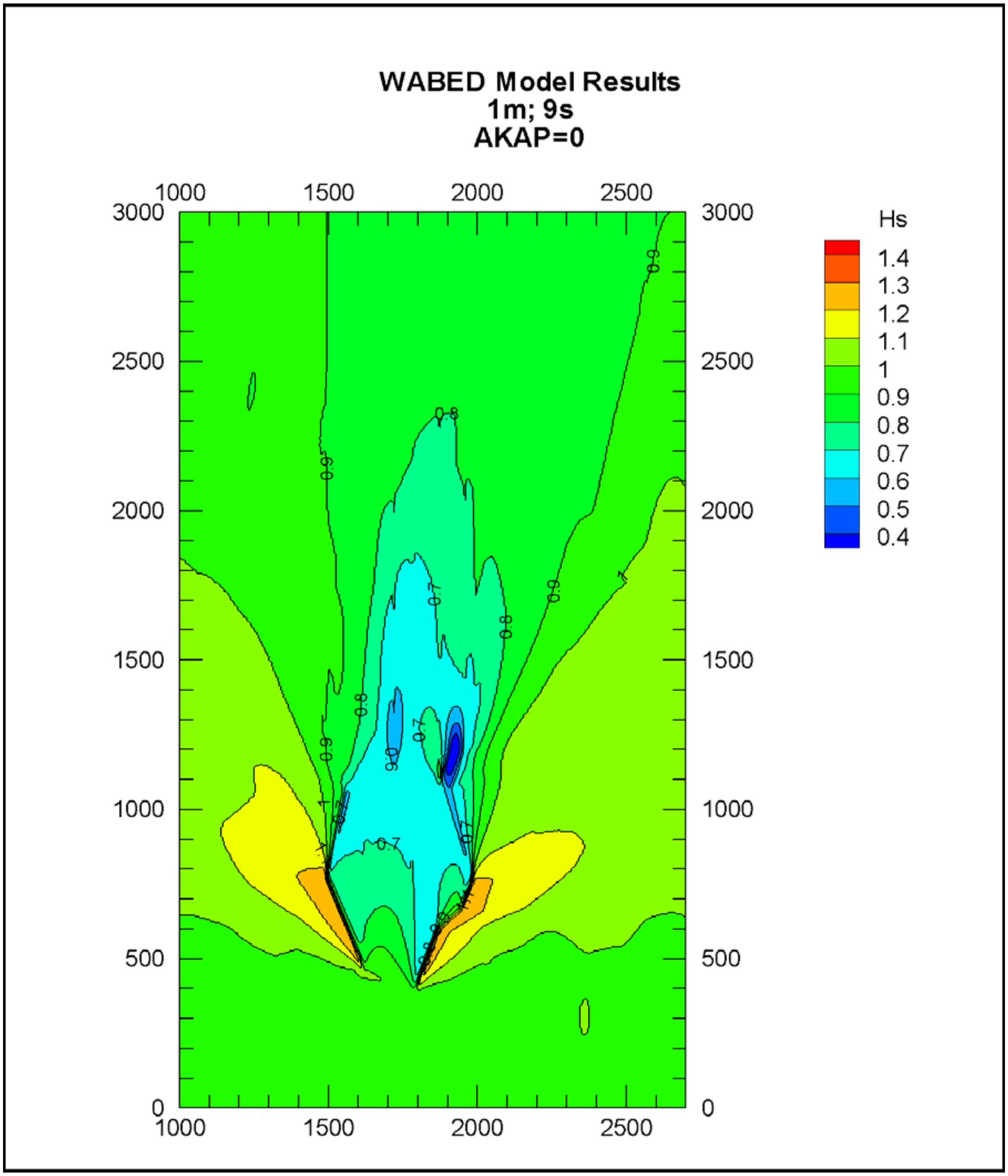

Figure 3.64 Colour Contour Plots of Significant Wave Height for T_p = 9 s by WABED with Diffraction Coefficient of *akap* = 0 (coordinates are in meters)

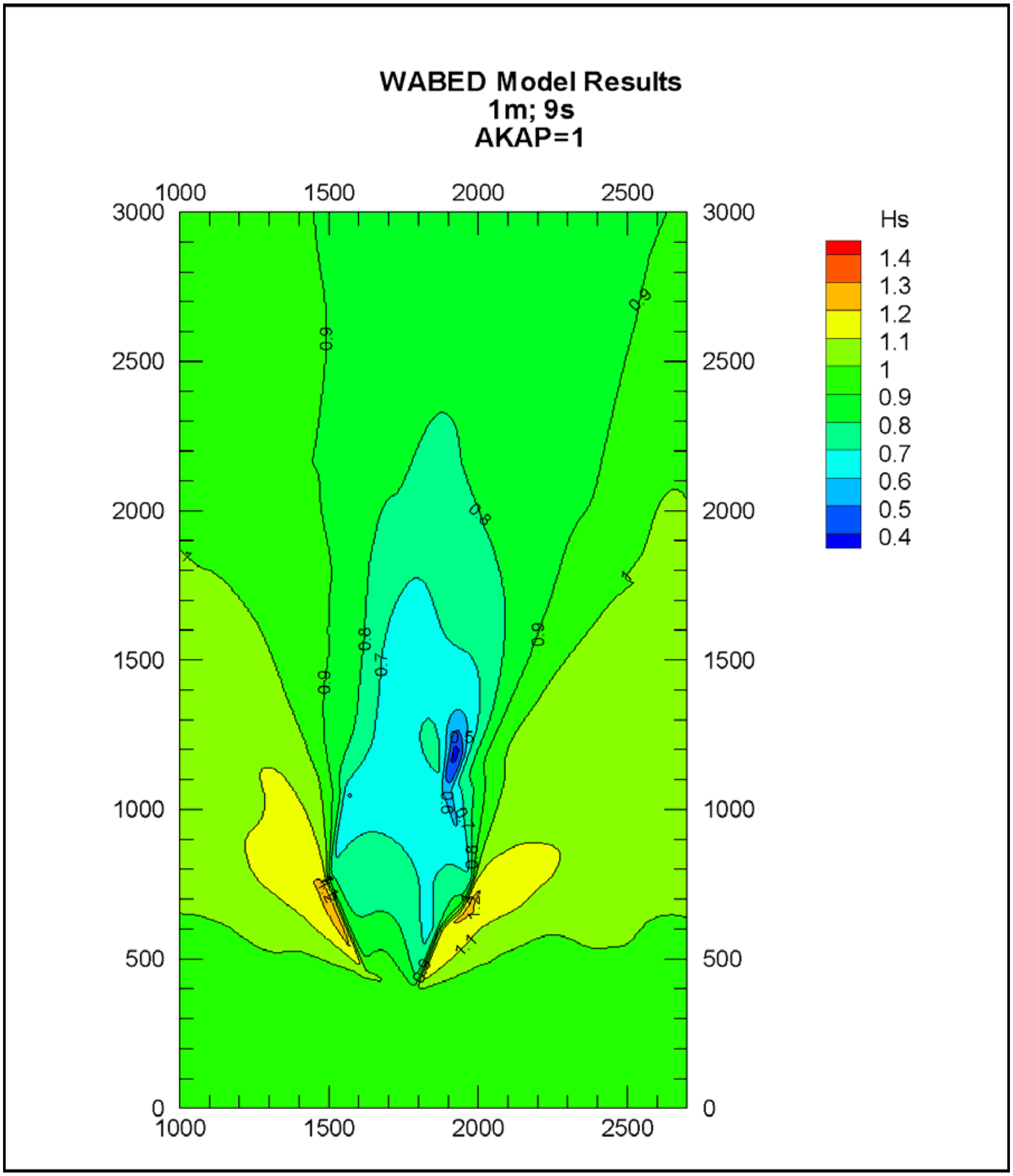

Figure 3.65 Colour Contour Plots of Significant Wave Height for T_p = 9 s by WABED with Diffraction Coefficient of *akap* = 1 (coordinates are in meters)

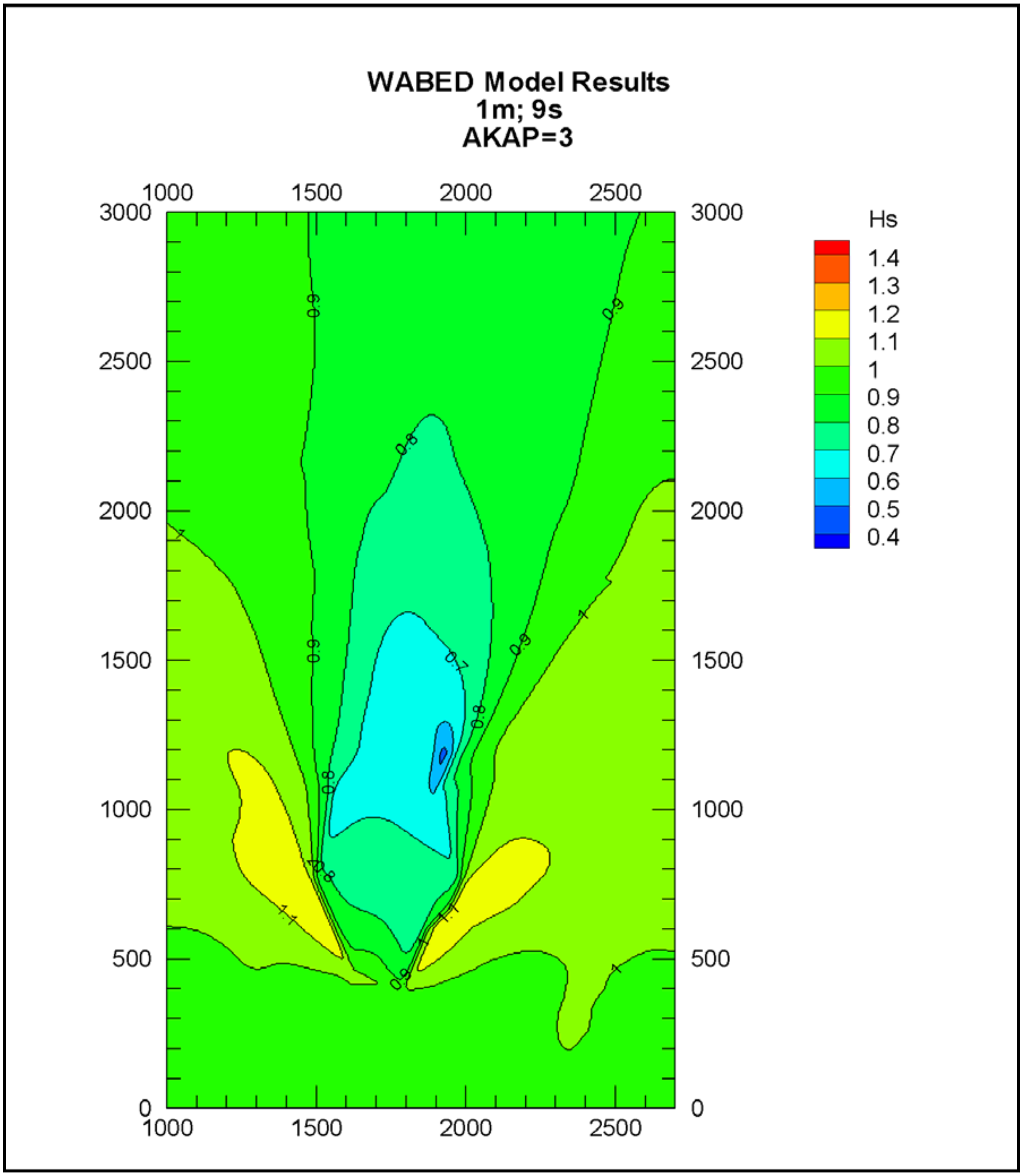

Figure 3.66 Colour Contour Plots of Significant Wave Height for T_p = 9 s by WABED with Diffraction Coefficient of *akap* = 3 (coordinates are in meters)

3.2.2.5 HYDROSED Model

HYDROSED is a Baird in-house 2DH hydrodynamic and sediment transport state of the art model for coastal areas. The spectral wave transformation module of *HYDROSED* was used for the present study. The wave field is calculated by the spectral energy conservation equation of Karlsson (1969), with the breaking dissipation term of Isobe (1987). *HYDROSED* resolves the directional spectrum in 10 frequency and 45 direction bins. The input spectrum is of Bretschneider-Mitsuyasu type with Mitsuyasu directional distribution function, which is calculated by the program. Spectral parameters were selected such that the resulting spectrum was very similar to the input spectrum of other models. *HYDROSED* is capable of incorporating the following physical processes:

- Wave propagation (in half plane), shoaling and refraction;
- Wave breaking, dissipation and recovery,

HYDROSED utilizes an input bathymetric grid in Cartesian coordinate system. For this application for the Holly Beach Dredge Pit, the model was used with the identical grid employed in the other wave models. Input settings included:

- 4° angular resolution;
- Ten frequency bins with equalized wave energy in each frequency interval;
- Bottom friction was not utilized.

No tuning or adjustment of the model was carried out. Figures 3.67 and 3.68 provide colour contour plots of significant wave height for the simulations conducted with 12 s and 9 s peak wave period, respectively. *HYDROSED* provided solutions that were similar in structure to the other phase-averaged models, such as STWAVE and WABED. *HYDROSED* calculates and input waves from one of the side boundaries depending on incoming wave direction. Predicted wave heights along the east (right) lateral boundary are slightly higher than the other models. This is believed to be due to interaction of incoming waves with refracted waves inside the domain. Appropriate treatment of side boundaries in terms of incoming waves is important in estimation of wave recovery behind the dredge pit.

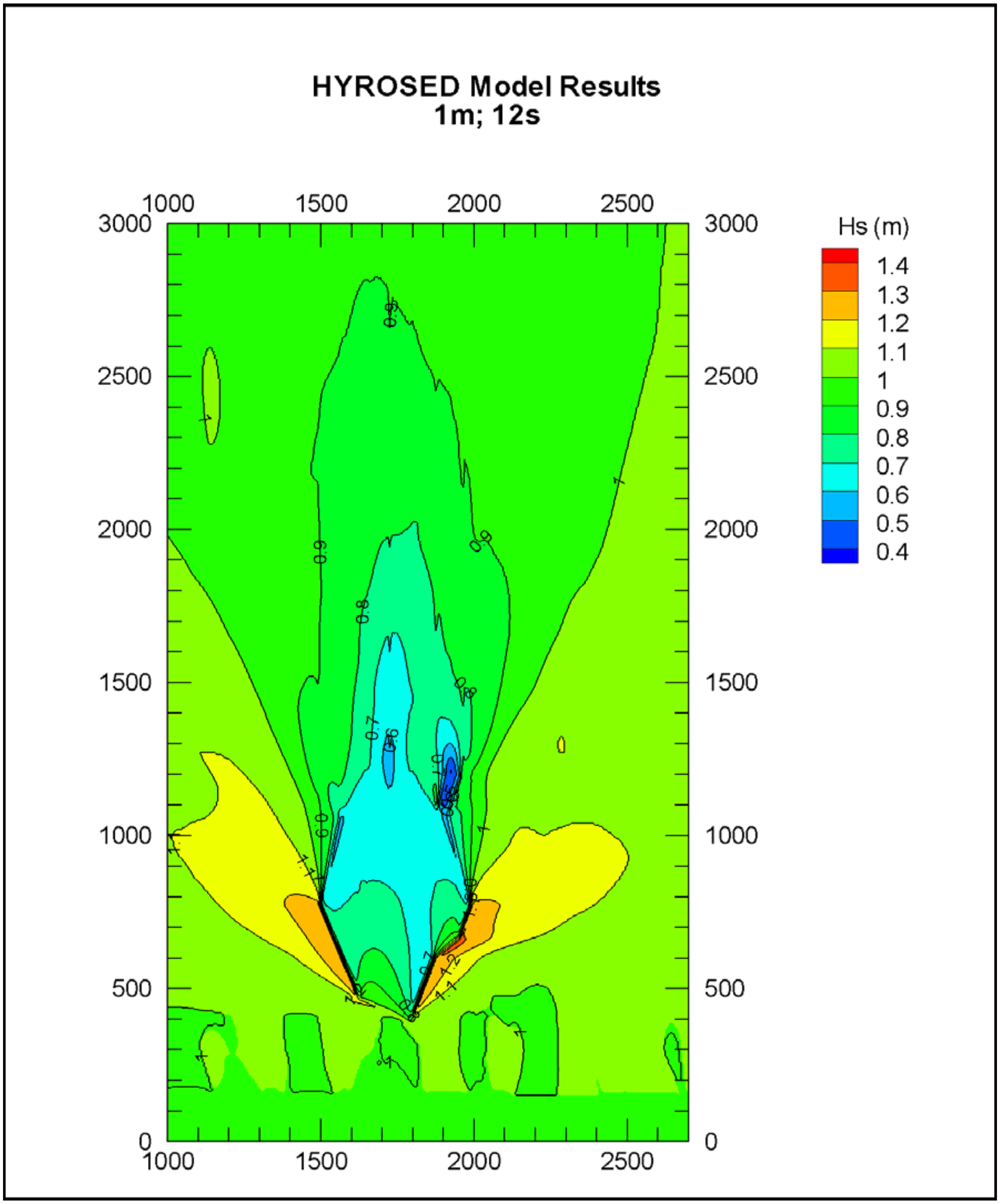

Figure 3.67 Colour Contour Plots of Significant Wave Height for Tp=12s by *HYDROSED*
(coordinates are in meters)

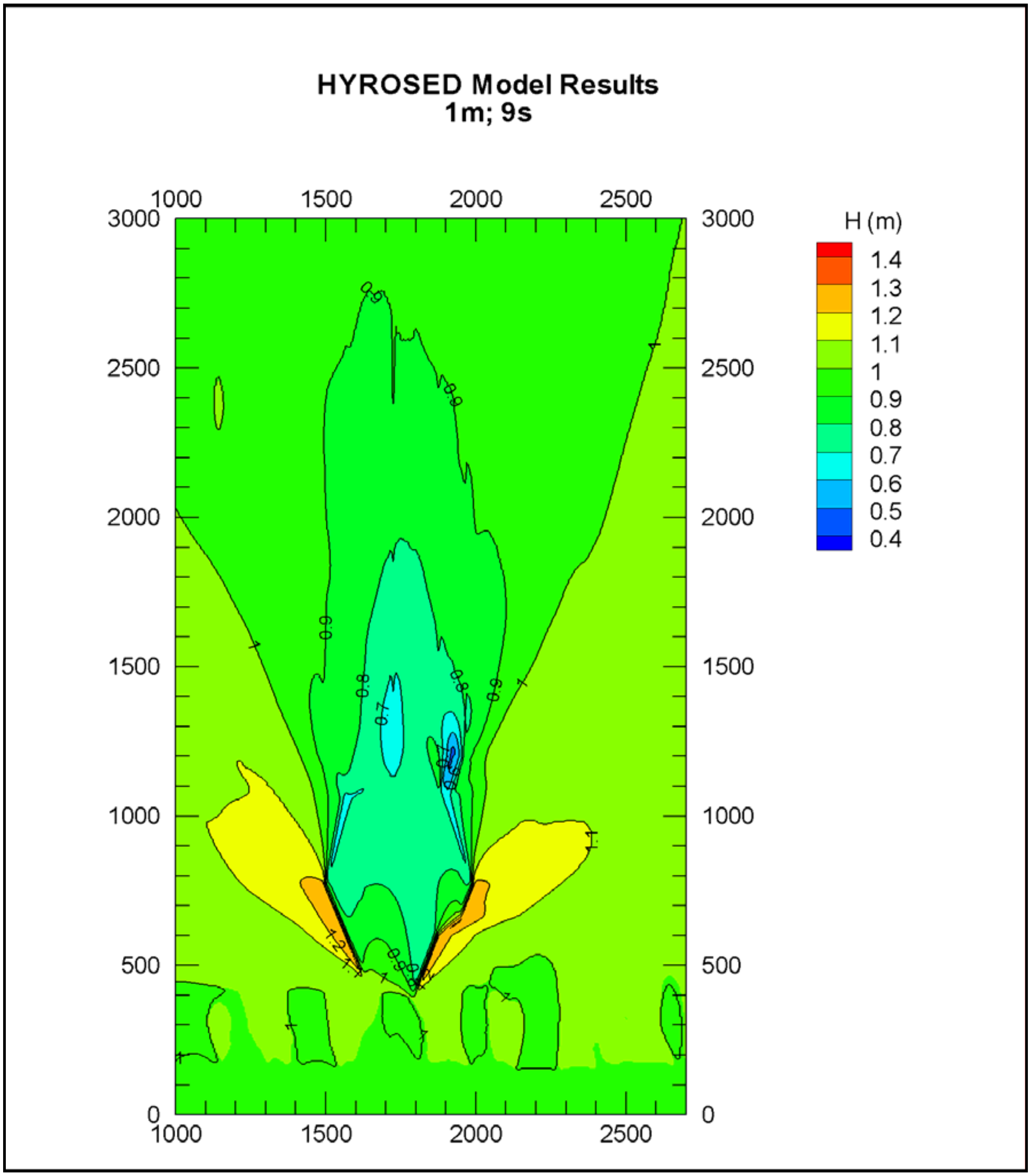

Figure 3.68 Colour Contour Plots of Significant Wave Height for Tp=9s by *HYDROSED*
(coordinates are in meters)

3.2.2.6 Wave Transformation Model Comparison

The results of the various models were compared along a series of alongshore and cross-shore transects. Figure 3.69 shows the overall calculation domain and the selected transects for comparison. Each transect is labeled with its distance from the bottom left corner of the grid. The two 30 º lines on both sides represent the area of lateral boundary effect. Model results are considered not valid between these lines and the side boundaries particularly for BW and SWAN models where there is no wave coming through the lateral boundaries.

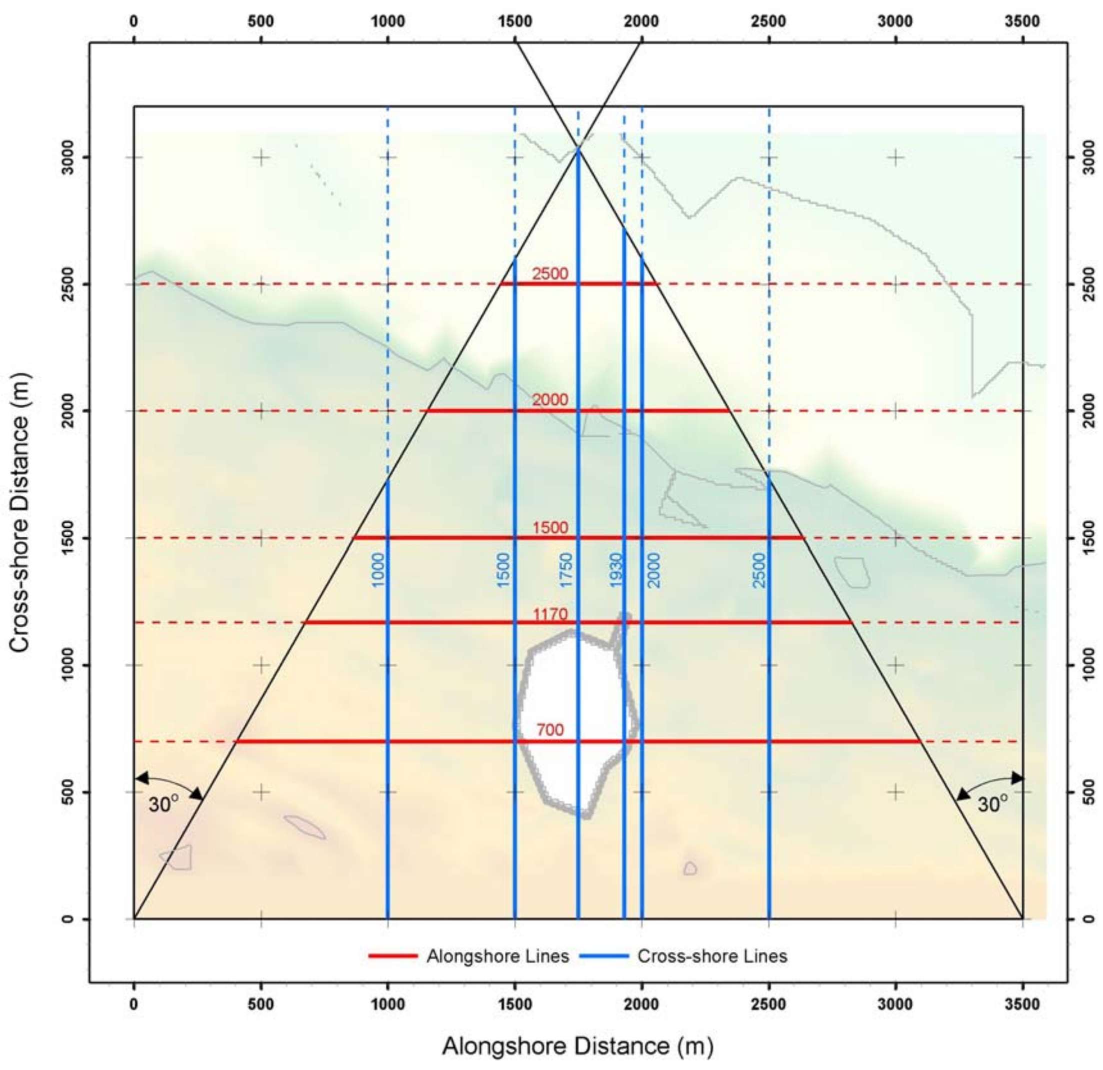

Figure 3.69 Calculation Domain and Comparison Profile Lines

In the following we will first discuss comparisons along the alongshore transects and then along the cross-shore transects. Figures 3.70 to 3.79 show alongshore comparisons. Figures 3.70 to 3.74 are for 12 s waves and Figures 3.75 to 3.79 are for 9 s waves. Figures 3.80 to 3.91 show the cross-shore comparisons. Figures 3.80 to 3.85 are for 12 s waves and Figures 3.86 to 3.91 are for 9 s waves. Note that the range of wave height shown in the vertical axis is changed in each figure to provide a better comparison of the lines.

Looking at comparison along 700 m alongshore transect (Figure 3.70), the results from all models are in close agreement. The predicted wave height inside the pit is very similar in all models (around 0.7 m). This is as an indication that all models have adequately reproduced wave refraction process over the suddenly increased depth. The BW model predicts the highest wave height on top of the east and west margins of the pit. Prediction of waves slightly higher than other models by BW may be attributed to 1) nonlinear nature of Boussinesq waves, 2) presence of reflected wave components and 3) violation of the mild-slope assumption (pit side slopes are 1:1.5) resulting in overestimation of shoaling effects. STWAVE, SWAN, WABED (*akap* = 0 and 1) and *HYDROSED* results at these locations are more or less similar and all models have done a reasonable job. However, WABED with diffraction coefficient of *akap* = 3 predicts the smallest wave height on the east/west margins. This was expected as this is a high wave energy zone that would leak wave energy to neighbouring areas through diffraction. BW and other models, however, indicate that diffraction effects may not be as severe as predicted by WABED with *akap* = 3. The higher wave heights on the east and west margins represent an additional process contributing to pit margin erosion, particularly for the east and west flanks of the pit.

Figure 3.71 shows the comparison at alongshore 1170 m line which is just outside the pit but goes through the small cut in the northeast corner of the pit. The results again are in rather close agreement. BW predicts the lowest wave height just north of the pit, while SWAN shows a strange peak at the west edge of the small cut. STWAVE and *HYDROSED* also show a similar peak but to a lesser degree. STWAVE predicts the lowest wave height (0.3 m) inside the small cut, while SWAN predicts the highest (0.5 m).

Figure 3.72 shows the comparison for the alongshore 1500 m line north of the pit. Most model results are similar, but BW predicts slightly more reduction (about 10 %) in wave height in the lee of the pit than other models. Comparison at the 2000 m line (Figure 3.73) further north of the pit shows that all models predict a similar reduction in wave height around the middle of this line. To the west of this area, SWAN, *HYDROSED*, and WABED with diffraction results are closer to BW predictions than STWAVE and WABED without diffraction. Towards the east *HYDROSED* predicts higher wave heights than other models. This is because of the interaction of incoming waves through the east boundary with refracted outgoing waves which is not incorporated in the BW model (i.e. no incoming waves from side boundary in BW simulations). It should be noted that in a small calculation domain such as the present grid, wave recovery process and recovery distance may not be properly simulated without appropriate treatment of side boundaries.

Figure 3.74 shows the comparison at the last alongshore line (2500 m) in the valid calculation range. Note the small range of wave height used for the vertical axis. STWAVE and WABED with no diffraction have predicted slightly larger wave heights than other models towards the west end of comparison line, while WABED with diffraction slightly underestimates wave heights towards the east end of the comparison line. SWAN and *HYDROSED* results are in close agreement with BW. Undulations in SWAN results are sometimes out of phase with those of BW. Models' results in the middle of comparison line are in close agreement and indicate between 80 % to 90 % wave recovery. This location is about 1500 m or approximately 3 times of the pit length from the pit. Complete wave recovery is expected at a distance roughly 4 times of the pit length. Examination of calculated wave direction indicates that wave direction is affected in the vicinity and along the edges of the pit, but is reestablished along the above comparison line. Similar trends are observed for the 9 s wave shown in Figures 3.75 to 3.79.

It is noted that the evaluation has been completed for relatively low wave heights. Nevertheless, this evaluation is applicable to most wave conditions at the site for the reasons explained in this paragraph. There are two wave transformation processes that are strongly influenced by wave height: 1) wave breaking; and 2) wave nonlinearity. These pits are in deep enough water that breaking is not an important process for the vast majority of conditions. Nonlinear wave models were not applied (even Boussineq model is only weakly nonlinear). Therefore, results of a 5 m wave height wave would be very similar to those of a 1 m wave, and the impact zone would be the same. Finally, it is likely that the shoreline is more influenced by the frequent larger waves than the very largest and infrequent waves.

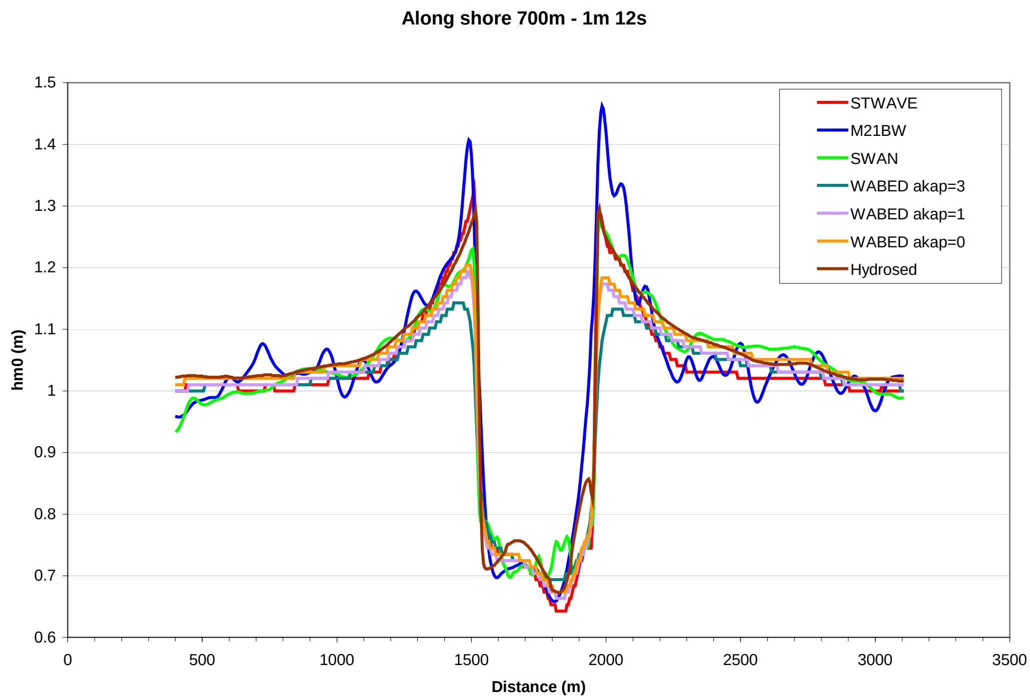

Figure 3.70 Wave Height Comparison for the 700 m Alongshore Line (12 s)

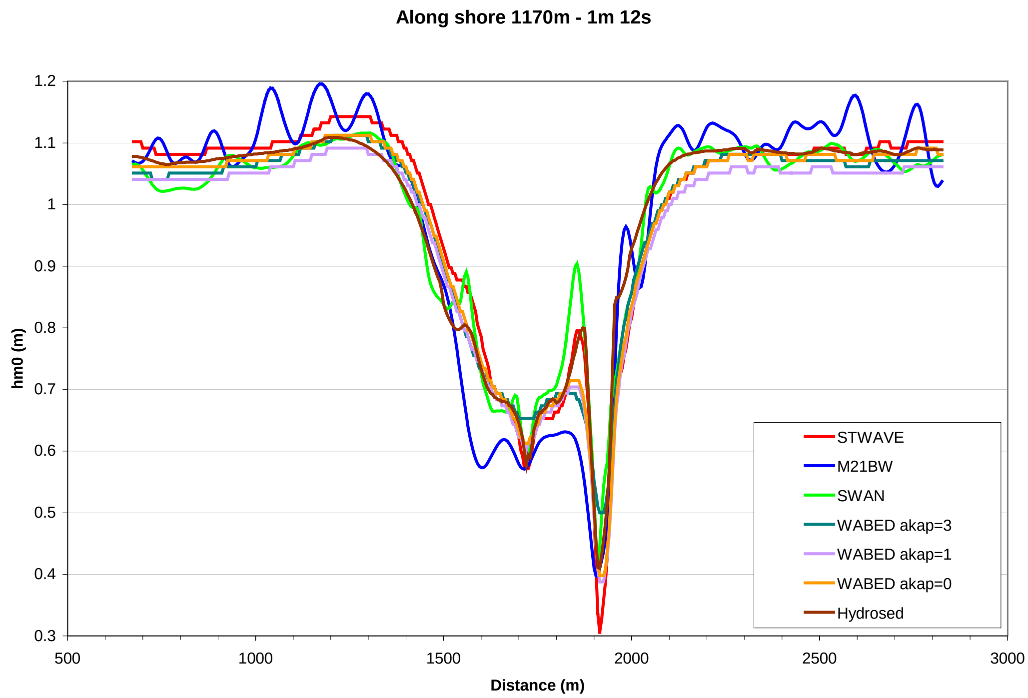

Figure 3.71 Wave Height Comparison for the 1170 m Alongshore Line (12 s)

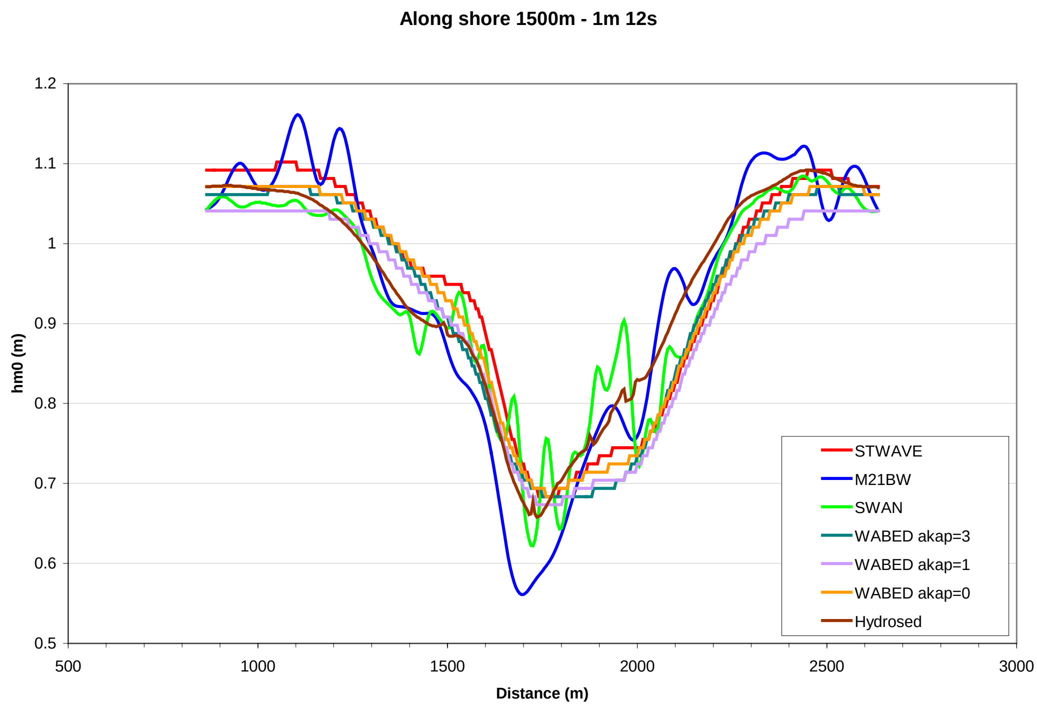

Figure 3.72 Wave Height Comparison for the 1500 m Alongshore Line (12 s)

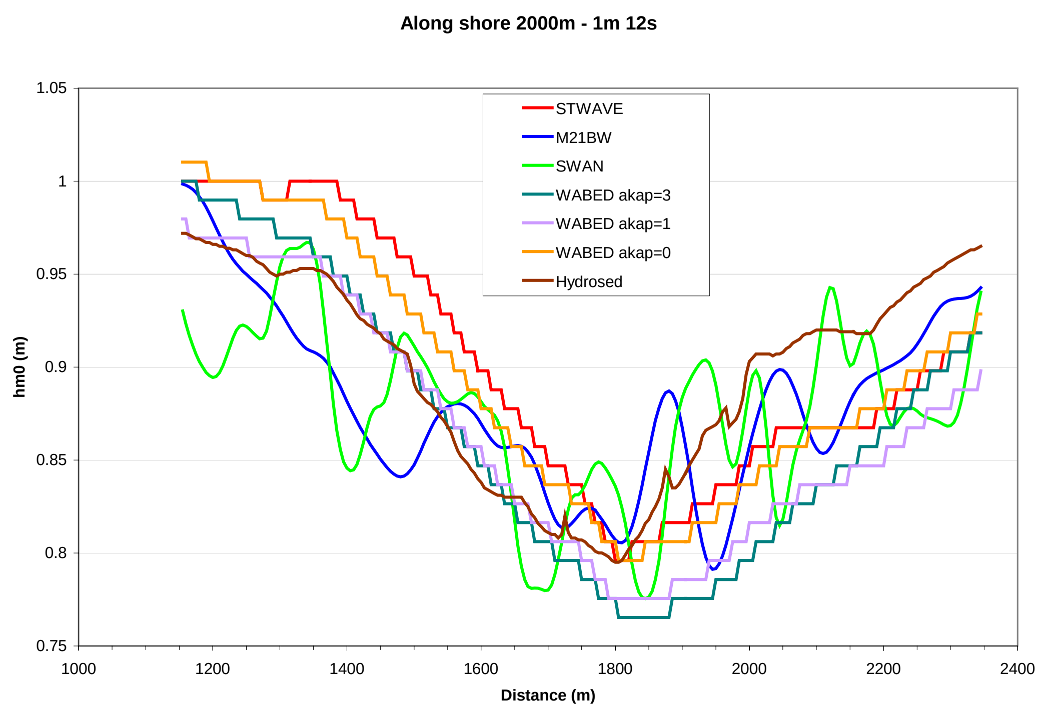

Figure 3.73 Wave Height Comparison for the 2000 m Alongshore Line (12 s)

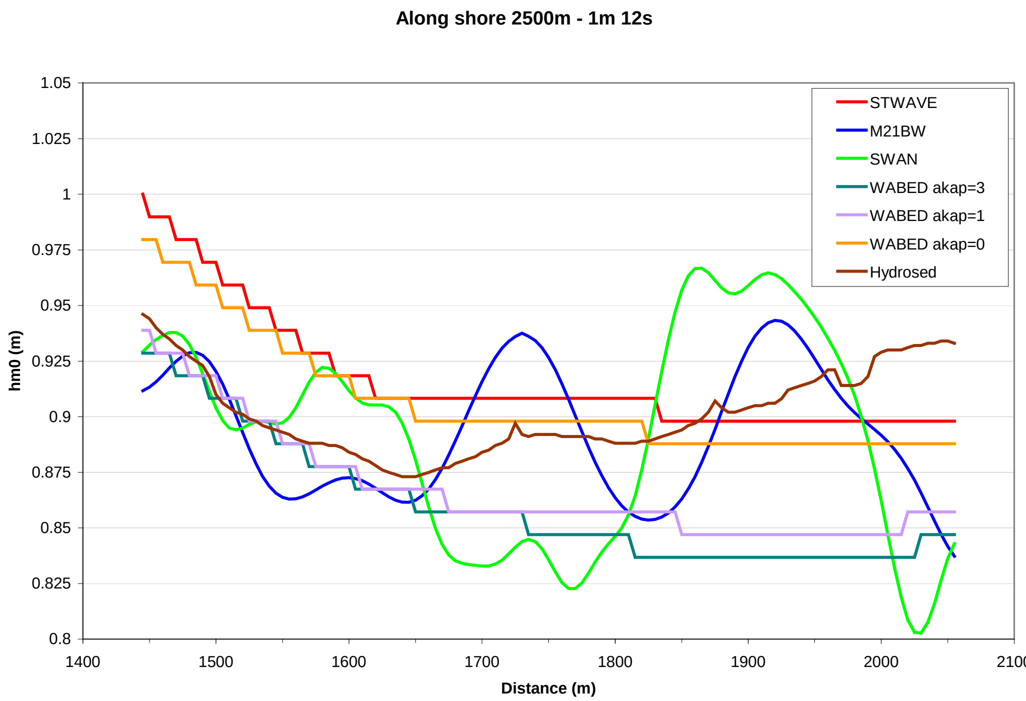

Figure 3.74 Wave Height Comparison for the 2500 m Alongshore Line (12 s)

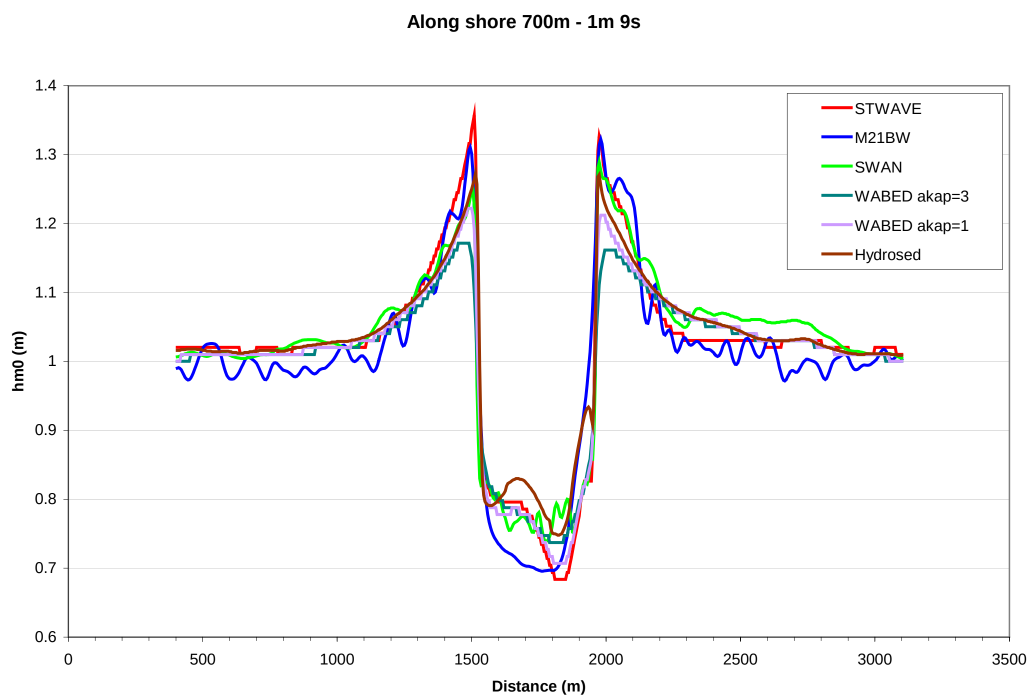

Figure 3.75 Wave Height Comparison for the 700 m Alongshore Line (9 s)

Figure 3.76 Wave Height Comparison for the 1170 m Alongshore Line (9 s)

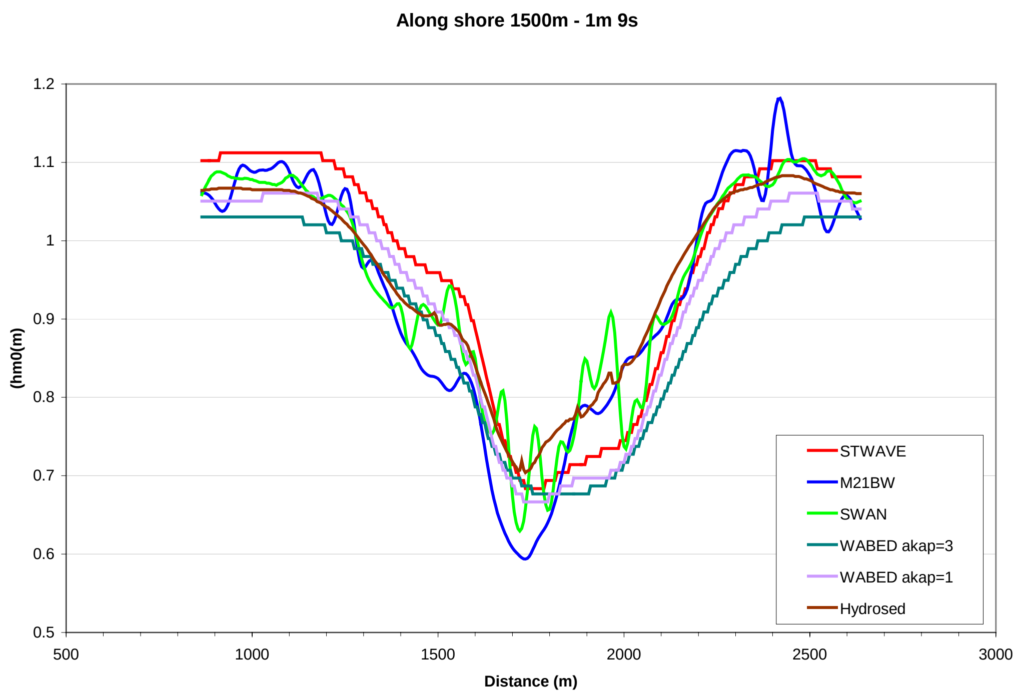

Figure 3.77 Wave Height Comparison for the 1500 m Alongshore Line (9 s)

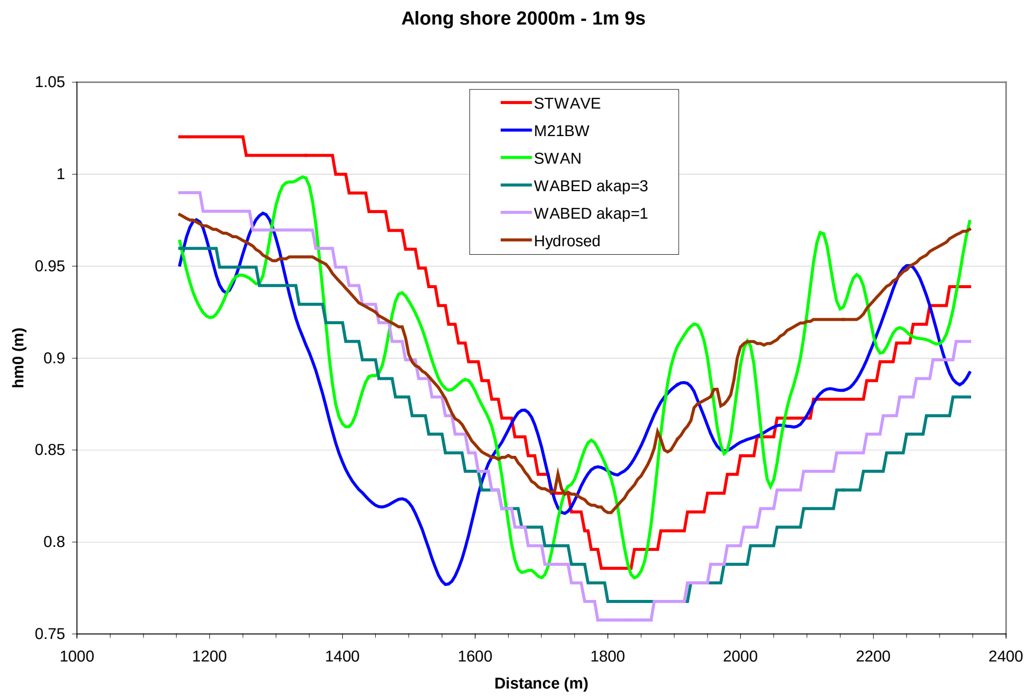

Figure 3.78 Wave Height Comparison for the 2000 m Alongshore Line (9 s)

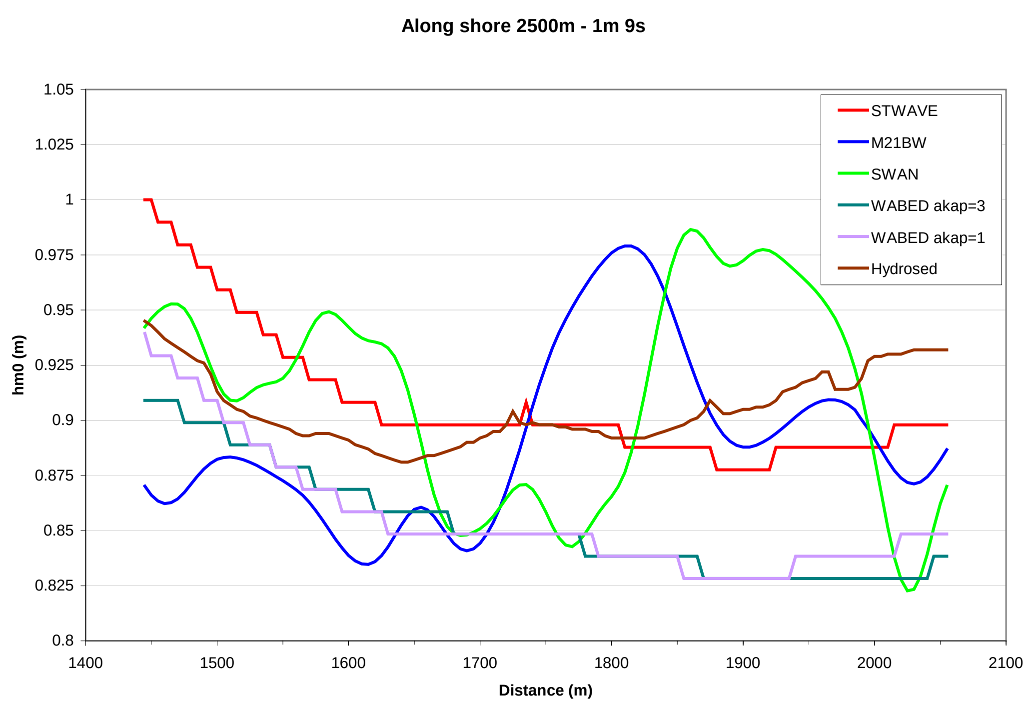

Figure 3.79 Wave Height Comparison for the 2500 m Alongshore Line (9 s)

Next, comparisons along the cross-shore lines for 12 s waves are discussed. Figure 3.80 shows the results along the 1000 m cross-shore line. BW predicts slightly higher wave height in the lobe of refracted waves on the west side of the pit. Other models have provided results close to each other and to BW results. Similarly, along the 1500 m cross-shore line (Figure 3.81), BW predicts larger wave height (1.4 m) just above the pit slope than other models and WABED with strong diffraction predicts the lowest wave height (1.15 m). Further to the north along this comparison line, models' predictions are very similar with STWAVE results being slightly higher than other models and BW results forming the lower envelope.

Along the centerline of the calculation domain (1750 m cross-shore line) model results are again in close agreement. Wave reflection at both south and north edges of the pit have been simulated by BW model. As a result, BW predicts a larger reduction than other models just north (outside) of the dredge pit (Figure 3.82). Further along this comparison line, however, all models' predictions become very close. Along the 1930 m cross-shore line (Figure 3.83) the models have simulated very similar results. WABED with diffraction tend to underestimate the wave height as one moves in down-wave direction outside the pit. Similar results were observed for 9 s waves and the corresponding figures are presented in Figures 3.86 to 3.91.

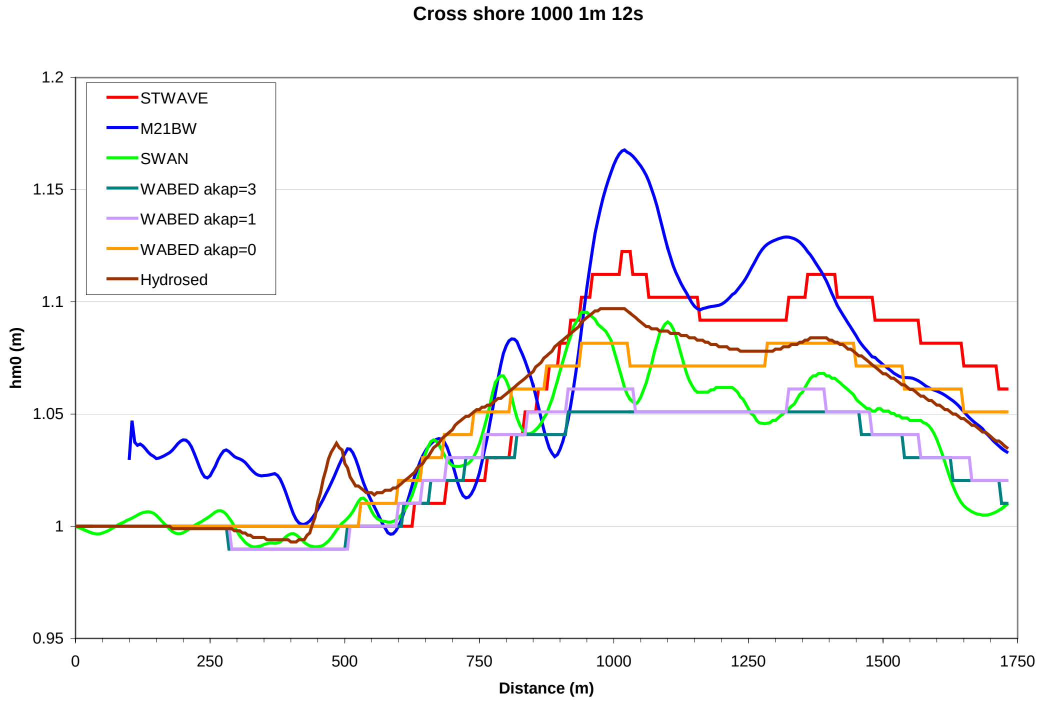

Figure 3.80 Wave Height Comparison for the 1000 m Cross Shore Line (12 s)

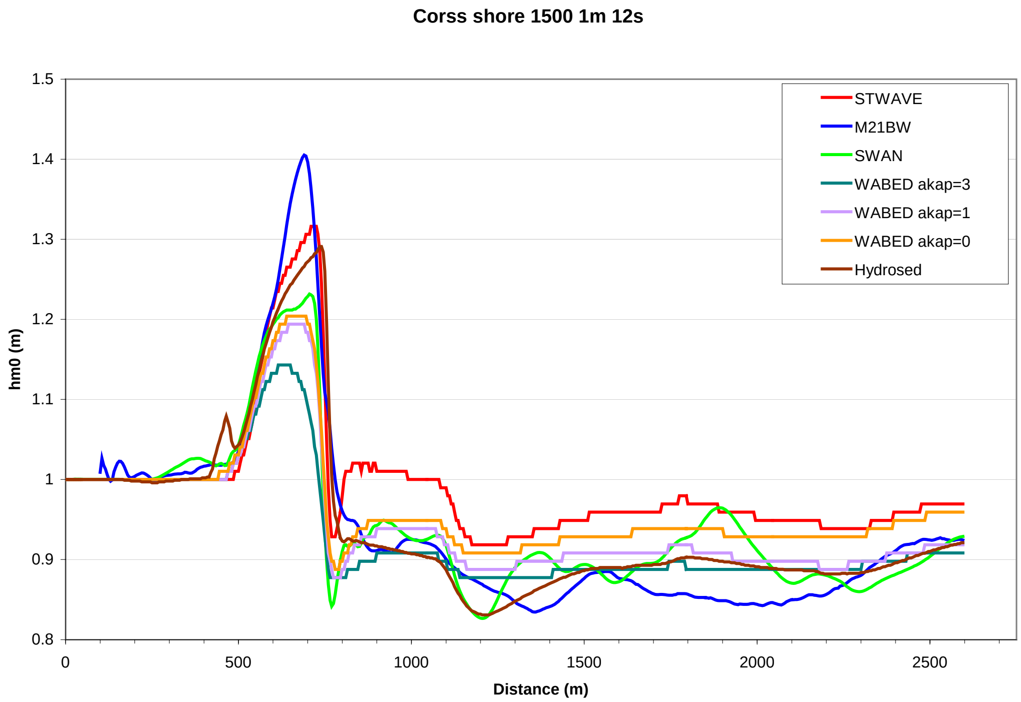

Figure 3.81 Wave Height Comparison for the 1500 m Cross Shore Line (12 s)

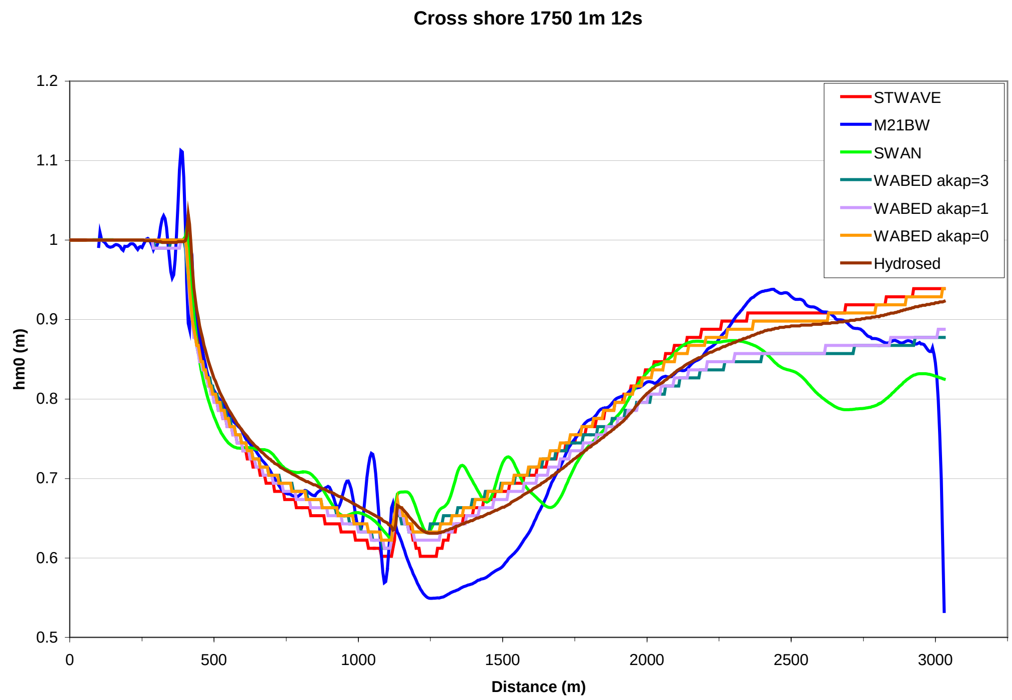

Figure 3.82 Wave Height Comparison for the 1750 m Cross Shore Line (12 s)

Figure 3.83 Wave Height Comparison for the 1930 m Cross Shore Line (12 s)

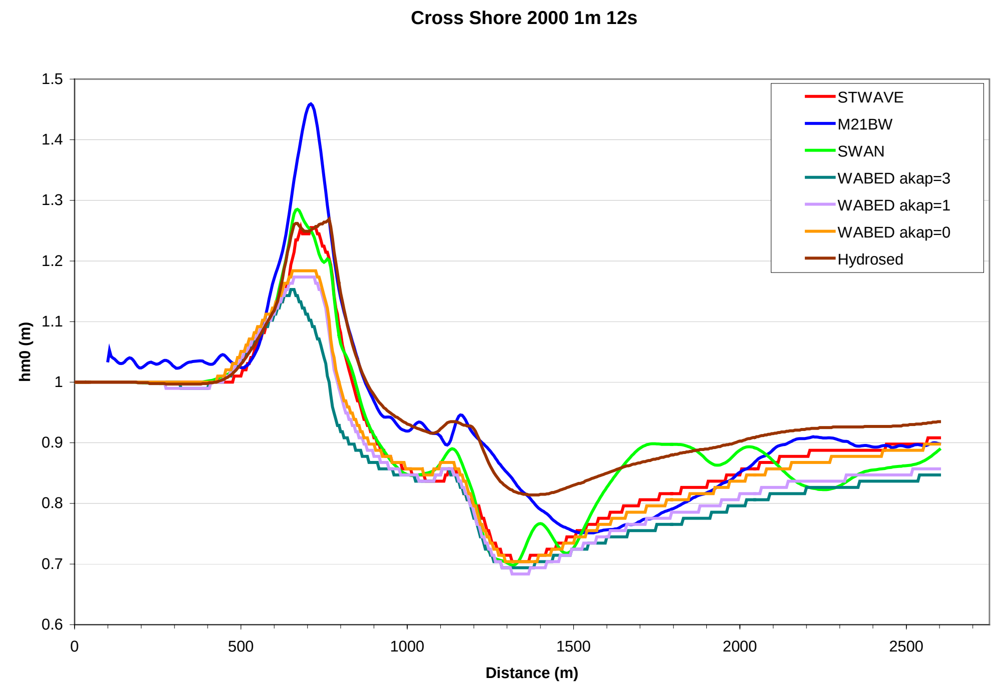

Figure 3.84 Wave Height Comparison for the 2000 m Cross Shore Line (12 s)

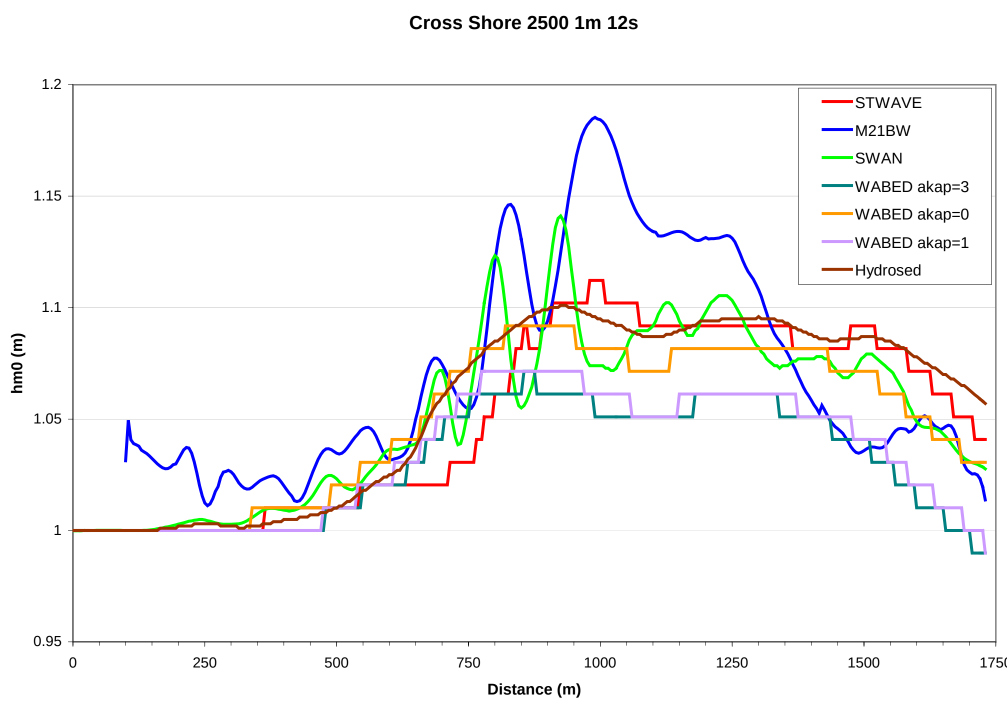

Figure 3.85 Wave Height Comparison for the 2500 m Cross Shore Line (12 s)

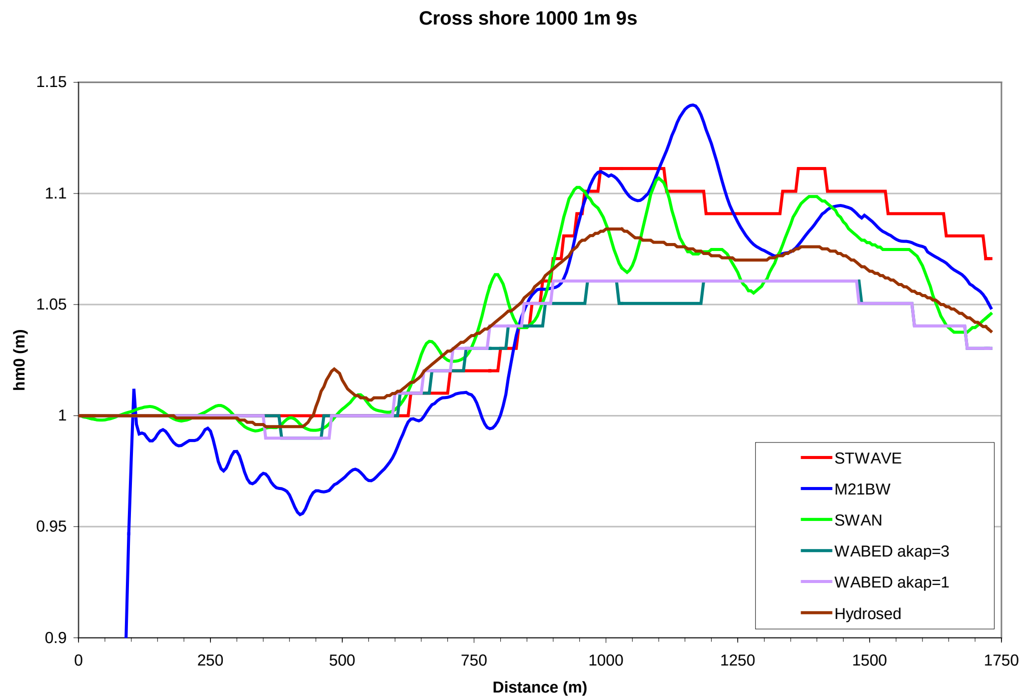

Figure 3.86 Wave Height Comparison for the 1000 m Cross Shore Line (9 s)

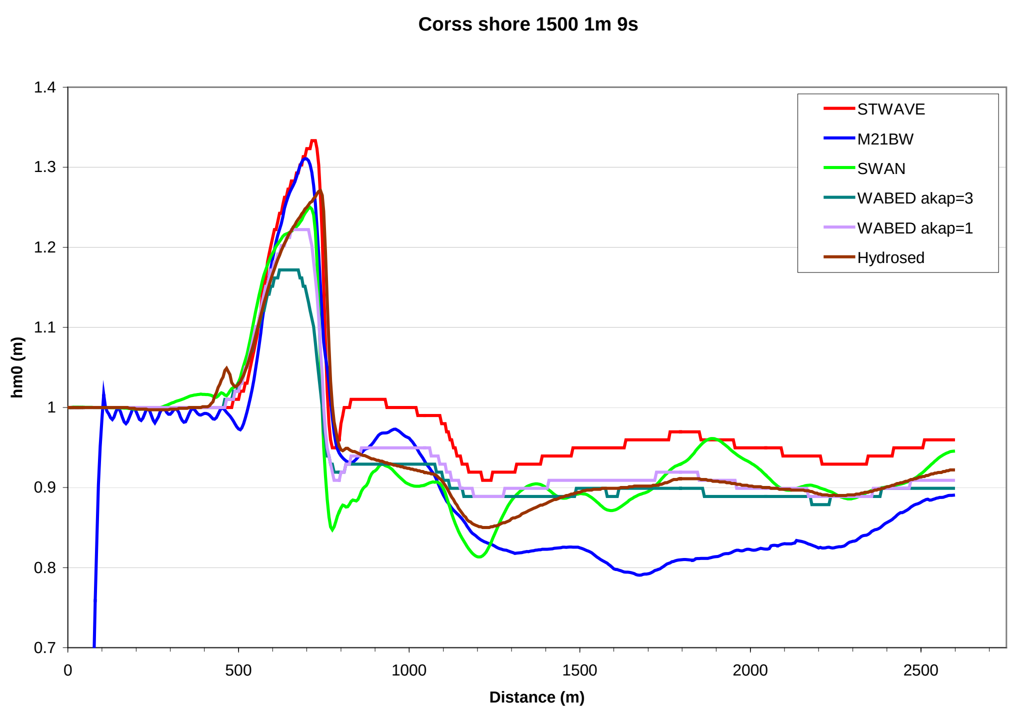

Figure 3.87 Wave Height Comparison for the 1500 m Cross Shore Line (9 s)

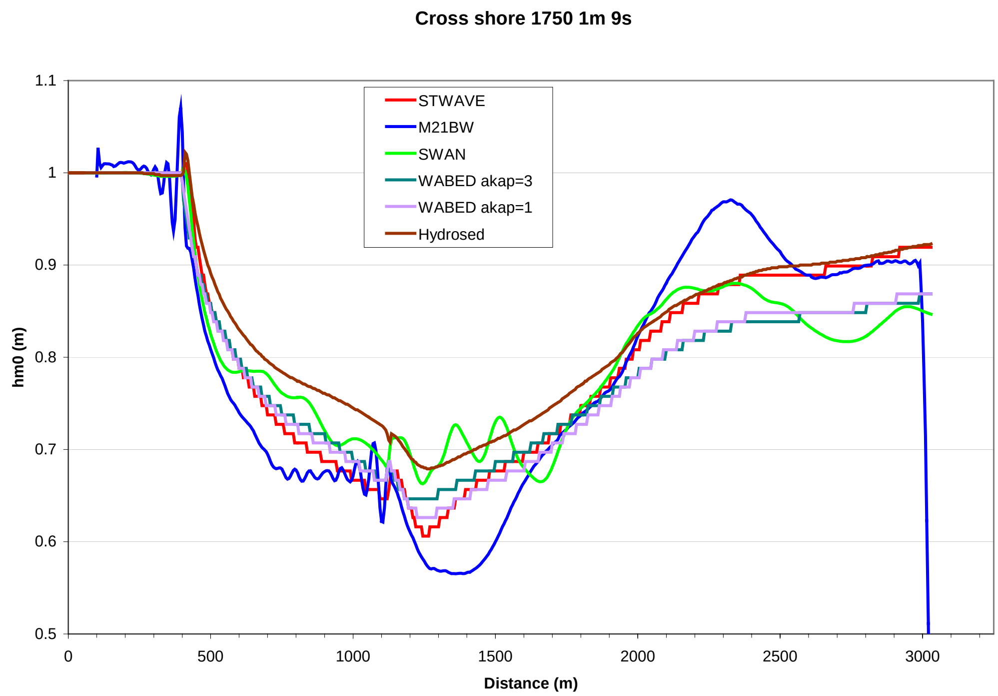

Figure 3.88 Wave Height Comparison for the 1750 m Cross Shore Line (9 s)

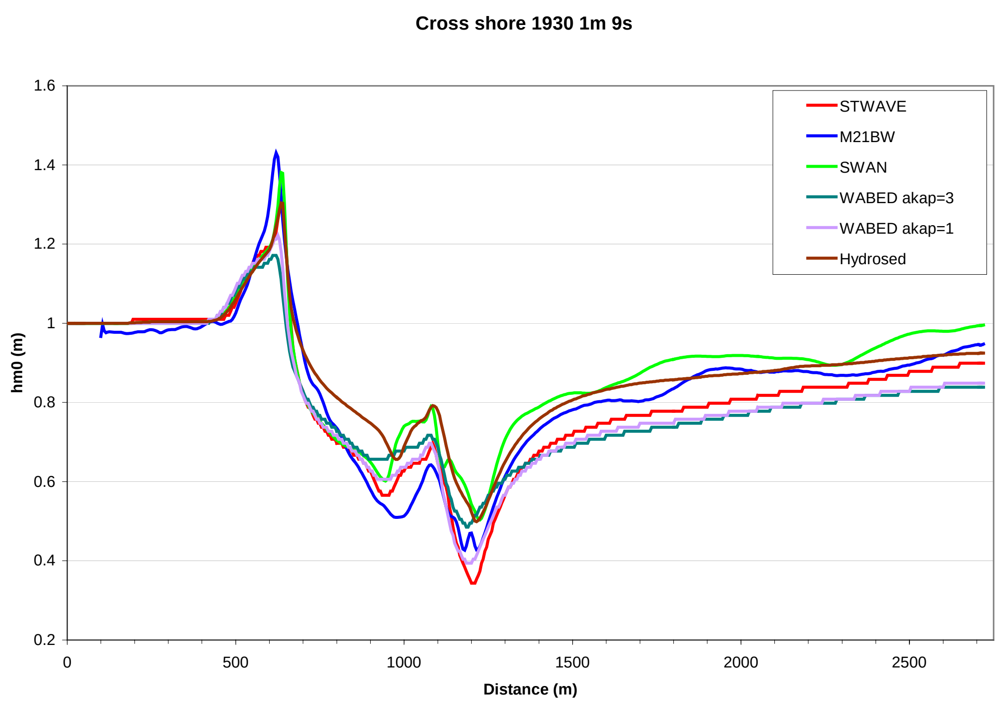

Figure 3.89 Wave Height Comparison for the 1930 m Cross Shore Line (9 s)

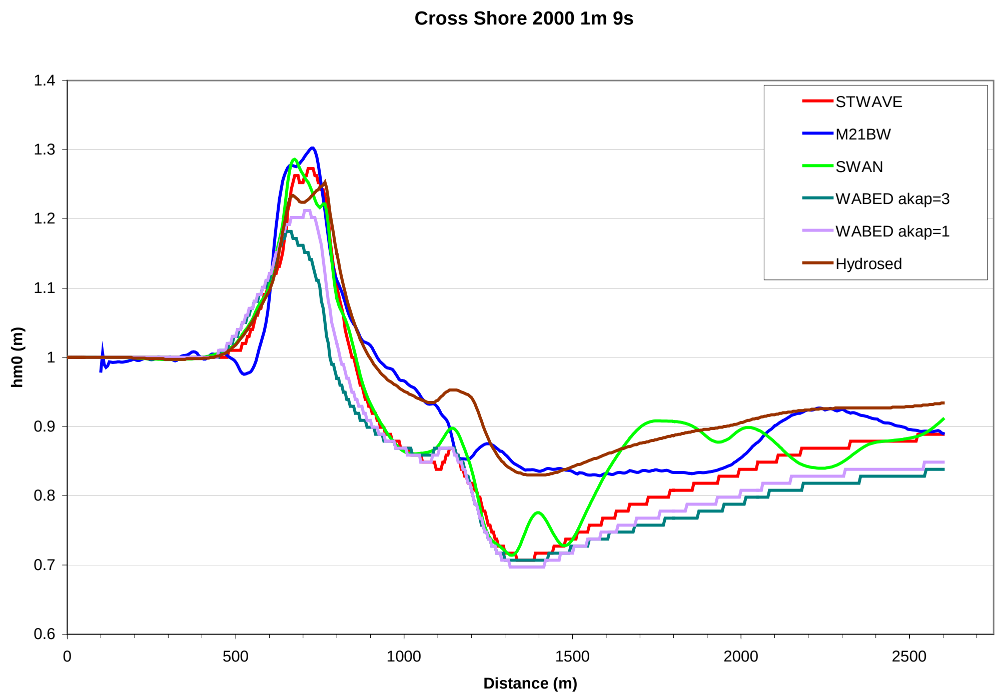

Figure 3.90 Wave Height Comparison for the 2000 m Cross Shore Line (9 s)

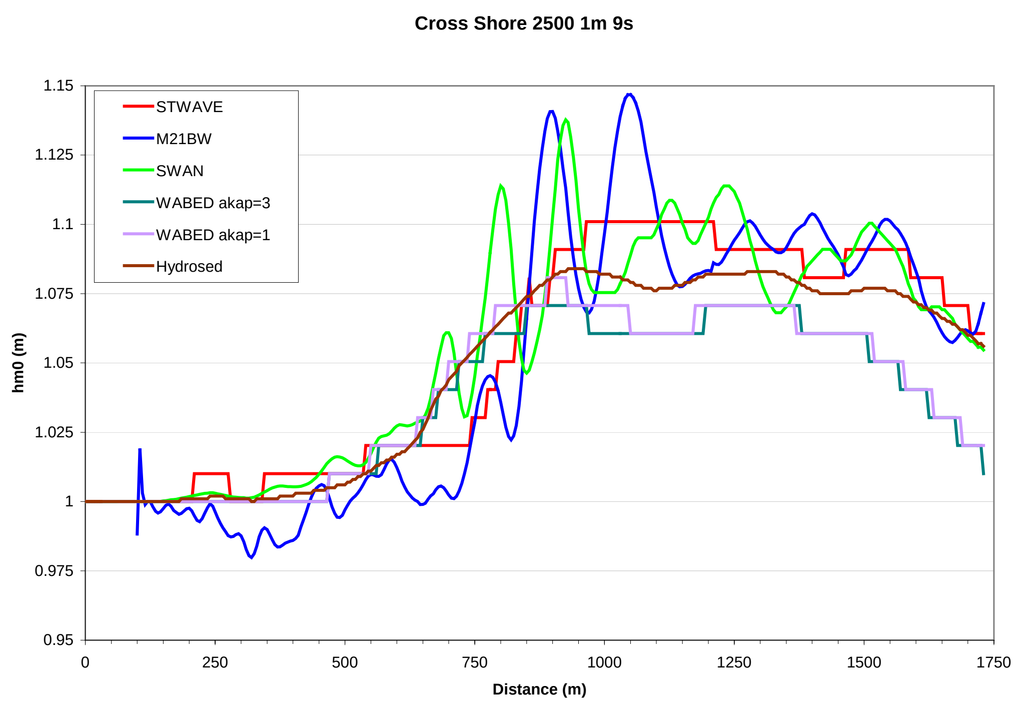

Figure 3.91 Wave Height Comparison for the 2500 m Cross Shore Line (9 s)

In conclusion, wave transformation results simulated by four spectral wave transformation models were compared with simulations by the Boussinesq model for two selected incoming wave conditions. The applied spectral models were: STWAVE, WABED, SWAN and *HYDROSED*. It was found that the most important wave-related processes over a dredge pit are wave refraction and shoaling, and both are well reproduced by the applied models. Wave diffraction was not of primary importance and inclusion of diffraction in WABED model resulted in less agreement between this model and BW and other model results. Nevertheless, it is noted that all of the models consider some form of smoothing through the consideration of multi-directional waves and through numerical diffusion. Wave reflection at the edges of the pit was only simulated by the BW model. Reflection effects on the wave field were local and were negligible in the wave field far from the pit.

The dredge pit considered for the present comparison was in about 30 ft (9 m) of water. The pit was dredged to –60 ft (-18 m) and had a dimension of about 500 m (E-W) by 700 m (N-S). The existence of the pit resulted in generation of a wave height reduction area over and inshore of the pit. Complete recovery of wave height and direction was found to occur in a distance about 4 times of the pit length. It is noted that winds could contribute to wave re-growth behind the pit resulting in a shorter recovery distance.

Borrow pits often have a rather rectangular shape with their longer side parallel to the shoreline orientation. There is an analogy between borrow pits and offshore breakwaters in terms of the ratio of breakwater (or borrow pit) length to its distance from the shoreline. Through further studies, it may be possible to define a critical (borrow pit length to distance from shore) ratio below which the effect of the pit on the shoreline becomes insignificant. Such a ratio would as well depend on the width to length ratio of the borrow pit and the gap length between two or more borrow pits (if applicable). Nearshore processes and sediment transport affecting the shoreline mostly occur in the surf zone and are governed by the breaking wave conditions. Severe transport of sediment occurs during extreme storm events. It is expected that the effect of a borrow pit such as the Holly Beach dredge pit can be minimized if the pit is located offshore in a distance more than 4 times of its length from the breaker line of the maximum storm waves attacking the shoreline. Further study is required to extend this concept to a borrow pits with arbitrary dimensions.

3.2.2.7 Influence of Pit Configuration on Near-Field Waves

The Boussinesq wave (BW) model and the grid described in Section 3.2.2.1 were applied to wave transformation over and around the dredge pit with different pit configurations to investigate the effect of changing dredge pit dimensions (length, width and depth). The results are discussed in this section. Calculations were completed for both wave conditions (9 s and 12 s), but only the results corresponding to 12 s waves are presented here. The results will be compared to the results from the initial BW runs obtained with the actual pit configurations. The pit configuration was shown in Figure 3.52 and the initial results (Figure 3.55) are repeated here for easier comparison as Figure 3.92. In the following discussion, pit length is defined as the dimension in the direction of wave propagation and pit width is defined as the direction along the wave crests normal to wave propagation direction.

The dredge pit considered in this study is in about 30 ft (9 m) of water. The pit was dredged to –60 ft (-18 m) and had a dimension of about 500 m (E-W) by 700 m (N-S). Effect of dredge pit depth on the wave field was examined for two additional dredge pit depths associated with total water depths of 40 and 50 ft (12 and 15 m) in the middle of the pit. These conditions would represent the pit being one-third (50 ft or 15 m deep) and two-thirds full (40 ft or 12 m deep). Figures 3.93 and 3.94 show the resulting wave height distributions for 40 and 50 ft (12 and 15 m) depth, respectively. Looking at Figures 3.92, 3.93 and 3.94, it is clear that wave focusing on side edges of the dredge pit reduces with decreasing the dredge pit depth. Wave heights on the side edges are smallest and wave height reduction over the pit is less significant for the 40 ft (12 m) deep pit. This was anticipated, as there is less refraction over a shallower pit slopes and therefore less wave energy is diverted towards the two sides of the pit. As a result, the effect of dredge pit on the wave field is smaller for a shallower pit. In the case of 40 ft (12 m) deep pit, the wave field is expected to recover over a distance of about 3 times the pit length moving inshore from the pit compared to approximately 4 times the pit length for the pit at its original depth.

Next, the effect of dredge pit length is examined. Figures 3.95 and 3.96 show the wave fields calculated for dredge pits half as long and twice as long as the actual pit length, respectively. Comparison of Figures 3.92 and 3.95 indicates that extent of wave focusing along the side edges and wave height reduction over the pit are both less for the shorter pit of Figure 3.95. It is also noticed that waves have almost recovered by the 2500 m coordinate or about 4 times of the pit length moving inshore from the pit. On the other hand, a comparison of Figures 3.92 and 3.96 shows much larger wave focusing and wave height reduction zones for the case of the longer dredge pit. It was noted in previous sections that wave refraction and subsequent wave focusing are the predominant wave transformation phenomena over a dredge pit. Of these two, wave refraction occurs along the front edge (width) of the pit while focusing takes place along the side edges (length). In the above example, wave focusing is clearly proportional to the pit length and more waves refract towards outside of the pit over the side edges in the case of longer pit length. Thus a longer pit results in higher disturbance of the wave field and requires a longer distance for wave recovery. The normalized recovery distance, however, is expected to be similar to the original results of approximately 4 times of the pit length.

Figures 3.97 and 3.98 show the wave fields calculated for dredge pits half as wide and twice as wide as the actual pit width, respectively. Comparison of Figures 3.92 and 3.97 indicates that focusing zones on the two sides of the pit are smaller in size for the narrow pit than those for the actual pit. Wave recovery in the lee of the narrow pit occurs over a shorter distance. This is because a narrow pit provides less chance for waves to refract and limiting the amount of wave energy available for focusing. Comparison of Figure 3.98 with Figure 3.92 shows that such a pit results in a similar degree of wave focusing as the actual pit. Focusing zones are obviously further apart from each other. Wave height reduction is mitigated and spread over the wider pit. The recovery distance is expected to be similar to the actual pit case or about 4 times of the pit length.

In summary, it was shown that dredge pit length (measured perpendicular to the wave crest orientation) and depth are the most important factors controlling the zone of influence of the pit on its surrounding wave field. Shallower and shorter pits cause less disturbance to the near-field wave conditions. Wave recovery depends on the pit depth relative to its surrounding depth. It is expected to occur in a distance of less than or equal to 4 times the pit length moving away from the pit in the wave propagation direction for depth ranges of the present example. Recovery distance appeared to be independent of the pit width. Therefore to minimize the impact to the wave field wide and short dredge pits are more desirable than square or narrow long pits.

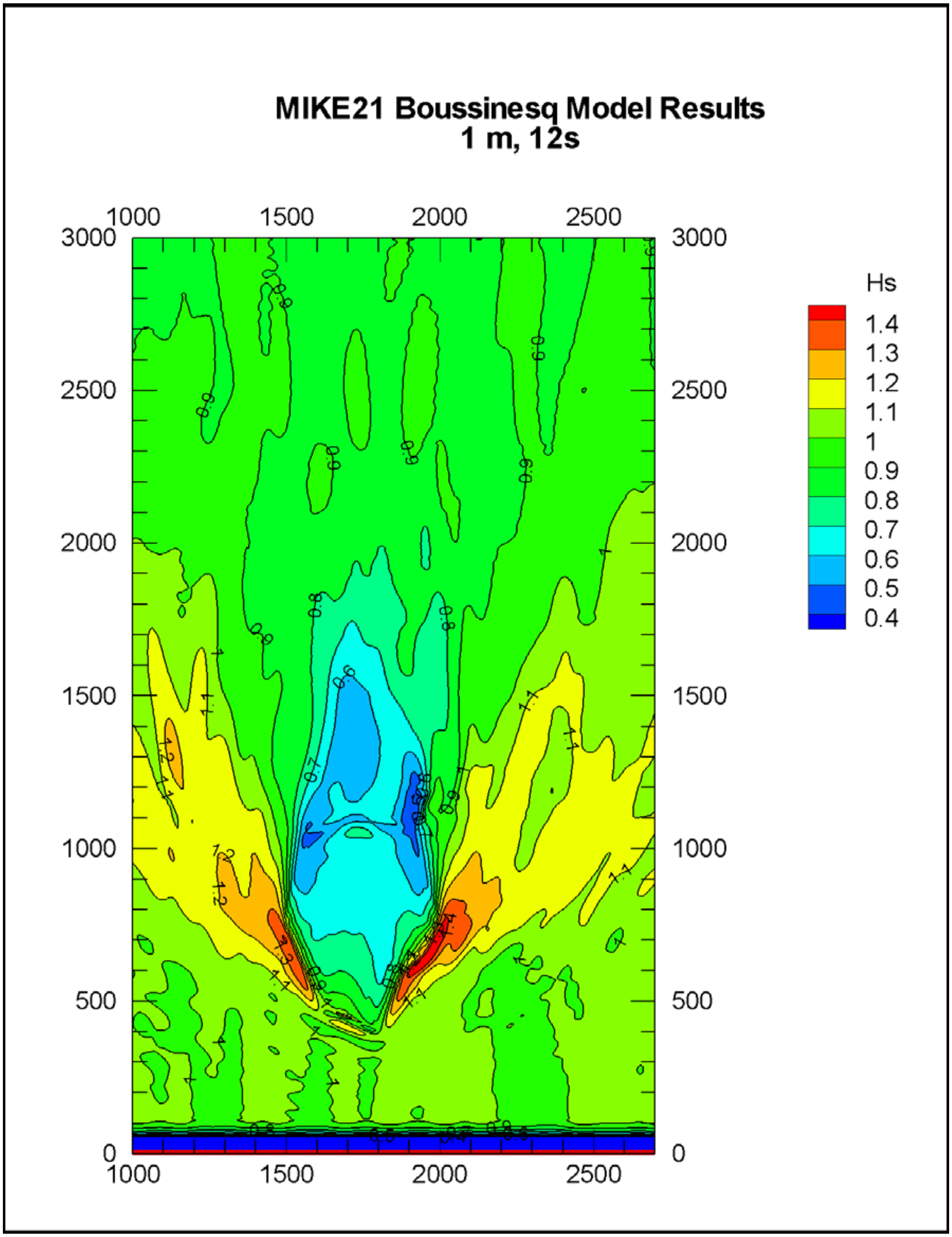

Figure 3.92 Distribution of Significant Wave Height from M21BW Results for Immediate Post-Dredge Depth of 18 m (Wave Condition: SSE, Hm0=1m, Tp=12 s and coordinates are in meters)

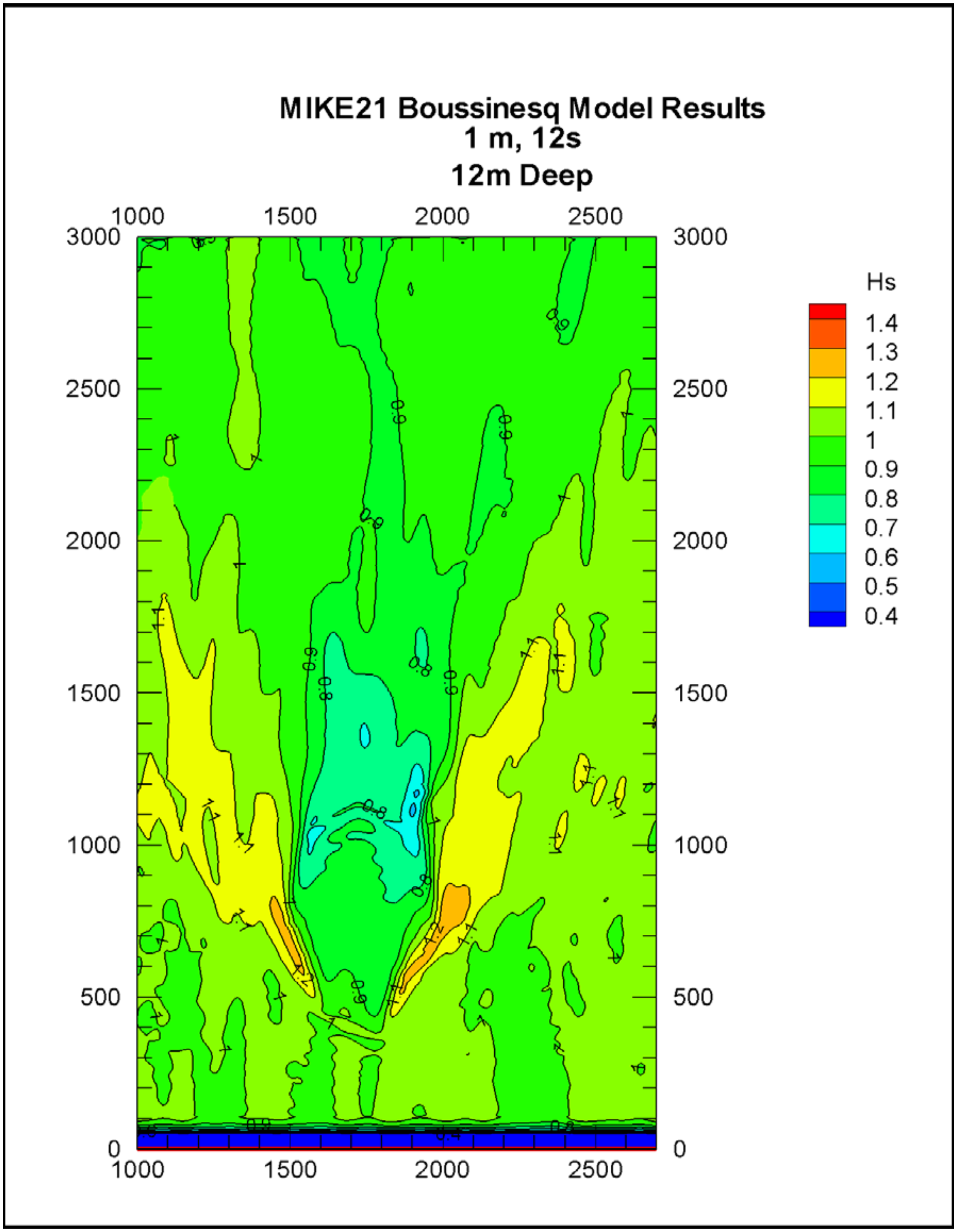

Figure 3.93 Distribution of Significant Wave Height from M21BW Results for a 12 m Dredge Pit (wave conditions same as Figure 3.92 and coordinates are in meters)

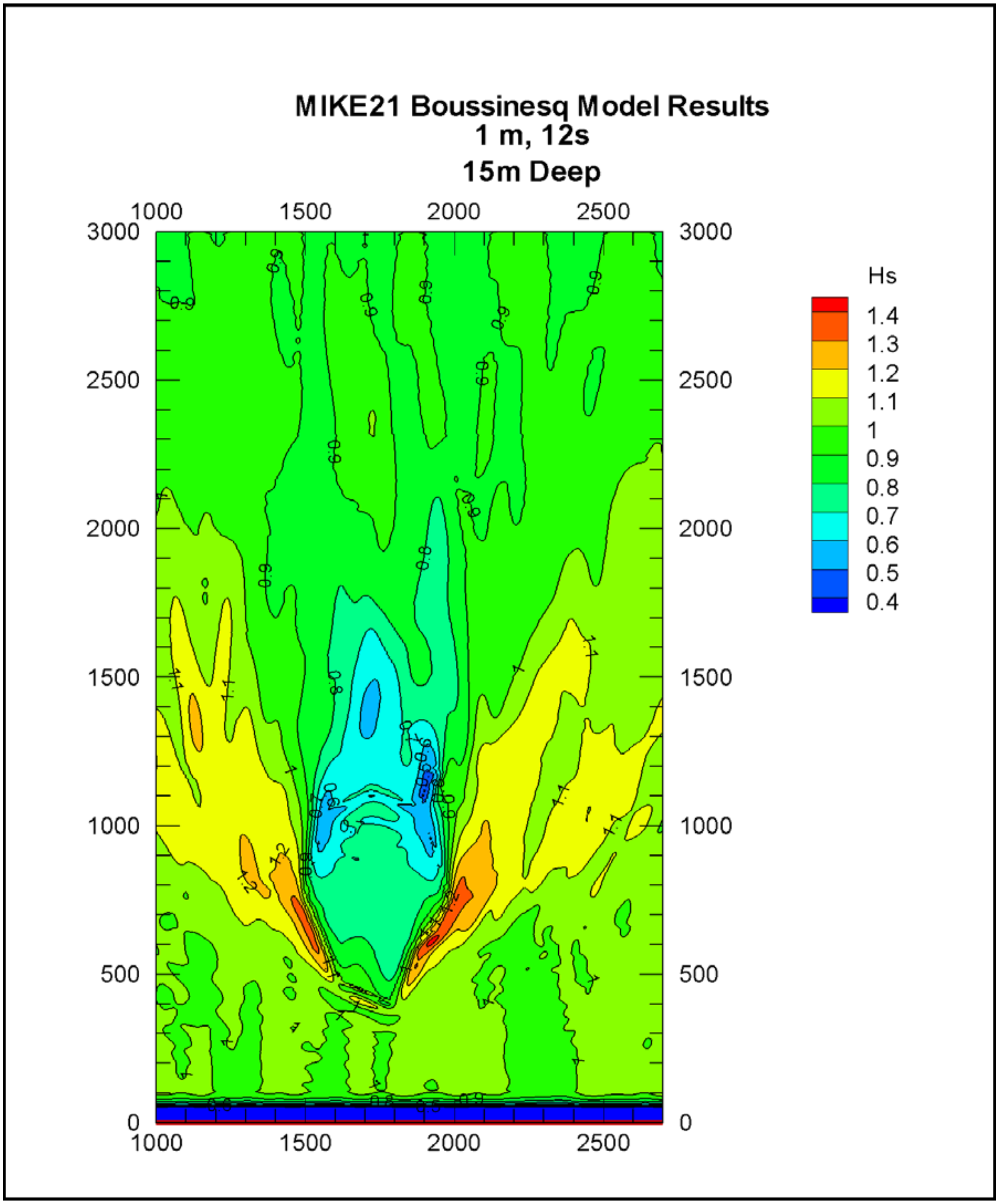

Figure 3.94 Distribution of Significant Wave Height from M21BW Results for a 15 m Dredge Pit (wave conditions same as Figure 3.92 and coordinates are in meters)

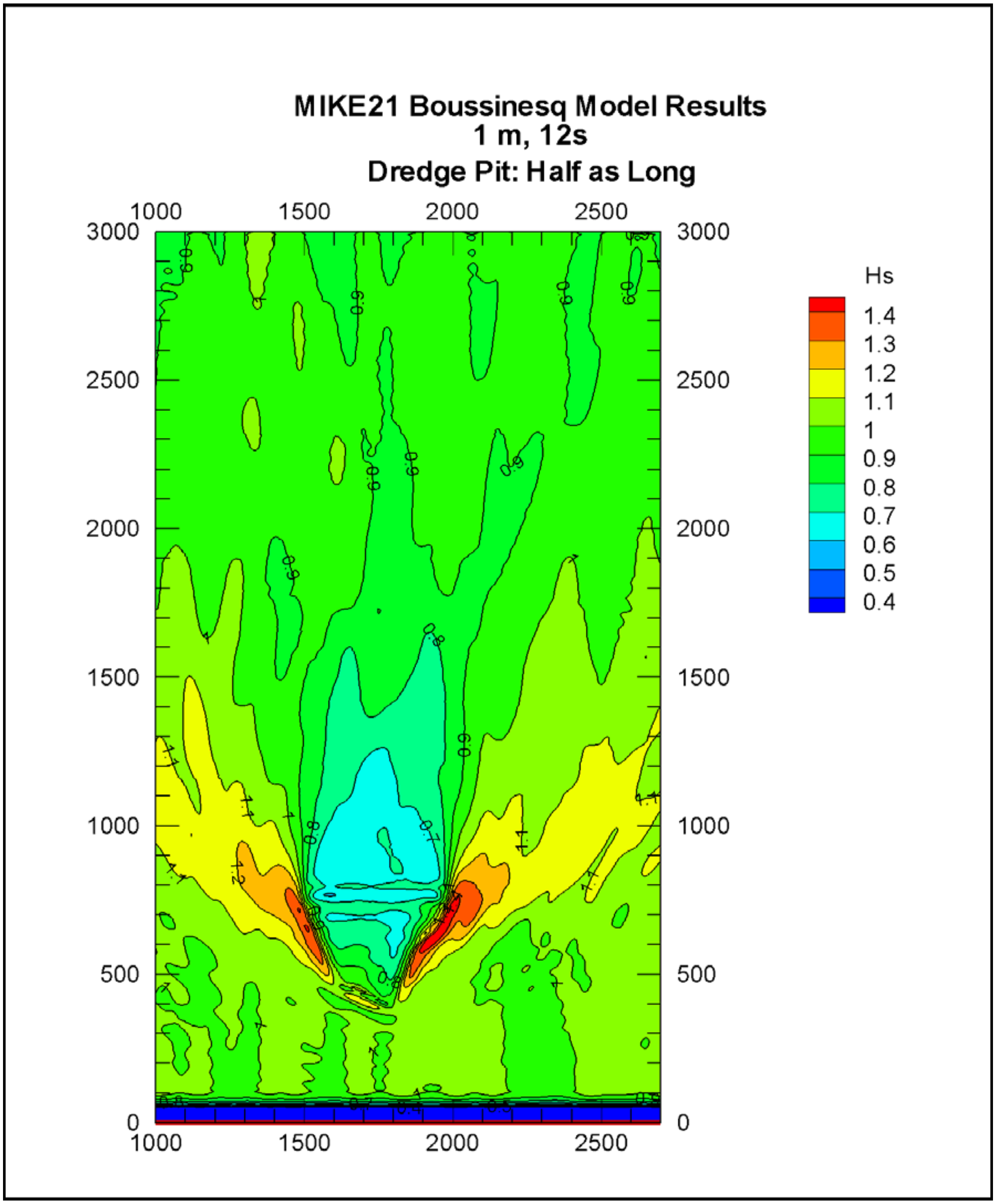

Figure 3.95 Distribution of Significant Wave Height from M21BW Results for the Half as Long Dredge Pit (wave conditions same as Figure 3.92 and coordinates are in meters)

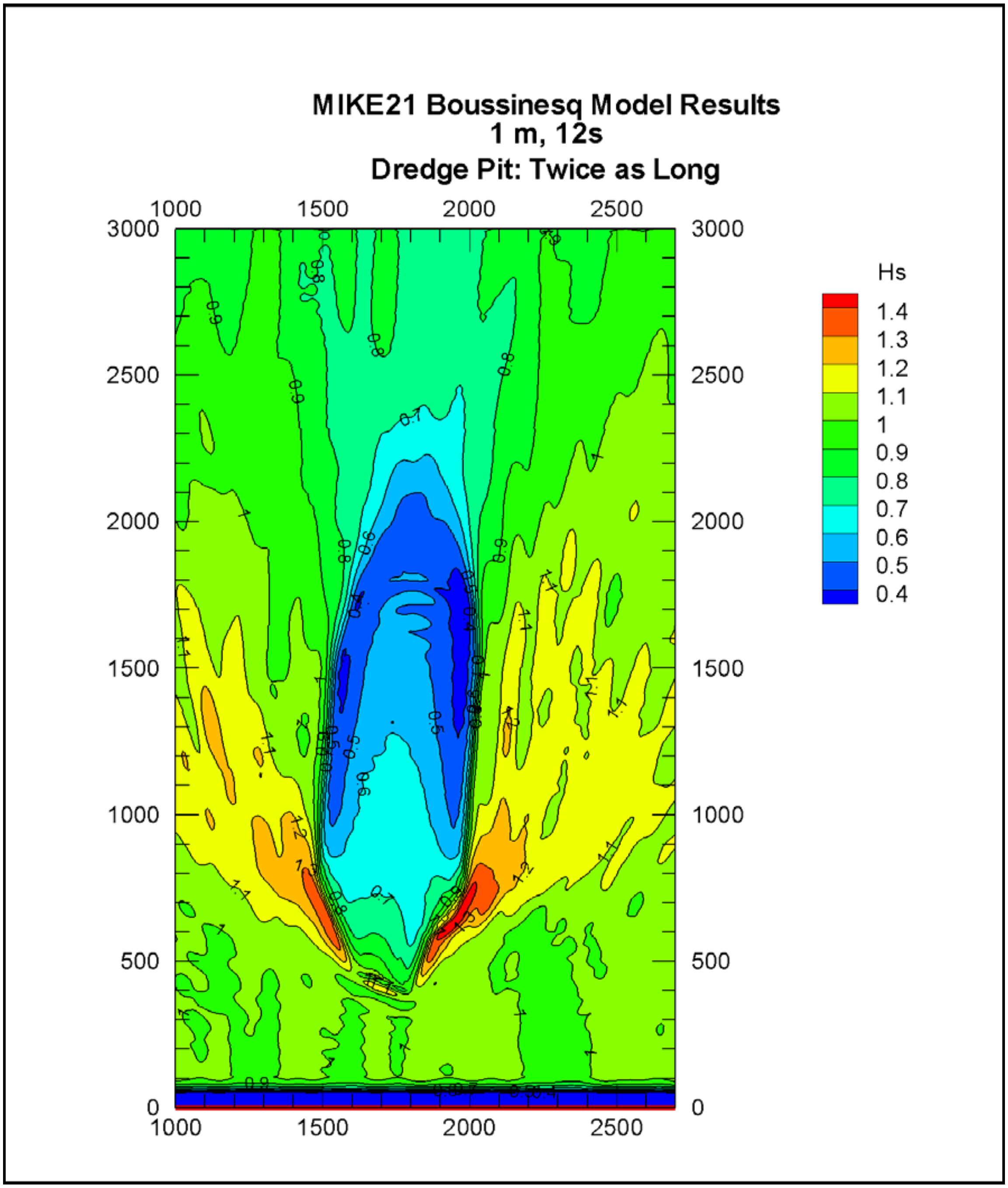

Figure 3.96 Distribution of Significant Wave Height from M21BW Results for the Twice as Long Dredge Pit (wave conditions same as Figure 3.92 and coordinates are in meters)

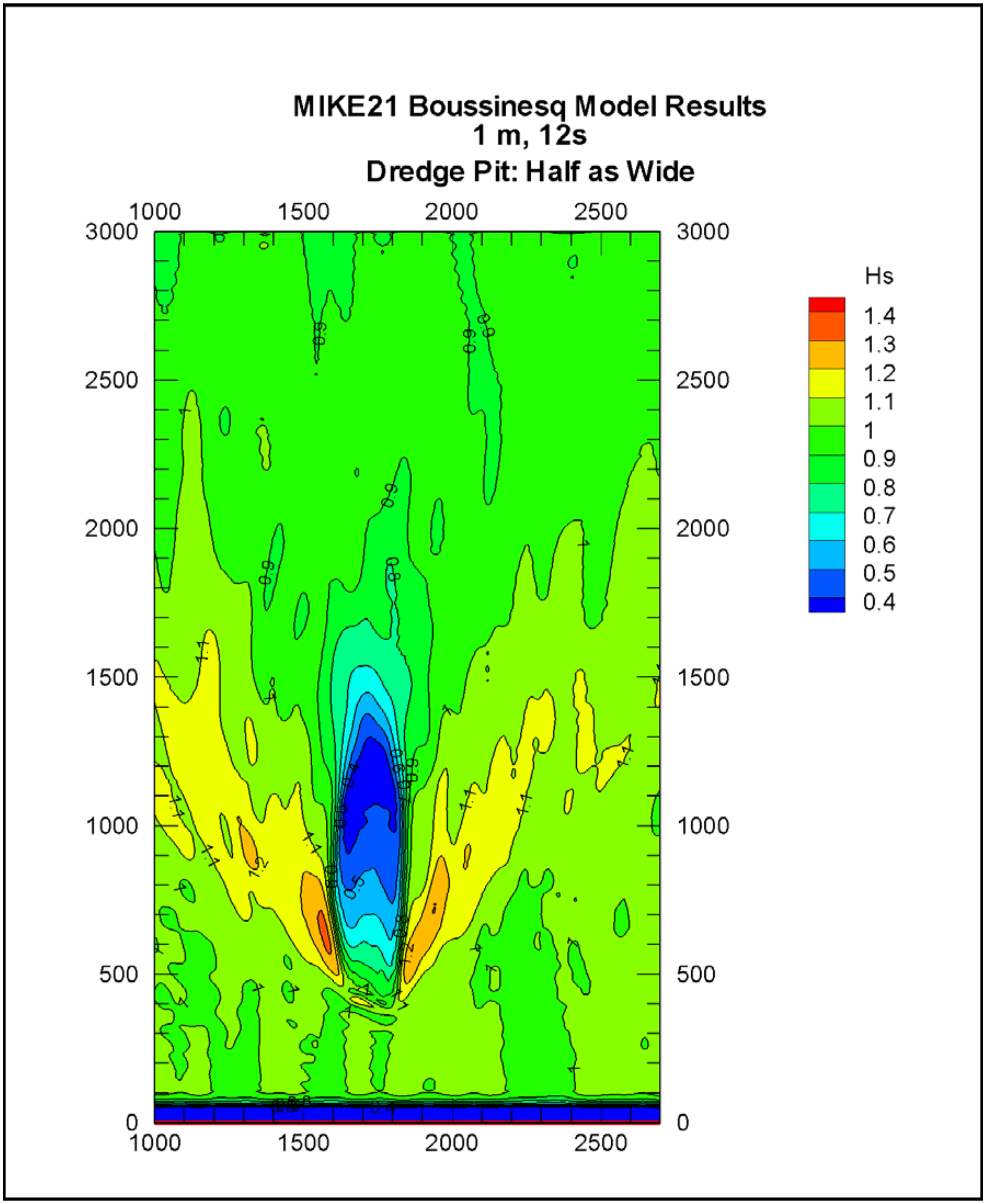

Figure 3.97 Distribution of Significant Wave Height from M21BW Results for the Half as Wide Dredge Pit (wave conditions same as Figure 3.92 and coordinates are in meters)

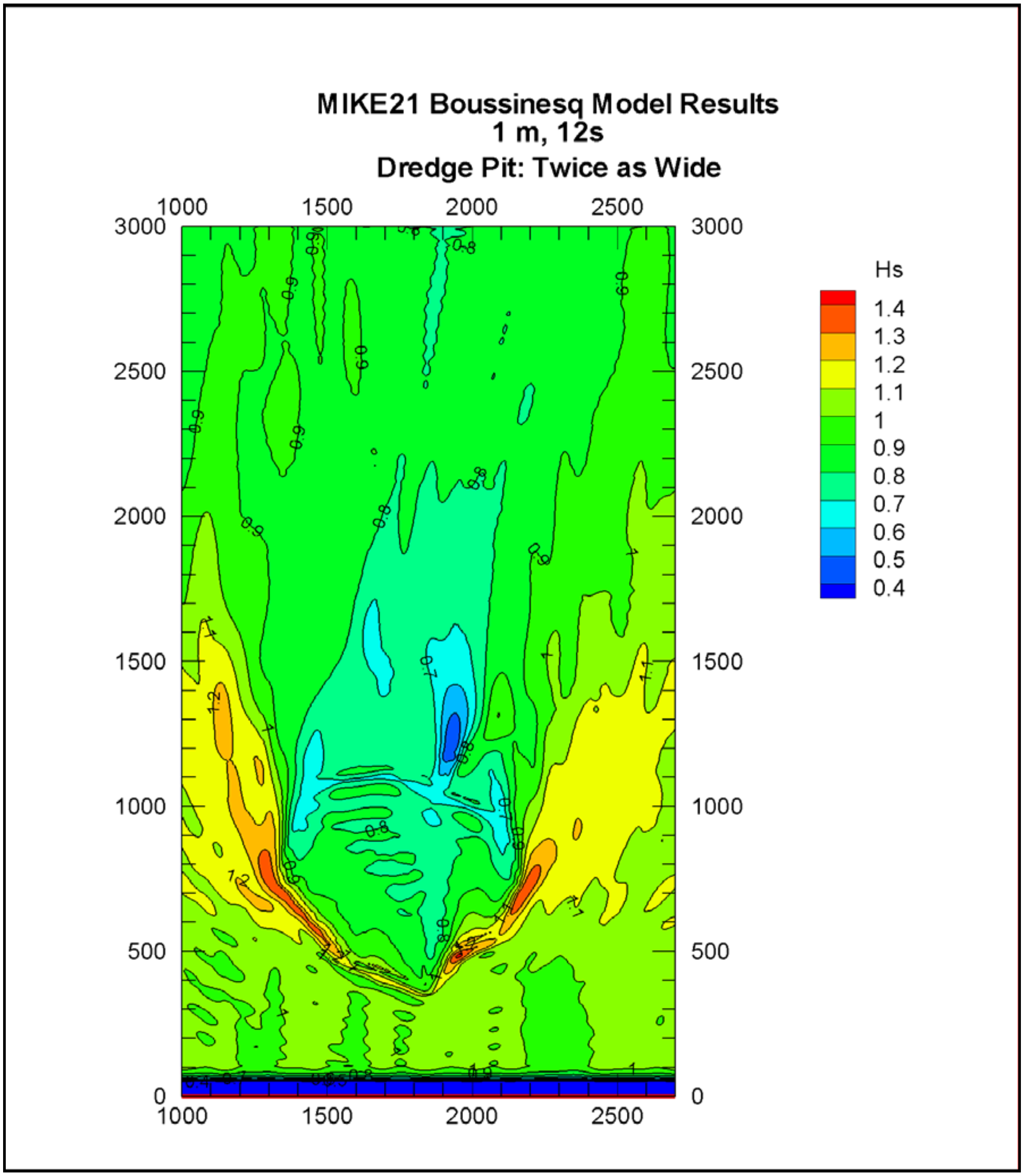

Figure 3.98 Distribution of Significant Wave Height from M21BW Results for the Twice as Wide Dredge Pit (wave conditions same as Figure 3.92 and coordinates are in meters)

3.2.3 Impact of Dredge Pits on Benthic Communities

The evolution of the impact of dredge pits on benthic communities assessed two hypotheses.

3.2.3.1 Impact of the Pit on Seabed Sediment and Water Quality

3.2.3.1.1 Sediment Sample Results

The first hypothesis (H_1) is that the seabed sediment and water quality characteristics will be different in the pit compared to the surrounding area. The three stations (1, 2 and 10) inside the pit were approximately 10 ft (3 m) deeper than the surrounding stations (Refer to Figure 3.36 for the station locations and Table 3.3 for a summary of the measurements at each station).

The sediment grain size distribution could be divided into three distinct groups (Figure 3.99, Table 3.3). Station 9, on the disposal mound, and Station 3, 180 m west of the pit, had the coarsest sediment of all the stations. Stations 4 to 7 and 11 to 12 had an intermediate grain size distribution. Station 8 and the stations within the pit (1, 2 and 10) had the finest sediment. Sediment at Station 8 contained a higher proportion of sand and silt but less clay than the stations inside the pit however.

The sediment grain size distributions for the stations in the pit (Stations 1, 2 and10) contained at least 80 % clay and less than 1 % sand and coarser sediment combined.

Sediment at all other stations outside the pit except Stations 3 and 9 contained 21 % to 69 % clay and 5 % to 55 % sand. Station 9 is located on top of a dredge disposal mound and the higher sand content is likely the result of skimming the upper surface of the sand as the last of the silt/clay cap was removed. Sediment at Stations 3 to 6 is slightly coarser than Station 7 and much coarser than Station 8. The reason for the lower proportion of fine sediments may be because Stations 3 to 6 are within the pit margin erosion zone (Nairn *et al.,* 2006).

It is however noted that the high sand content at Station 3 may also be related to this location being a dredge disposal zone. The overlying clay layer at Stations 3 to 6 has been eroded, exposing underlying sand. The reason that sediment at Stations 3, 5 and 6 is coarser than Station 4, is probably because the west side of the pit initially had a thinner layer of clay overlying the sediment than at Station 4.

The dredge pit filled in approximately 13 ft (4 m) between April 2003 and December 2004 (21 months) and 11 ft (3.5 m) between December 2004 and June 2006 (17 months). This accretion decreased the pit depth from the original 60 ft (18.5 m) to 36 ft (11 m) between April 2003 and June 2006. Lower flow velocities inside the pit favor deposition of finer sediment, which is the dominant reason why sediment inside the pit is finer than outside it. At first it seemed that the infilling of the dredge pit may be related to the two major hurricanes that hit the dredge pit within nine months prior to June 2006 sampling. Hurricanes Katrina and Rita were both category 5 strength on the Saffir-Simpson scale. While the eye of Hurricane Katrina passed within 250 miles (400 km) east of the study area in August 2005, Hurricane Rita passed directly over the study area in September 2005. During Hurricane Rita, Holly Beach was exposed to a 16 - 20 ft (5 - 6 m) storm surge and consequently suffered beach erosion and severe building destruction (Turner *et al.*, 2006; USGS, 2005). However predicted accretion rates modeled without the influence of extreme events such as hurricanes by Nairn *et al*. (2006) were similar to the actual accretion rate, as described in Section 3.2.1.1.2. Therefore, it is likely that the effects of the hurricanes on the pit were minor. Overall, the sediment inside the pit was much finer than outside of it.

3.2.3.1.2 Water Quality Sample Results

Mid-depth water column and near bed temperature, salinity and pH were similar at all stations in June 2006 (see Table 3.3). Only a single mid-water depth was sampled for water quality in March 2007. Therefore there are no bottom data for March 2007. There were minimal differences in mid-depth water quality between stations sampled in March 2007, but substantial differences between water quality in June 2006 and March 2007. In the week prior to the sampling effort in March 2007, there was excessive rainfall and freshwater inflow, which lowered the salinities in the study area to 23 ppt. The resulting increased inflow also was associated with increased dissolved oxygen and pH relative to the June 2006 samples.

The drop in temperature from around 84^{o}F (29 °C) in June 2006 to 60 ^{o}F (16 °C) in March 2007 was a combination of seasonal effects and effects of the increased inflow. Mean vertical profile dissolved oxygen concentrations in June 2006 were 0.7 - 1.1 mg l-1 lower at stations inside the pit than the rest of the stations, however bottom dissolved oxygen values inside the pit were within the range of bottom dissolved oxygen values of the undisturbed stations. However, as noted in Section 3.1.3, this was simply the result of deeper water at the pit and not an influence of the pit on dissolved oxygen levels. Near-bed dissolved oxygen concentrations both in and out of the dredge pit were between 3.0 and 3.5 mg l-1. There were no anoxic or hypoxic conditions observed.

Hypoxia episodically occurs between May and September in the northern Gulf of Mexico with peak occurrences between mid-July and mid-August (Harper *et al*., 1981; Gaston, 1985; Rabalais *et al*., 2002). It is estimated that bottom water hypoxia occurred approximately 25 % of the time in mid-summer weeks between 1985 and 2001 in the same area as this current study (Rabalais *et al*., 2002). While hypoxia was not observed in this study, there was strong dissolved oxygen stratification in June 2006, and it is likely that hypoxia does occur in the study area because it is a regional scale phenomenon. There is a high probability that a single bottom sample on a single day would not detect hypoxia in the study area. The single measurement also says nothing about the extent, intensity, duration and frequency of any hypoxic events. Overall, water quality was the same inside and outside the pit.

3.2.3.2 Impact of the Pit on Benthic Communities

The second hypothesis (H_2) is that the different physical environment in the pit compared to the surrounding area will result in significant differences in benthic macrofaunal communities. Based on species abundances, macrofauna communities in the pit were 31 % similar to the other stations outside the pit, except for Station 3, which had only 24 % similarity with any other station at Station 9, which had only 15 % similarity with any other station (Figure 3.100). Again, it is noted that the Station 9 sample was taken on top of a dredge disposal mound. Also, Station 3 had the highest influence of the coarsening effect in the pit margin erosion zone, or it also related to a localized dredge disposal mound. Only seven macrofauna species were found inside the pit, four in 2006 and five in 2007 (two occurred in samples from both years). In June 2006, the polychaete *Paraprionospio pinnata* made up over 90 % of all organisms found in the pit. However, in March 2007 this species made up only 33 % of species in the pit (Table 3.4). Inside the pit, the density of *P. pinnata* decreased from 1400 - 1600 n m^{-2} in June 2006 to 140 n m^{-2} in March 2007. The largest densities of *P. pinnata* outside the pit were Stations 4, 7 and 8 (1200 - 2200 n m^{-2}). Stations 4, 7 and 8 also had the finest sediment outside the pit of the stations sampled in 2006 (Figure 3.99). *P. pinnata* occurred in much lower densities (70 - 600 n m^{-2}) in all stations sampled in 2007 that had comparable grain size distributions (Stations 11, 12).

Table 3.3 Summary of Physical Parameters Measured at Each Station
(Mean of vertical sections for sediments and vertical profiles for water quality measures)

Station	Date sampled	Mean Rubble (%)	Mean Sand (%)	Mean Silt (%)	Mean Clay (%)	Mean Temp (EC)	Mean Salinity (psu)	Mean D.O. (mg l^{-1})	Mean pH	Bottom Temp (EC)	Bottom Salinity (psu)	Bottom D.O. (mg l^{-1})	Bottom pH	Total Depth (ft)	Total Depth (m)
1	10 Jun 2006	0.0	0.9	19.0	80.1	28.33	31.74	4.92	7.99	27.79	32.22	3.12	7.88	36.4	11.1
2	11 Jun 2006	0.0	0.3	17.3	82.4	28.36	31.74	4.99	7.99	27.73	32.23	3.11	7.87	36.3	11.1
3	11 Jun 2006	5.7	93.1	0.2	1.0	28.86	31.59	5.85	8.04	27.92	32.20	3.32	7.87	26.3	8.0
4	10 Jun 2006	0.2	26.5	18.2	55.2	28.62	31.58	5.70	8.03	27.80	32.20	3.27	7.88	26.8	8.2
5	11 Jun 2006	15.8	54.5	8.7	21.0	28.71	31.57	5.81	8.04	27.91	32.20	3.30	7.87	27.1	8.3
6	11 Jun 2006	10.0	42.1	10.5	37.3	28.81	31.71	5.98	8.04	27.91	32.20	3.30	7.87	26.2	8.0
7	10 Jun 2006	0.3	18.0	16.8	64.9	28.76	31.60	5.71	8.03	27.84	32.22	2.98	7.84	26.0	7.9
8	10 Jun 2006	0.5	5.3	25.7	68.5	28.62	31.48	5.88	8.05	27.93	32.12	3.45	7.89	26.3	8.0
9	04 Mar 2007	8.1	89.1	1.4	1.5	16.06	22.87	11.11	8.26	-	-	-	-	22.0	6.7
10	04 Mar 2007	0.1	0.3	19.8	79.8	16.04	22.91	11.06	8.38	-	-	-	-	35.6	10.9
11	04 Mar 2007	4.6	36.0	15.3	44.0	15.98	23.07	10.74	8.33	-	-	-	-	28.5	8.7
12	04 Mar 2007	2.1	24.7	16.8	56.4	16.00	22.99	11.10	8.42	-	-	-	-	28.5	8.7

(Temp = temperature, D.O. = dissolved oxygen)

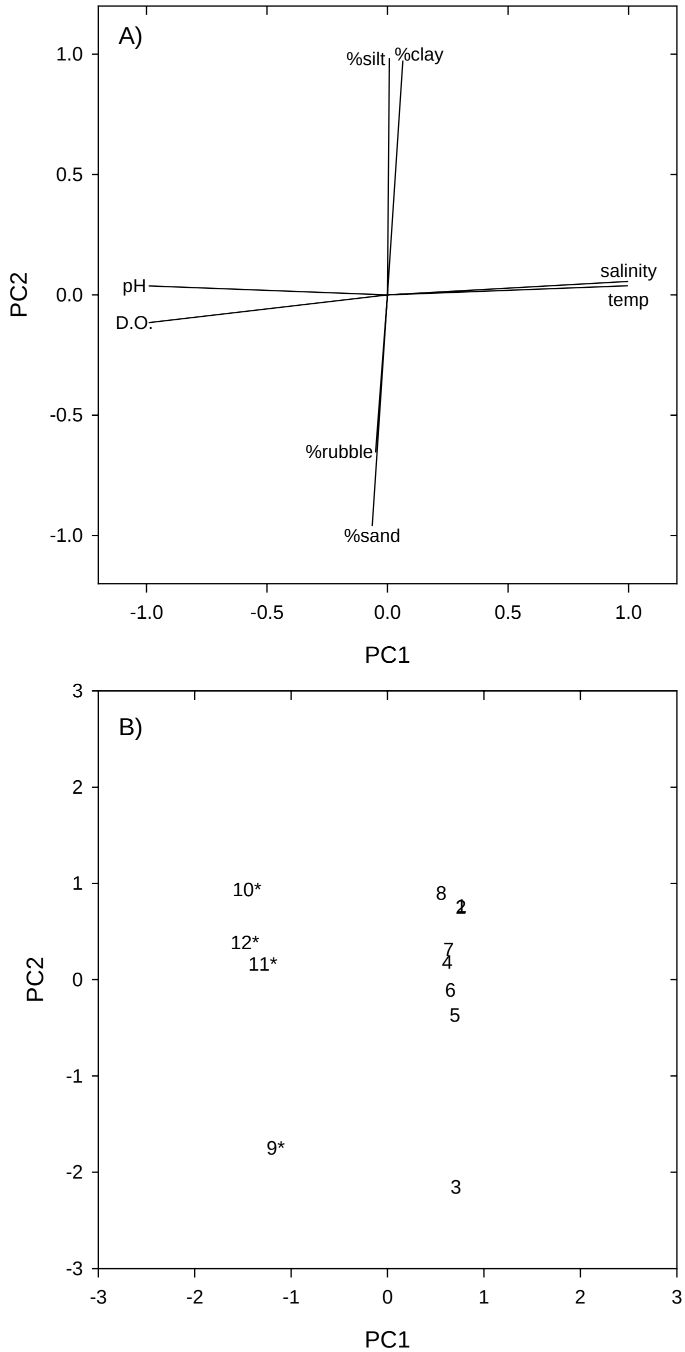

Figure 3.99 Plots of the First Two Principal Components (PC) Resulting from Analysis of Sediment Data
A) PC variable loadings and B) PC station cores
(D.O. = Dissolved Oxygen, *denotes that station was sampled on March 2007 rather than June 2006)

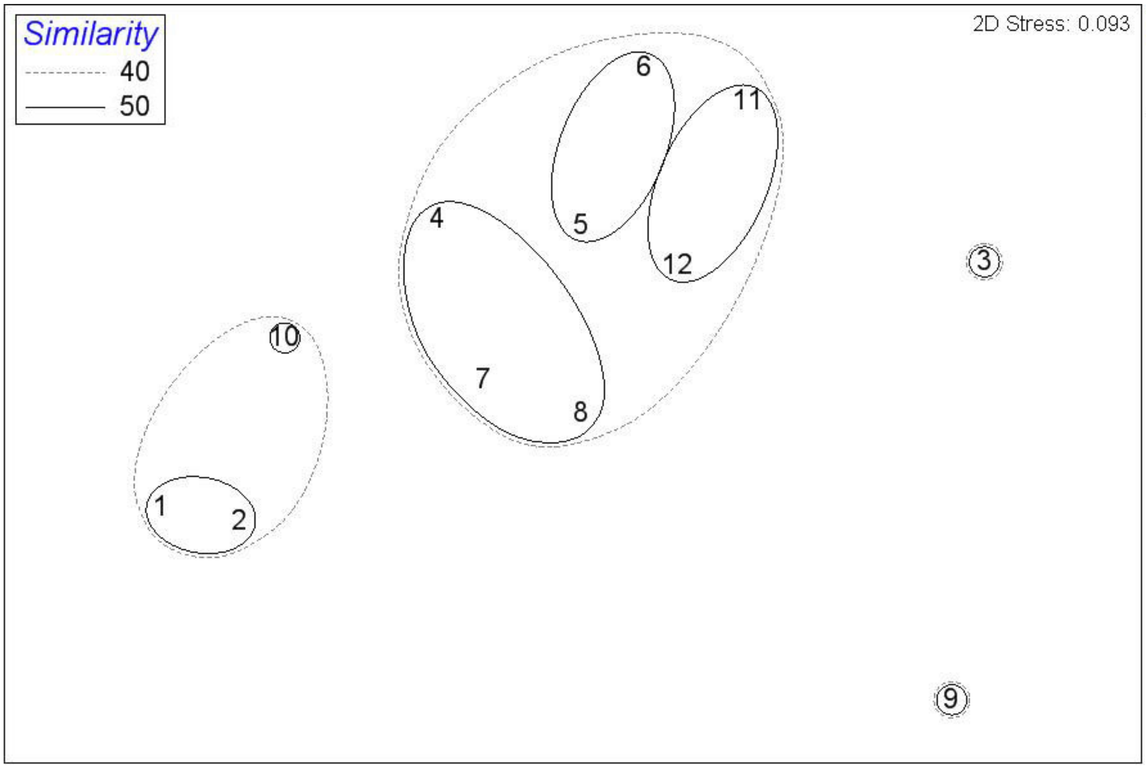

Figure 3.100 Non-Metric Multi-Dimensional Scaling Analysis of Species Abundances at Each Station

Table 3.4 Species Abundance for Each Station and as an Overall Mean (Abundances are in n m $^{-2}$)

Species name	Taxa	Station												Mean	Mean as	Cum. %
		1	2	3	4	5	6	7	8	9	10	11	12		%	
Mediomastus ambiseta	P	0	57	0	2,950	10,835	11,459	2,212	1,985	0	0	2,978	6,027	3,209	46.8	46.8
Paraprionospio pinnata	P	1,588	1,418	170	1,418	624	794	2,212	1,191	0	142	71	567	850	12.4	59.2
Spiophanes bombyx	P	0	0	1,135	0	0	0	0	0	0	0	4,609	213	496	7.2	66.5
Magelona phyllisae	P	0	0	0	0	2,042	454	57	57	71	0	1,347	496	377	5.5	72.0
Nemertinea (unidentified)	N	0	0	340	113	908	794	57	170	355	0	213	71	252	3.7	75.7
Cossura delta	P	0	0	57	340	511	340	57	113	0	71	496	851	236	3.5	79.1
Ampharete parvidentata	P	0	0	0	0	57	0	0	0	0	71	780	1,135	170	2.5	81.6
Phoronis architecta	O	0	0	57	0	57	227	0	0.00	496	0	1,064	71	164	2.4	84.0
Sigambra tentaculata	P	57	57	0	340	284	227	113	170	0	71	213	355	157	2.3	86.3
Hobsonia florida	P	0	0	0	0	0	0	0	0	0	0	0	1,773	148	2.2	88.5
Mulinia lateralis	M	0	0	57	0	0	57	0	0	0	0	851	71	86	1.3	89.7
Glycinde solitaria	P	0	0	0	57	284	170	57	0	0	71	71	71	65	0.9	90.7
Tellina sp.	M	57	0	0	0	284	227	0	0	0	0	142	0	59	0.9	91.5
Polinices duplicatus	M	0	0	0	0	0	0	0	0	0	0	496	0	41	0.6	92.1
Diopatra cuprea	P	0	0	0	0	113	340	0	0	0	0	0	0	38	0.6	92.7
Ancistrosyllis sp.	P	0	0	0	0	0	57	0	0	0	0	284	0	28	0.4	93.1
Oligochaetes (unidentified)	P	0	0	0	57	0	57	0	227	0	0	0	0	28	0.4	93.5
Oxyurostylis sp.	C	0	0	0	57	0	0	0	0	0	0	213	71	28	0.4	93.9
Apoprionospio pygmaea	P	0	0	284	0	0	0	0	0	0	0	0	0	24	0.3	94.3
Oweniidae (unidentified)	P	0	0	0	0	0	0	0	0	0	0	284	0	24	0.3	94.6
Gastropoda (unidentified)	M	0	0	0	0	0	0	57	0	0	0	213	0	22	0.3	94.9
Sthenelais sp.	P	0	0	113	0	0	0	0	57	0	0	0	71	20	0.3	95.2
Anaitides longipes	P	0	0	57	0	0	170	0	0	0	0	0	0	19	0.3	95.5
Mysella planulata	M	0	0	0	0	0	0	0	0	0	0	71	142	18	0.3	95.8
Solen viridis	M	0	0	0	0	0	0	0	0	0	0	213	0	18	0.3	96.0
Gyptis vittata	P	0	0	0	0	0	0	0	0	0	0	142	71	18	0.3	96.3
Paguridae juv.	C	0	0	57	0	0	0	0	0	0	0	142	0	17	0.2	96.5

Species name	Taxa	Station												Mean	Mean as	Cum. %
		1	2	3	4	5	6	7	8	9	10	11	12		%	
Bivalvia (unidentified)	M	0	0	57	0	0	113	0	0	0	0	0	0	14	0.2	96.7
Ampelisca abdita	C	0	0	0	0	57	113	0	0	0	0	0	0	14	0.2	96.9
Ophiuroidea (unidentified)	OP	0	0	0	57	0	113	0	0	0	0	0	0	14	0.2	97.2
Lumbrineridae (unidentified)	P	0	0	0	0	0	57	0	0	0	0	0	71	11	0.2	97.3
Turbellaria (unidentified)	O	0	0	0	57	57	0	0	0	0	0	0	0	9	0.1	97.4
Syllis sp.	P	0	0	0	0	57	0	0	57	0	0	0	0	9	0.1	97.6
Trachypenaeus constrictus	C	0	0	0	0	0	113	0	0	0	0	0	0	9	0.1	97.7
Calappidae (unidentified)	C	0	0	57	0	0	57	0	0	0	0	0	0	9	0.1	97.9
Malmgreniella taylori	P	0	0	0	0	0	0	0	0	0	0	71	0	6	0.1	97.9
Pseudeurythoe sp. A	P	0	0	0	0	0	0	0	0	0	0	71	0	6	0.1	98.0
Amphinomidae (unidentified)	P	0	0	0	0	0	0	0	0	0	0	71	0	6	0.1	98.1
Aglaophamus verrilli	P	0	0	0	0	0	0	0	0	0	0	71	0	6	0.1	98.2
Polydora websteri	P	0	0	0	0	0	0	0	0	0	0	71	0	6	0.1	98.3
Scolelepis squamata	P	0	0	0	0	0	0	0	0	71	0	0	0	6	0.1	98.4
Tharyx sp.	P	0	0	0	0	0	0	0	0	0	0	0	71	6	0.1	98.5
Echiuridae (unidentified)	O	0	0	0	0	0	0	0	0	0	0	71	0	6	0.1	98.5
Anthozoa (unidentified)	O	0	0	0	0	57	0	0	0	0	0	0	0	5	0.1	98.6
Nassarius sp.	M	0	0	0	0	0	0	0	57	0	0	0	0	5	0.1	98.7
Nuculana sp.	M	0	0	0	0	0	0	0	57	0	0	0	0	5	0.1	98.8
Malmgreniella sp.	P	0	0	0	0	0	57	0	0	0	0	0	0	5	0.1	98.8
Paleanotus chrysolepis	P	0	0	0	0	0	57	0	0	0	0	0	0	5	0.1	98.9
Paleanotus sp.	P	0	0	0	0	57	0	0	0	0	0	0	0	5	0.1	99.0
Eurythoe sp.	P	0	0	0	57	0	0	0	0	0	0	0	0	5	0.1	99.0
Ancistrosyllis papillosa	P	0	0	0	0	57	0	0	0	0	0	0	0	5	0.1	99.1
Pilargiidae (unidentified)	P	0	0	0	0	0	0	57	0	0	0	0	0	5	0.1	99.2
Podarke obscura	P	0	0	57	0	0	0	0	0	0	0	0	0	5	0.1	99.2
Websterinereis tridentata	P	0	0	0	0	0	57	0	0	0	0	0	0	5	0.1	99.3
Laeonereis culveri	P	0	0	0	0	0	57	0	0	0	0	0	0	5	0.1	99.4
Nereidae (unidentified)	P	0	0	0	0	0	57	0	0	0	0	0	0	5	0.1	99.4
Dorvillea sp.	P	0	0	0	57	0	0	0	0	0	0	0	0	5	0.1	99.5

Species name	Taxa	Station												Mean	Mean as	Cum. %
		1	2	3	4	5	6	7	8	9	10	11	12		%	
Maldanidae (unidentified)	P	0	0	0	0	0	57	0	0	0	0	0	0	5	0.1	99.6
Sabellidae (unidentified)	P	0	0	0	0	0	0	0	57	0	0	0	0	5	0.1	99.7
Callianassa biformis	C	0	0	0	0	57	0	0	0	0	0	0	0	5	0.1	99.7
Pinnixa sp.	C	0	0	57	0	0	0	0	0	0	0	0	0	5	0.1	99.8
Oxyurostylis smithi	C	0	0	0	0	57	0	0	0	0	0	0	0	5	0.1	99.9
Corophium sp.	C	0	0	0	0	0	57	0	0	0	0	0	0	5	0.1	99.9
Listriella sp.	C	0	0	57	0	0	0	0	0	0	0	0	0	5	0.1	100.0
Total		1,702	1,532	2,609	5,559	16,451	16,338	4,879	4,198	993	425	15,317	12,197	6,850	100	
Total number of species		3	3	15	12	19	27	9	12	4	5	27	18	12.8		

Taxa groups: P = polychaete, N = nemertean, M = mollusk, C = crustacean, OP = ophiuroid, O = other

Tellina sp. was the only mollusk found within the pit and was only found in one sample. The polychaete *Mediomastus ambiseta* occurred in high densities (2,000 - 11,000 n m^{-2}) in all stations outside the pit regardless of sample date except for Stations 3 and 9 where none of the species were found. *M. ambiseta* was found in very low densities (0 - 57 n m^{-2}) inside the pit. In a previous study located within 3.1 – 6.2 miles (5 - 10 km) of the current study, *M. californiensis* (probably misidentified *M. ambiseta* specimens) was found to be sensitive to hypoxia (Gaston, 1985). This may support the possibility that the pit experienced more hypoxia or anoxia than the surrounding unexcavated area. However, Mannino and Montagna (1997) found that *M. ambiseta* was more abundant in sandier sediments than other sediment sizes, so the absence of *M. ambiseta* in the pit could be a result of a different sediment size distribution. The macrofaunal community in this current study relates most with the combination of silt and clay concentrations in the sediment and station depth (Table 3.5). Overall, macrofauna communities are different inside the pit, correlating with the change in sediment size rather than from hypoxia or any other water column variable. Differences at Stations 3 and 9 outside the pit (where sediment likely became coarser either directly (dredge disposal zone) or indirectly (pit margin erosion)) can also be attributed to the dredging project.

Table 3.5 Environmental Variables that Correlated Highest with Macrofaunal Communities as Determined by the BIO-ENV Procedure (The highest correlation had a significant level of p = 0.001)

No. Of Variables	Pearson Correlation (Δ_w)	Variables Selected
4	0.720	Sand, Silt, Clay, Dissolved Oxygen
1	0.719	Sand
4	0.714	Sand, Silt, Clay, Salinity
2	0.713	Sand, Clay
4	0.710	Sand, Silt, Clay, Temperature
3	0.707	Sand, Silt, Clay
1	0.703	Clay
3	0.699	Sand, Clay, Dissolved Oxygen
2	0.696	Sand, Silt
5	0.694	Rubble, Sand, Silt, Clay, Dissolved Oxygen

There are two broad mechanisms in which benthic macrofauna populations can become reestablished after a disturbance such as the creation of a dredge excavation pit: 1) lateral encroachment of individuals from the surrounding environment; and 2) recruitment of larvae (adapted from Sousa, 2001). The individuals of the one dominant species inside the pit, *P. pinnata*, were similar in size to individuals outside the pit; therefore recent recruitment of larvae in the pit is not apparent. Initial mechanisms of recruitment to the pit cannot be determined because not enough sampling events occurred over time; however, any recent population increases, if any, will have come from lateral encroachment from the area surrounding the pit. The species present inside the pit were a subset of the species present outside the pit. This means that the change in community structure in the pit was caused by a loss of species rather than by replacement of a different set of species and the source of the pit fauna was immigration or recruitment from the surrounding area. The "loss" of species likely relates to that subset of benthic species that are unable to survive the high sedimentation rates in the pit.

Based on macrofaunal biomass of each taxon, there was a 74 % difference (26 % similarity) between communities inside and outside of the pit (Figure 3.101). The stations in the pit contained organisms from only 1 or 2 taxa compared to 3 to 6 taxa at all other stations (Table 3.6). Polychaetes were still the most dominant taxa by weight at all stations except Station 9 on top of the dredge disposal mound. The total biomass at Station 9 was comprised of only 28.6 % compared with 53.6 - 100 % at all other stations. The greatest proportion of polychaetes biomass relative to the total biomass was inside the pit, at Stations 1, 2 and 10 (99.6 - 100 %).

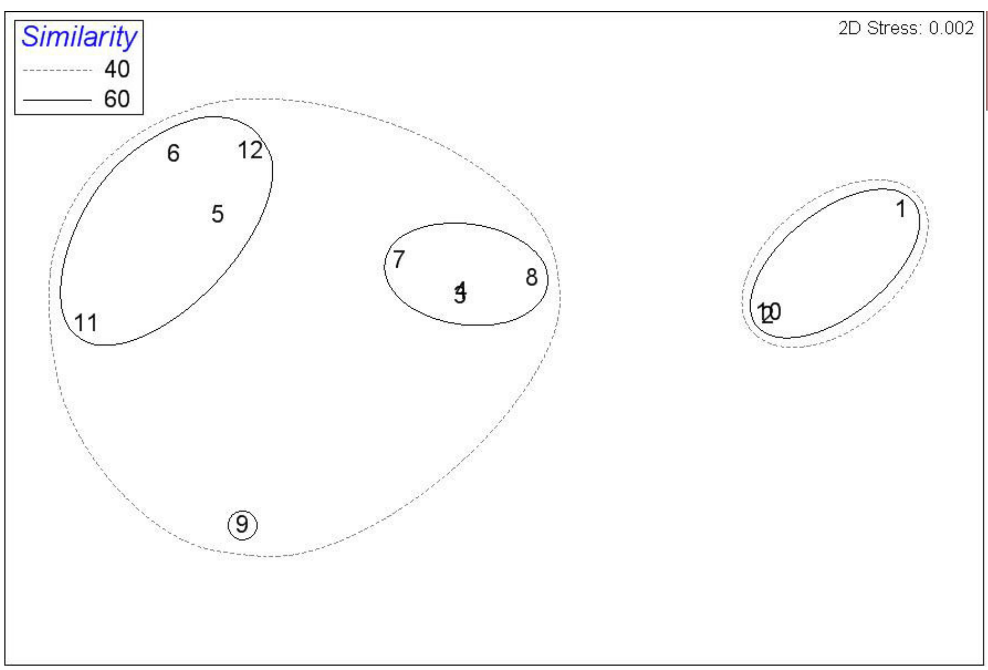

Figure 3.101 Non-Metric Multi-Dimensional Scaling Analysis of Biomass of Each Taxa at Each Station
(Samples 3 and 4 lay on top of one another, as do samples 2 and 10)

Table 3.6 Abundance and Biomass of Each Major Taxa

Taxa	Station												Mean	Mean
	1	2	3	4	5	6	7	8	9	10	11	12		as %
Abundance (n m^2)														
Polychaete	1,645	1,532	1,872	5,219	14,919	14,295	4,765	3,801	142	425	11,629	11,771	6,001	88.0
Nemertean	0	0	340	113	908	851	57	170	0	0	1,985	142	262	3.8
Mollusc	57	0	113	0	284	397	57	113	355	0	213	71	256	3.8
Crustacean	0	0	227	57	170	340	0	0	496	0	1,135	71	184	2.7
Other	0	0	57	57	170	227	0	0	0	0	355	71	102	1.5
Ophiuroid	0	0	0	57	0	113	0	0	0	0	0	0	14	0.2
Total	1,702	1,532	2,609	5,503	16,451	16,224	4,879	4,084	993	425	15,317	12,126	6,820	100.0
% Polychaetes	96.7	100.0	71.7	94.8	90.7	88.1	97.7	93.1	14.3	100.0	75.9	97.1		
Biomass (g m^2)														
Polychaete	0.13	0.26	0.96	1.06	5.45	7.34	1.57	0.66	1.42	0.25	4.88	3.22	2.27	73.2
Mollusc	0.00	0	0.01	0	0.00	0.84	0.00	0.01	0.93	0	3.77	0.01	0.40	12.8
Nemertean	0	0	0.10	0.00	0.19	0.07	0.02	0.03	2.62	0	0.20	0.02	0.27	8.7
Crustacean	0	0	0.03	0.00	0.08	0.1	0	0	0	0	0.14	0.60	0.14	4.4
Other	0	0	0.00	0.00	0.00	0.0	0	0	0	0	0.10	0.01	0.03	0.8
Ophiuroid	0	0	0	0.00	0.00	0.0	0	0	0	0	0.00	0.00	0.00	0.0
Total	0.1	0.3	1.1	1.1	5.7	8.4	1.6	0.7	5.0	0.3	9.1	3.9	3.1	100.0
% Polychaetes	99.6	100.0	87.1	99.3	95.2	87.6	98.6	93.3	28.6	100.0	53.6	83.3		

The stations inside the pit had lower total biomass and N1 diversity than any other station outside the pit, although this relationship was only significant with some of the stations outside of the pit (Table 3.7). Abundance was also lower inside the pit, with the exception of Station 9, on the disposal mound, which had the second lowest total abundance. The lower abundance and diversity in fine sediments compared with sandy sediments is consistent with estuarine studies in a Texas estuary (Mannino and Montagna, 1997). The comparatively low abundance, biomass and diversity are also typical of a disturbed area (Pearson and Rosenberg, 1978; Gaston, 1985; Montagna *et al*., 2002; Palmer *et al.*, 2002; Balthis, 2006). The constant accretion of sediment of approximately 8 ft yr^{-1} (2.4 m yr^{-1}) inside the dredge pit since excavation in April 2003, in addition to any possible hypoxic events that may occur, will hinder the succession of the macrofaunal community (Rhoads *et al*., 1978, Peterson, 1985). The disposal mound at Station 9 is probably subject to greater erosion rates than the surrounding area because it protrudes above the rest of the sea floor. Elevated erosion rates will have a similar effect on macrofauna communities as other disturbances such as accretion or hypoxia.

Macrofaunal communities recovered within 30 months of dredging in a series of meter-deep South Carolina dredge pits (Jutte *et al.,* 2002). The original pit excavation depth in the present study was 10 times deeper than the South Carolina depths described in Jutte *et al.* (2002); therefore, it is understandable that the recovery was not as rapid. This greater depth will require a longer stabilization and physical recovery time. At the current rate of sedimentation, the pit should be filled up within 1.3 years, however the accretion rate is predicted to slow so that the dredge pit will not be totally full until 2010 or 2011 (Nairn *et al*., 2006).

Thirty-eight months after excavation (April 2003 - June 2006), the excavation pit is still physically and biologically different from the surrounding area. Although water quality appeared to be very similar inside and outside the pit at the time of sampling, the water column is temporally dynamic, and a survey over time would be required to prove that water quality played no vital role in the differences in macrofaunal communities. The sediment inside the pit is finer in size and softer than the sediment well beyond the influence of the pit, but is most different from the sediment located at the periphery of the pit, the pit margin erosion zone. The difference in sediment size between inside and outside of the pit correlated strongly with macrofaunal community differences in the study area. The high accretion rates occurring in the pit are deleterious to many organisms. Predicted reduced accretion rates should allow larger numbers and a higher diversity of organisms to settle and survive in the pit. The macrofaunal community inside the pit is not likely to recover until the sediment inside the pit is similar to that occurring outside the pit and any accretion events are similar to the background roles for areas beyond the influence at the pit.

Table 3.7 Analysis of Variance and Tukey Grouping for N1 Diversity, Biomass and Abundance at Each Station (All analyses were carried out using log transformed data)

Source	Degrees of Freedom	Type III Sum of Squares	Mean Square	F Value	Pr > F
Abundance (n m^{-2})					
Station	11	148.439	13.494	4.95	<0.0001
MS(Error)	44	119.902	2.725		
Biomass (g m^{-2})					
Station	11	24.399	2.218	6.71	<0.0001
MS(Error)	44	14.549	0.331		
Diversity (N1)					
Station	11	159.379	14.489	11.24	<0.0001
MS(Error)	44	56.714	1.289		

Abundance												
Mean (n m^{-2})	16,451	16,224	15,315	12,197	5,503	4,879	4,084	2,609	1,532	1,702	993	425
Station	5	6	11	12	4	7	8	3	2	1	9	10
Tukey groups												
Biomass												
Mean (g m^{-2})	9.11	8.38	3.87	5.72	4.98	1.60	1.10	1.07	0.71	0.26	0.25	0.13
Station	11	6	12	5	9	7	3	4	8	2	10	1
Tukey groups												
N1 Diversity												
Mean	7.69	4.28	4.06	3.87	3.61	3.54	3.31	2.60	1.63	1.50	1.22	1.02
Station	11*	12*	3	4	5	6	8	7	9*	10*	2	1
Tukey groups												

MS=mean square, *only 4 replicates taken at this station

3.2.4 Impact of Dredge Pit on Mobile Invertebrate Production and Demersal Fish

The most applicable approach to estimate how decreases in benthic biomass will affect demersal fish and mobile invertebrates is the bioenergetic method proposed by French McCay and Rowe (2003). The method requires several parameters be estimated: 1) decrease in benthic production per unit area, 2) the total area affected, 3) the expected time to no impact is apparent (recovery rate), and 4) a bioenergetic efficiency (or trophic efficiency).

For the Holly Beach dredge pit study, we can estimate the decrease in production per unit area utilizing data from Montagana and Palmer (2007). The study measured benthic community structure 38 months after the dredging of buried sand from a mud capped borrow pit. Eight stations were sampled: two sampling stations were located within the pit (Stations 1, 2 and 10), two 65 ft (20 m) from the pit edge (Stations 4 and 5), one 330 ft (100 m) away from the pit edge (Station 6), one 650 ft (200 m) from the pit edge (Station 3), and two at least 0.6 mile (1 km) from the edge of the pit (Stations 7 and 8). An additional four stations were sampled 47 months after pit exacavation: three were situated outside the pit at distance of 230 ft (70 m) (on a disposal mound), 330 ft (100 m) and 720 ft (220 m) and one inside (Station 10) the excavation pit.

Macrobenthic samples were taken at each station, along with hydrographic measurements in the water column and sediment samples. Using the average biomass at Stations 3, 6, 7, 8, 11 and 12 as the reference value for a non-dredged area and the average biomass at Stations 1, 2 and 10 as the value for dredged sites, the average decrease in benthic biomass resulting from the pit was 94 % or 3.78 g m^{-2}. Using the highest and lowest value we can quantify the range of potential benthic degradation. The minimum decrease in biomass is estimated at 57.2 % or 0.4 g m^{-2} (using 0.3 g m^{-2} at Station 2 or 10 and 0.7 g m^{-2} at Station 8) and the maximum at 99 % or 9.0 g m^{-2} (using 0.1 g m^{-2} at Station 1 and 9.1 g m^{-2} at Station 11). Because biomass represents only a measure of current standing stock, biomass would underestimate the degree to which prey is reduced for demersal consumers. Production (P), which takes into account future growth and mortality, can be estimated from standing biomass (B) if there is some prior knowledge of both growth (G) and mortality rates (Z) (Kneib, 2003). These vital rates can be related to production with the equation $P = GB \{(e^{G-Z} - 1)/(G-Z)\}$. Several published estimates of the P/B relationship exist for benthic macrofauna. Applying a P/B ratio of 2.2 yr^{-1} (based on 120 studies that reported polychaete P/B ratios in Cusson and Bourget, 2005, and averaging those that were conducted in mud/sand environments), the potential loss of prey can be expressed as an annual estimate: average = 8.3 g m^{-2} yr^{-1} with a range of 0.9 g m^{-2} yr^{-1} to 19.8 g m^{-2} yr^{-1}.

For the second data requirement, the total area affected, surveys of the borrow pit can be used to estimate the spatial extent of disturbance. Total surface area of the excavated pit was 190,600 m^2 (Steve Langendyk, pers. comm). Multiplying by the estimate of benthic production loss, the average loss is 1,582 kg yr^{-1} with a range of 172 to kg yr^{-1} to 3,774 kg yr^{-1}.

Estimating the recovery rate of the benthic community to pre-dredge or reference site values will allow determination of the total loss over multiple years. In their study, Montagana and Palmer (2007) reported decreased abundance, biomass and diversity of benthic infauna within the Holly Beach dredge pit after 38 and 47 months. The original pit was dredged to a depth of 50 to 60 ft (15 to 18 m) beneath the sediment surface in April 2003. Post-dredge bathymetry collected 20 months later reported a pit depth of 48 ft (14.6 m) and 38 ft (11.6 m) by June 2006. Based on these observed filling rates and the application of the MISED 3D numerical model, Nairn *et al*. (2006) predicted complete filling of the pit between 2010 and 2011. If we assume that total recovery of the benthic community will occur when the pit is filled, then the recovery time should be approximately 9 yrs. On the other hand, this may represent an underestimate of the recovery time because sufficient time will need to elapse for physical sorting of surficial pit sediments to match the pre-existing sediment condition. Montagana and Palmer (2007) noted difference in sediment types between samples collected within the pit and those collected from reference Stations 7 and 8. The pit sediment had a clay content of at least 80 % and was very soft, whereas the reference station clay content was 64.9 to 68.5 % and the sediment was much more firm. If we assume another 2 years are required for sorting of sediments to match pre-dredge or reference area sediment grain sizes, the recovery time is 11 years (again, this is likely conservative for the same reasons explained above). Applying this recovery time to our annual estimate of lost benthic invertebrate production gives a total average loss from the time of dredging of 17,402 kg with a range of 1,892 to 41,415 kg. The wide range in estimated values of lost benthic production is a result of the spatial variability in sediment type; therefore, the average represents a reasonable estimate of lost production (i.e. the variability is not due to unexplained scatter, and thus uncertainty in the results).

The loss of benthic invertebrate production can be expressed in terms of the subsequent higher trophic level (potential lost of demersal fish and mobile invertebrate) by multiplying the lost benthic invertebrate production by ecological or trophic transfer efficiency. Estimates of ecological efficiency, predator production per unit production of prey, for fish and mobile invertebrate predators feeding on invertebrate prey, range from 3 – 30 % (French McCay and Rowe, 2003). Ecological efficiency of 10 % is the most commonly applied value (Pauly & Christensen, 1995; ECOPATH). Taxonomic (fish vs. non-insect invertebrate) and size differences are key factors in explaining variability in trophic efficiency. Efficiencies are generally higher for non-insect invertebrates than for fish and higher for smaller fish than larger fish. Based on their review of ecological efficiencies, French McCay and Rowe (2003) applied a value of 20 % for invertebrates and fish < 200 g. They used an efficiency of 10 % for fish between 200 and 1000 g and 4 % for fish > 1000 g. Based on a review of the NMFS SEMAP trawl survey in this area of the Gulf of Mexico, the majority of predators on the polychaete prey base are most likely invertebrates (shrimp and crabs) and juvenile fish (< 200 g). Consequently, the efficiency of 20 % is probably more reflective of this predator community. Applying this value to the calculated lost benthic invertebrate production, the average loss of demersal fish and invertebrate production is estimated at 3,480 kg (0.2 x 17, 402 kg) with a range of 378 to 8,283 kg over an 11-year recovery period (again, considering the 11-year recovery period is likely conservative). On an annual basis the average demersal fish and invertebrate production lost would be 316 kg yr^{-1}.

The estimated loss of benthic production and subsequent bioenergetic calculations for equivalency to demersal fish and mobile invertebrates derived from the above data make several assumptions that affect the magnitude of loss. First and foremost, this estimate assumes that all benthic invertebrate production would have been consumed by predators. Although 100 % loss to predators is high, benthic invertebrates in soft-sediment habitats that lack structural refuge have been documented to experience extremely high predation rates (e.g., Olafsson *et al*., 1994). Field and tethering experiments conducted in nearshore areas often demonstrate 90-100 % mortality (e.g., Summerson and Peterson, 1984; Heck *et al*., 2003). Hypoxic conditions, which appear in the Holly Beach dredge pit area, approximately once every four years (Rabalais *et al*. 2002; Montagana and Palmer, 2007), would cause considerable mortality and prevent transfer of some fraction of the annual benthic invertebrate production to higher trophic levels (Baird *et al*. 2004; Powers *et al*., 2005). Consequently, some fraction of this benthic invertebrate production would be lost periodically whether the pit was dredged or not. A second assumption is that the level of benthic prey reduction is constant throughout the recovery process. It is plausible that biomass may increase over time within the pit as the pit continues to fill reaching values near the reference station prior to complete infilling. This potential overestimate of benthic invertebrate prey loss in later years of the recovery period is balanced to some degree by applying the value measured at 38 – 47 months to the annual loss of prior years. A critical assumption of this analysis is that predators realize a decrease in food consumption as a result of the loss of benthic invertebrate prey in the excavated pit. Because these demersal predators are mobile, they have the ability to forage in nearby unaffected areas. The assumption that this migration would result in increased densities of predators in surrounding, unaffected areas and hence decreased prey availability for the community is one that needs to be further explored. Studies documenting a similar negative growth response of estuarine demersal fish to benthic defaunation caused by hypoxia provide support for this assumption (Eby and Crowder, 2002; Eby *et al*., 2005; Powers *et al*., 2005).

Finally, the estimate of lost benthic production does not compensate the public for the delay in restoring complete functionality of the habitat. In a compensatory context, a discounting factor (usually 3 % annually, French McCay and Rowe, 2003) would be used to compensate for this delay and uncertainty in recovery estimates. Application of this discounting factor has substantial implications on recommendations for pit dredging. Figure 3.102 illustrates lost of production over time with and without the application of the discounting factor. If discounting were used to adjust for the delay in recovery, then shallow pits, even over a greater surface area would be preferential to deeper pits over a smaller surface area because of the longer time necessary for full recovery.

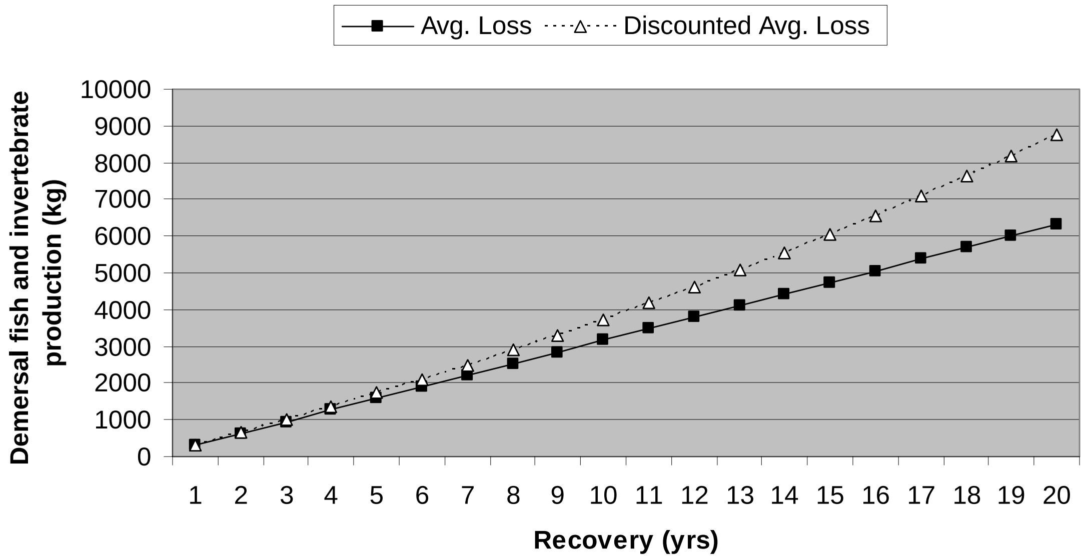

Figure 3.102 Cumulative Estimated Loss of Demersal Fish and Invertebrate Production Resulting from Loss of Benthic Invertebrate Production within the Holly Beach Dredge Pit (Recovery time is estimated at 9-11 years, although a wide range is included for illustration)

The average annual estimate of lost demersal fish production is relatively small (316 kg yr^{-1}) when one considers the harvest levels of many of the commercially important species in the area. For example, the harvest of penaeid shrimp from Louisiana coastal waters (including the continental shelf) has averaged around 115 million lbs (52 million kg) over the last 25 years (National Marine Fisheries Statistics). Although our estimate pales in comparison, it does point to tangible effects of the loss of benthic invertebrate production resulting from the extraction of sand resources from the pit. The possibility of cumulative losses resulting from multiple sand mining projects with extended recovery times of pits will greatly increase the overall production loss. While this damage estimate is likely never to match the magnitude of demersal fish and invertebrates harvested, cumulative impacts may result in higher and more significant (from a management perspective) damages.

4.0 SYNTHESIS OF FINDINGS AND RECOMMENDATIONS

This section provides a summary of the physical, biological and biophysical impacts of dredge pits based on the various background (Section 2) and specific analyses (Section 3) completed as part of this project. Recommendations are also made to address uncertainties in our understanding and approaches associated with evaluating the impacts of dredge pits in non-topographic settings.

Predictive techniques for evaluating the impacts are summarized in Section 5 on Guidelines for Evaluating and Mitigating Impacts of Dredge Pits.

The presentation of conclusions and recommendations has been organized around the five primary impacts of: morphologic evolution; possible shoreline impacts; impacts to water quality; impacts to benthic communities; and impacts to higher trophic levels. Differences in impacts between muddy and sandy seafloor settings are also summarized; although some of the impacts are common to both, many are distinct to the specific setting.

The primary focus of this investigation is the impacts of pits that are dredged on non-topographic features. Non-topographic features are distinguished from shoals and ridges and include buried paleo-channels and sand plains or sheets. Ultimately we have taken the definition to mean that the post-dredging outcome is a pit in a relatively flat and featureless seafloor, even in a regional sense (i.e. parts of the very large Ship Shoal feature off Louisiana may be relatively flat but on a regional basis this feature is a shoal). Nevertheless, that is not to say that some of the findings and guidelines developed as a result of this investigation may not be applicable to those locations where the distinction between pits on non-topographic features and pits on shoals is not well defined. Also, the report addresses in greater detail pits in muddy seafloor settings, as these are more of an immediate concern for MMS.

4.1 Morphologic Evolution

This section provides a discussion of the physical impacts associated with the creation and evolution of dredge pits. The focus of the investigation is on the impacts unique to dredge pits versus the more general and well-known impacts such as dredge plumes that have been addressed in more detail in other MMS reports.

Morphologic change occurs differently for pits in sandy and muddy settings. Sandy pits evolve mostly through slope change and may migrate. This study and Nairn *et al.* (2005) were the first to find that muddy pits remain stationary and fill with suspended sediment derived from pit margin erosion and from background levels as the flow speed slows over the pit. It is necessary to predict the rate and manner of pit evolution with time in order to evaluate the nature and timing of the impact to benthic communities and higher trophic levels. These predictions may be made with simple analytical techniques, 2DV and 3D models, with the choice of approach dependant on the significance of the morphologic evolution to the impacts.

4.1.1 Pits in Muddy Seafloor Settings – Origin and Evolution

This section provides a discussion of the origin of buried channel deposits that are primary target for dredge pits in muddy settings.

A review of the knowledge of buried channels along the western Gulf of Mexico and central Atlantic coasts was completed to provide an indication of where dredging for sand in buried channels may be feasible and to provide overview level information on the characteristics of these deposits. A conceptual model for the formation of lowstand valley fills or buried channels was developed by M.O. Hayes (see Section 2.1 and Appendix A.1). The key situations associated with finding sand with a relatively thin layer of mud include: 1) a river with a significant area of upland watershed (as opposed to a coastal plain river); 2) the development of a lowstand delta, also associated with upland rivers; and 3) the development of a tidal inlet during a lowstand in sea level rise (either for coastal plain or upland river valleys). It was found that the greatest potential for exploiting buried channel deposits exists in Texas, Louisiana and South Carolina. The only existing example of a buried channel deposit being dredged on the OCS is the Holly Beach Dredge Pit offshore western Louisiana. Another buried channel deposit at Sandy Point offshore the west flank of the Mississippi River has been proposed for dredging to provide sand for the CWPRA Pelican Island Restoration project. In general, it was found that there is very little quantitative information on the thickness of muddy caps over buried channels, or on the potential width and depth of sand deposits. In addition, the available evidence suggests these dimensions are very site-specific and variable.

Dredge pits in muddy settings could be created by either Cutter Suction Dredges (CSDs) or Trailing Suction Hopper Dredges (TSHDs). There may be a preference for CSDs for the following reasons: 1) they have greater capability to dredge deeper pits with steeper sides (and deeper pits reduce the total amount of stripping required, thus reducing cost of the dredging); 2) the optimal run distance for TSHDs is approximately 6000 ft (1829 m) which may be less than the width of a dredge pit in a muddy setting; and 3) it is easier to dispose of stripped sediment in a controlled manner close to the pit when with a CSD. TSHDs become the favored equipment as distances from shore increase. The only key differences associated with CSD operation in terms of impacts would be the potential for a steeper sided and deeper pit.

Prior to the Nairn *et al.* (2005) investigation for MMS on the impact of dredge pits on oil and gas infrastructure, there had been no distinction or systematic evaluation of the differences between morphologic evolution in muddy and sandy seafloor settings. As summarized below, this is a key and new finding that is fundamentally important to the evaluation of impacts of dredge pits.

There are two direct morphologic impacts associated with dredging a pit in a muddy setting. The first is the creation of the pit itself and the second is the creation of dredge disposal mounds associated with the unsuitable muddy sediments that are removed to expose the desired sandy sediments with low fines content. Following the completion of dredging, the indirect morphologic impacts include pit infilling, pit margin erosion and changes to the disposal mounds.

Pit infilling occurs at a rate dependent on several factors including the pit dimensions in plan, pit depth, flow speed and orientation relative to the pit, and most importantly, the background suspended sediment concentration (for more details on the direct influence of these different parameters see Nairn *et al.*, 2005). In simple terms, the pit fills in due to the reduction of flow speed over the pit that allows more sediment to settle and deposit in the pit. As this process occurs there is diffusion of more sediment into the pit area to counter-balance the greater loss of sediment from the water column to deposition, compared to surrounding areas beyond the edge of the pit. The rate of pit infilling may be relatively constant initially but decelerates exponentially for the latter part of the infilling process.

Pit margin erosion is driven by three factors: 1) the need to fill the adjacent pit and the increased re-suspension around the margins of the pit to counter-balance the reduction in suspended sediment through enhanced deposition over the pit; 2) the flow attraction effect where flow speeds are increased around the pit to accommodate the high flow conveyance potential over the pit (due to the deeper water); and 3) wave focusing effects on the two sides of the pit related to refraction of waves away from the middle of pit towards the side margins. Pit margin erosion can extend for some distance beyond the edge of the pit (25 to 50 % of the width of the pit) and result in vertical erosion from several inches to 2 feet (0.6 m) or more. The pit margin erosion will cease when underlying sandy sediments are exposed, if they exist. Pit margin erosion is greatest early in the pit evolution process, then decreases and eventually reverses towards the latter stages of pit infilling (when the pit margin zone itself is infilled). For the same quantity of sand recovered, shallower pit with a larger surface area will result in greater pit margin erosion.

Dredged disposal mounds are eroded at varying rates depending on the local environmental conditions and the way in which the stripped sediment is placed. Often the last layer placed on the mound will be relatively sandy sediment, as it will be taken from the interface between the sand and overlying muddy sediment. When sandy sediment is placed over the mound it effectively provides a quasi-stable armor that significantly reduces the rate at which the mound erodes. This has the negative consequences of: 1) prolonging the time for pit infilling by preventing the finer buried sediments from being eroded and returning to the pit; and 2) reducing the rate of erosion for the disposal mound lengthening the period of direct impacts associated with the mound (i.e. primarily the change in grain size).

There are potential grain size changes associated with the substrate for the three main morphologic impacts. The sediment that fills in the pit may be finer and will mostly likely be softer than the pre-existing conditions. With time the natural substrate conditions will be re-established, probably a short time after complete infilling of the pit.

The substrate of the pit margin erosion zone may become coarser as finer sediment is removed and deposited in the adjacent pit. Again, this impact will be temporary and eventually, not long after the pit is full, the substrate will return to its pre-existing grain size state. There is no existing information on the time to recovery to pre-existing substrate grain size either in the pit or pit margin erosion zone (i.e. from monitoring of other dredge pits) and this remains an important gap in our understanding.

The dredge disposal mound may feature coarser sediment than the pre-existing condition – this will be the case where the mound projects significantly above the surrounding seafloor and features muddy sediment capped by sandy sediment. In this case the substrate grain size change may persist well after filling of the pit is complete. The dredged disposal mound will be eroded (or buried) much sooner if: 1) the sandy fraction of the dredge spoil is placed near or below the pre-existing bed level (for example, in an area that is stripped but not dredged; and 2) the muddy fraction is left exposed (i.e. without a sand cap).

4.1.2 Pits in Sandy Seafloor Settings

The morphologic evolution of dredge pits in sandy settings differs from those in muddy settings. The pit mostly fills through a slope adjustment and migration process that has been very well studied in the past (see Van Rijn *et al.*, 2005). Since the migration process is relatively slow (no more than 10’s of feet per year) this migration is unlikely to significantly influence benthic communities as it occurs. In areas with low wave energy or current speeds (i.e. either due to mild forcing conditions or deep water) the pits may not fill at all. There is also the possibility in these low wave and current energy environments that the pits may infill with finer sediment, particularly if they are significantly deeper than the surrounding seafloor.

There are no issues associated with dredged disposal mounds in sandy settings because, by definition, no stripping of muddy caps is required. In addition, this means that for the same volume of beach nourishment sand pits in sandy settings will be shallower.

Changes in substrate are limited to the floor of the pit where finer sediment can accumulate depending on the background levels and grain size of suspended sediment. For slowly evolving or stable pits this change in substrate may be long-term or permanent. In the case of rapidly evolving pits, the substrate will be fully sand or at least similar to adjacent sea bed conditions as soon as the pit is mostly filled in.

4.1.3 Recommendations

Beach sand deposits are most likely to be associated with lowstand valley fills or deltas of upland rivers or with lowstand tidal inlets associated with either upland or coastal plain rivers.

The Holly Beach Dredge Pit has now been monitored through a four-year period during which time it has reached a level of more than two-thirds full. This may represent the most comprehensive data worldwide on the evolution of an offshore dredge pit in a muddy setting (based on a review of the worldwide literature as outlined in Nairn *et al.* (2005)). It would be advisable to confirm that the final stages of filling occur as projected through one or two additional hydrographic surveys over the next four years (2007 to 2011).

Sediment sampling should also be completed with the hydrographic surveys to confirm that the sediment grain size in the pit area (and the pit margin erosion zone) returns to the conditions associated with undisturbed areas further away from the pit, and the time to recovery of pre-existing substrate grain size conditions.

For future dredge pits such as the proposed Sandy Point pit for the CWPRA Pelican Island project it would be advisable to: a) measure the background currents and suspended sediment concentrations through an average year prior to dredging; and b) after dredging monitor bathymetric and sediment grain size change associated with: 1) pit evolution; 2) pit margin erosion; and 3) the dredge spoil mound evolution. This would provide a second data set to evaluate the predictive performance of morphologic response models for dredge pits in muddy seafloor settings.

When and if a pit is dredged in a sandy setting such as Ship Shoal, monitoring program to evaluate the morphologic evolution (and any changes in substrate grain size) should be implemented to test the performance predictive techniques.

4.2 Possible Shoreline Impacts

The two key potential shoreline impacts associated with dredge pits are: 1) the influence on wave transformation, and thus cross-shore and longshore sand transport processes and the associated shoreline change; and 2) impacts to sand transport pathways that may negatively influence the littoral sediment budget.

The impacts of pits on wave transformation processes are almost the same whether a pit is dredged in a muddy or sandy seafloor environment. The differences are explained in Sections 4.2.1 and 4.2.2 on pits in muddy and sand environments, respectively. Impacts to sand transport pathways are also addressed in the following subsidiary sections.

A key potential indirect impact of dredge pits is the possibility that the presence of the pit will modify the waves that reach the shoreline, and therefore possibly impact longshore and cross-shore sand transport and potentially, shoreline change. It is imperative to evaluate the potential impact of dredging on shoreline evolution as the purpose of many of the these projects it to provide beach nourishment sand to address shoreline erosion problems and it would be counter-productive to mitigate erosion at one location at the expense of increasing it at another location.

Several phase-averaged wave transformation models (including the STWAVE, SWAN and WABED models commonly applied in MMS studies) were inter-compared and evaluated against the results of a phase-resolving Boussinesq wave model. The assumption was that the Boussinesq model results would provide the best estimate of actual conditions. Wave measurements offshore and inshore of the Holly Beach Dredge Pit were beyond the scope of this investigation. It was determined that wave refraction and shoaling were the most important processes and that wave diffraction, reflection and non-linear effects were much less important to consider, particularly for far-field (i.e. shoreline) impact assessment. These secondary processes were more important to consider when near-field influences such as the pattern of wave height increases and decreases around the pit were important to consider, and in these cases, phase-resolving models such as the Boussinesq wave model would be appropriate to apply. Near field patterns of wave height change are likely important to the pit margin erosion process. Inputs to wave transformation models should include realistic frequency and directional spectra.

Wave focusing and scattering occurs around the pit as waves are refracted in different directions on the pit slope resulting in areas of higher and lower waves than adjacent undisturbed areas. Typically waves become larger on either side of the pit and along two lobes extending away from the pit (laterally) and towards the shore on the inshore side and this wave focusing may contribute to pit margin erosion. These patterns are related to wave refracting away from the center of the pit as they traverse the pit side slopes. There is also a zone of reduced wave heights over the inshore (down-wave) part of the pit and immediately in the lee of the pit. These zones of lower waves heights result from the opposite “scattering” effect of waves being refracted away from the center of the pit by the pit side slopes.

At the Holly Beach Dredge Pit it was determined that the zone of far field influence, in terms of significant change to wave heights, did not extend more than four times the width of the pit (measured perpendicular to the wave direction) inshore of the pit. The distance for full recovery would be decreased in the case of heavy winds (which are usually associated with larger wave conditions that are of greatest concern for shoreline change) through additional wind-growth. In general it was found that the dredge pit length (measured perpendicular to the wave crest orientation) and depth are the most important factors controlling the zone of influence of the pit on its surrounding wave field. Shallower and shorter pits cause less disturbance to the near-field wave conditions. Recovery distance appears to be independent of the pit width. Therefore to minimize the impact to the wave field wide and short dredge pits are more desirable than square or narrow long pits.

Assessment of the impact of altered nearshore wave climates associated with the presence of pits was not evaluated in detail as part of this project. Nevertheless, the literature review completed for this project indicated that it is becoming standard practice to link a one-line (e.g. GENESIS) or 2D morphologic model (e.g. Delft3D) to wave transformation models in order to evaluate the potential for impact to longshore and cross-shore sand transport and shoreline change.

The influence of dredge pits on circulation patterns is local and related to the flow attraction effect as summarized in Section 4.1.1 above. Beyond the pit margin erosion zone there is no regional influence on currents, and therefore no additional effects to nearshore processes.

4.2.1 Pits in Muddy Seafloor Settings

The key distinguishing factor between wave transformation impacts associated with pits in muddy and sandy settings is the wave dissipation due to damping by muddy sediments that are deposited in the pit. This damping effect can have a local effect of reducing wave heights on the immediate leeward side of the pit. While this may have an important local influence, it is unlikely to result in expanding significantly the zone of influence estimated without consideration for damping by mud deposition in the pit.

With dredge pits in muddy seafloor settings there is no concern with interrupting sand transport pathways that may provide sand to the nearshore zone (i.e. due to the absence of distinct sand transport pathways in muddy settings).

4.2.2 Pits in Sandy Seafloor Settings

The only differences to the impact to waves for pits sandy settings (i.e. compared to wave impacts for pits in muddy settings) are: 1) the potential for sandy pits to migrate where there is a strong residual current or sediment transport direction, thus changing the location of wave impacts with time; and 2) the absence of the wave dissipation effect related to the infilling of the pit with mud.

There are two potential impacts to sand transport pathways that must be evaluated for pits in sandy settings: 1) the trapping of sand that would have otherwise made its way to shore to supply the littoral zone; and 2) the potential for sand to be transported offshore to fill the pit (referred to as a “drawdown” effect). Although it was beyond the scope of this investigation to evaluate these effects in detail, it is likely they are of minor concern given the long distance offshore of OCS pits (i.e. greater than 3 miles).

4.2.3 Recommendations

There is a need for field data to provide directional wave measurements at an offshore location (to define incident waves) and at locations around the pit (either side and inshore at several locations) to validate numerical models and improve our understanding of the processes. This information has not been reported in the literature for an offshore pit at any location. It is possible this type of evaluation could also be completed in a physical model experiment. A physical model may be less costly and more expedient than a field data collection campaign as it does not rely on the uncertainty of capturing a wide range of wave and current conditions during a field campaign. The physical model investigation could also evaluate a wide range of pit configurations at relatively low additional cost.

There is also a need to evaluate the influence of dissipation by soft mud that is deposited in pits, particularly for muddy seafloor settings. Mud dissipation over short distances (such as the length of a pit in the cross-shore direction) is not well understood. This type of investigation is not conducive to physical modeling owing to scaling issues associated with the mud and is best addressed through field measurements. The Holly Beach Dredge Pit may be an ideal candidate for this type of field investigation.

It is likely that some generic ratio of pit width to distance from shore could be developed to define the inshore extent of significant impact of pits on waves (such as the rules of thumb for breakwater impacts on the shoreline related to the ratio of breakwater length to distance from shore). However, the development of such a ratio would require extensive field measurements and/or a physical model together with numerical modeling. The measurements would be used to validate the numerical model and the numerical modeling could be applied to extend the results to a wider range of conditions.

As part of this investigation a series of generic numerical model runs were completed to evaluate the influence on the nearby wave field of pit length (in the direction of wave attack), pit width (perpendicular to the direction of wave attack) and pit depth. It is noted the results were not confirmed with field measurements or physical model tests. A key finding from this investigation resulted in this recommendation: to minimize the impact to the wave field, wide and short dredge pits are more desirable than square or narrow long pits.

The development of generic zones of influence would also require a consideration of sectors of shoreline with similar incident wave conditions, as the zone of influence will vary depending on the range of dominant wave periods, and to a less extent wave height.

4.3 Water Quality Impacts

The two primary water quality impacts are re-suspension of fine sediment during the dredging processes and the potential for the depletion of dissolved oxygen in dredge pits.

4.3.1 Pits in Muddy Seafloor Settings

The key water quality impact associated specifically with dredge pits is the potential for the development of hypoxic or anoxic conditions in the pit. Pits in muddy seafloor settings are more prone to this development for two reasons: 1) pits in muddy seafloor settings are necessarily deeper for the same quantity of sand removed due to the need to strip the muddy sediment (and to minimize the extent of stripping for cost considerations) and the deeper the pit the greater potential for reduced circulation and mixing with oxygen-rich surface water; and 2) the organic matter that settles in the pits leads to the consumption of dissolved oxygen as it is metabolized by various processes.

In the case study completed on the Holly Beach Dredge Pit, in the one snapshot of dissolved oxygen conditions inside and outside the pit, there was evidence of temperature and dissolved oxygen stratification in the lower half of the water column, both inside and outside (and well beyond) the pit featuring relatively low dissolved oxygen levels (i.e. approximately 3 mg/l). Therefore, while no conclusion could be reached on the extent that pits will encourage the development of diminished dissolved oxygen levels, it was found that regional reductions in dissolved oxygen in the Gulf of Mexico may diminish the importance of reductions in dissolved oxygen that might be associated with the influence of the pit itself. Often muddy seafloor settings are associated with the potential for regional dissolved oxygen depletion as this process is often driven by heavy nutrient loading from rivers and these rivers also supply the fine sediment that is deposited to create a muddy seafloor.

The potential impacts to benthic communities associated with dissolved oxygen depletion in dredge pits are summarized in Section 4.4.1.

It is also important to note that water quality impacts associated with the depletion of dissolved oxygen are temporary in nature and will no longer represent an impact once the pit is mostly filled in.

A general impact of dredging on water quality is the re-suspension of sediment associated with the dredging process (i.e. at the cutter or suction head and at overspill by Trailing Hopper Suction Dredges). This impact has been addressed by many others including the Baird (2004) detailed assessment and numerical model development describing suspended sediment plumes from hopper dredges. This impact has therefore only been addressed in the context of the difference between pits in sandy and muddy settings.

By definition, the seafloor in muddy settings features a high content of silt and clay. As such, the background suspended sediment concentration levels in these areas will be high due to frequent re-suspension by wave action, and in some areas due to the influence of sediment laden river discharge plumes. Therefore, it is likely that any re-suspension of sediment and elevated turbidity levels associated with dredging will be well within the natural range of conditions.

4.3.2 *Pits in Sandy Seafloor Settings*

The development of hypoxia or anoxia in dredge pits in sandy settings is possible, though less likely than those in muddy settings for two reasons: 1) these pits are usually shallower as there is no need to strip muddy sediment; and 2) sandy pits are less likely to fill with finer sediment (which are less abundant in sandy settings) that has an oxygen demand capable of depleting dissolved oxygen at the bottom of the pit.

The general impact associated with plumes of fine sediments created during the dredging process is a greater concern for pits in sandy settings owing to the potential to alter the sediment characteristics of nearby seafloor subject to sedimentation of fine sediment.

4.3.3 *Recommendations*

In order to better understand the development of anoxic or hypoxic conditions in dredge pits it is recommended that continuous monitoring over the entire water column be completed for the period of at least one year. A possible opportunity to complete this assessment would be the proposed Sandy Point dredge pits for the CWPRA Pelican Island Restoration project. The proposed pit at this location is very deep at 75 ft (23 m) below the seafloor.

More information is also required on the regional patterns of dissolved oxygen depletion expanding on the work of Rabalais *et al.* (2002) to provide a more detailed temporal assessment and information on stratification through the water column. This information will aid in the assessment of the importance of oxygen depletion due solely to the presence of a dredge pit.

Once this information is available it may be possible to apply and test a numerical model of hydrodynamics and ecological processes in order to evaluate the performance of such models to predict the depletion of dissolved oxygen. Numerical models could then be applied to evaluate dredge pits on an individual basis or a series of possible pits could be evaluated to provide some general guidance on how the development of hypoxic or anoxic conditions depends on the various influencing factors.

4.4 Impacts to Benthic Communities

The primary direct impact of dredge pits is defaunation of the seabed in the dredged area. Indirect impacts result from: 1) sedimentation associated with deposition from plumes created during the dredging process; and 2) erosion and sedimentation that occurs as a result of morphologic evolution of the pit. These impacts differ and have different implications for pits in muddy and sandy settings and are summarized in the following sections.

4.4.1 Pits in Muddy Seafloor Settings

The key biological impact in any dredging project that is unavoidable is the defaunation of seafloor in the borrow pit area. The key questions that must be addressed to evaluate the impact of defaunation are the timing and extent of full recovery to pre-existing benthic community structure and abundance.

For deeper pits associated with muddy-capped deposits, the infilling rates will be relatively high and this sedimentation process will inhibit recovery. The monitoring of the Holly Beach Dredge Pit showed that sedimentation rates were 0.9 ft (27 cm)/month for the first year or so after dredging in April 2003 but have decreased to 0.3 ft (9 cm)/month more recently. The high sedimentation rates are likely responsible for the low species diversity in the bed of the pit. The stations in the pit contained organisms from only 1 or 2 taxa compared to 3 to 6 taxa at all other stations outside the pit. Biomass was also significantly lower within the pit. The species inside the pit were a subset of those found outside and would have made there way into the pit through immigration or recruitment. Overall at the Holly Beach Dredge Pit site the dominant species were polychaetes representing 97 to 100 % of abundance inside the pit and 72 to 98 % abundance outside the pit.

The placement of the dredge disposal mounds associated with stripping the muddy cap also results in the direct destruction of benthic communities. As noted in Section 4.1.1, these mounds also evolve with time through erosion. When sandier sediment is placed over the top of the mound altered benthic communities may colonize the mound due to a change in sediment type. Long-term impacts can be avoided by ensuring that the mounds are quickly eroded, by avoiding the unintentional capping with more erosion-resistant sandy sediment.

An indirect impact to benthic communities associated with pits in muddy seafloor settings may occur in the pit margin erosion zone. At the Holly Beach test site, in areas where the muddy cover was relatively thin, pit margin erosion changed the sediment type from muddy to sandy; this change also results in a change in the benthic community composition from one associated with muddy deposits to one associated with sandy deposits.

Therefore, while there is some limited initial recovery in the pit, and possibly a change in benthic community composition in parts of the pit margin erosion zone, where sandy sediment becomes exposed, full recovery and return to pre-existing communities will only occur once the pit, and the extended pit consisting of the pit margin erosion zone, are filled and covered with muddy sediment.

Recovery time for benthic communities in muddy sediments is almost always less than two years and generally only a few months (see Newell and Seiderer, 2003). Therefore, for dredge pits the time to full recovery will be the sum of the time for the pit to fill in, plus the time for the pit to return to pre-existing sediment conditions, plus a few months at most for the subsequent benthic recovery. The benthic community recovery will be accelerated somewhat by the initial recovery that takes place during the filling of the pit, that is, by the most sedimentation tolerant species that can survive in the infilling pit.

The indirect impact to benthic communities due to reductions to dissolved oxygen levels within a pit will not be significant unless recovery of benthic species within the pit during infilling is significant. At the Holly Beach Dredge Pit the recovery of benthic species within the pit was very limited due to the rapid sedimentation rates.

Therefore in summary, there is a tradeoff on impacts between deep, small footprint pits where there is less area defaunated both in terms of the pit and the disposal mound but recovery takes longer (and there is greater potential for oxygen depletion) and shallow, large footprint pits where there is more area defaunated but time to recovery is shorter.

4.4.2 Pits in Sandy Seafloor Settings

Defaunation is also the primary biological impact of pits dredged in sandy areas. Recovery time for benthic communities associated with sandy seafloor conditions is typically in the range of 1 to 3 years (see Newell and Seiderer, 2003). Therefore, the total time for the benthic community to recover will be the time for the pit to fill plus probably less than 2 years (as some recovery will occur during the infilling process). In the case where the pit does not fill and/or fills partly with fine sediment, the change to the benthic community may be permanent.

In locations where pits migrate, the zone of impact to benthic communities will be larger.

For slowly evolving or stable pits in sandy settings where there is sufficient background suspended sediment, the impacts may also include the alteration of benthic communities resulting from the possible change of the pit floor from sandy to muddy.

4.4.3 Recommendations

There are several areas of insufficient understanding or uncertainty related to the processes that result in impacts to benthic communities.

A key gap in understanding is the ability to predict the change in benthic community structure resulting from a change in grain size on the sea bed. This is an issue for both the pit floor (which can become finer and softer for pits in both muddy and sandy settings) and the surrounding area (which can become coarser through pit margin erosion for muddy settings and finer in sandy settings due to sedimentation from dredge plumes). More research is required on this topic, ideally in the vicinity of pits so that the findings are directly applicable to pits in offshore areas. Principal Component Analysis (PCA) was applied to reveal relationships between physical variables and the benthic community structure from the samples in and around the Holly Beach Dredge Pit. Strong relationships were determined between benthic community structure and seafloor grain size and water depth (the latter probably representing the sedimentation rate influence within the pit where water depth was greater).

The rate of recovery for benthic communities associated with sandy and muddy sediment settings is relatively well defined from empirical evidence. A knowledge gap related to recovery is the impact of heavy sedimentation on benthic recovery for pits in muddy settings, although the Holly Beach example has provided some evidence for this situation. To be conservative, it has been proposed here that this “interim” recovery during the pit infilling period be ignored in the evaluation of impacts to higher trophic levels. More information on recovery time for the benthic communities could be gained from two or three additional surveys of the benthic species in and around the Holly Beach Dredge Pit in the next 5 or 6 years (2007 to 2013).

One other aspect of uncertainty in the impact evaluation procedure relates to the time between substantial completion of infilling of the dredge pit in terms of a return to undisturbed seabed level and sediment conditions (in muddy or sandy seafloor settings) and the additional time for recovery of benthic communities to pre-disturbed conditions to occur. However, where infilling occurs over 5 to 10 years, this additional time to recovery (after infilling) may be a small in terms of the evaluation of full time to recovery since the recovery in muddy sediments is generally less than 1 to 2 years. More information on this process could be gained from additional benthic sampling of the Holly Beach Dredge Pit.

4.5 Impacts to Higher Trophic Levels

The potential impacts to demersal fish and mobile invertebrate species include: 1) loss and or modification to benthic prey resources; 2) degradation of nursery or spawning area; and 3) susceptibility to the hypoxia in the lower part of the water column (evaluated based on mobility). These possible impacts were evaluated for the various life stages of all key demersal fish and invertebrate species on the US Atlantic and Gulf coasts. Based on this review, the most probable mechanism by which higher trophic levels are impacted by dredging is through lost prey resources or changes in the prey base. If the higher trophic levels are food-limited, the loss of prey production will be directly proportional to net loss in production of predators. This represents the maximum possible impact due to the food-limited assumption.

As a conservative method of quantifying the impact of lost prey base to higher trophic levels, the bioenergetics approach proposed by French McCay and Rowe (2003) may be applied. This approach has the advantage of ***quantifying*** impacts in terms of lost demersal and benthic invertebrate production, which in turn can be compared to harvest levels for commercially important demersal and invertebrate species. Also, the impact of individual projects can be accumulated in order to evaluate cumulative impacts with time for OCS dredging projects in different regions.

Section 3.2.4 of the report provides the methodology applied to determine the lost prey base associated with pit dredging and estimated time to recovery for the Holly Beach Dredge Pit. The calculation of the decrease in production at the invertebrate and demersal fish level requires the following inputs: surface area of the pit; lost benthic production (determined from biomass, growth and mortality rates using information from benthic samples within and beyond the influence of the pit); time to recovery for the benthic communities; and an ecological or trophic transfer efficiency.

This approach was demonstrated for the Holly Beach Dredge Pit. The pit has a total surface area of 190,600 m^2 and an estimated benthic production loss of 1,582 kg yr^{-1} based on the benthic sampling. Applying a recovery time of 11 years (9 years for the pit to fill and 2 years after that for return to pre-existing sediment conditions, note that this is a conservative estimate) to the annual estimate of lost benthic invertebrate production gives a total average loss from the time of dredging of 17,402 kg. The loss of benthic invertebrate production can be expressed in terms of the influence to the higher trophic levels (i.e. potential loss of demersal fish and mobile invertebrates) by multiplying the lost benthic invertebrate production by ecological or trophic transfer efficiency. Based on their review of ecological efficiencies, French McCay and Rowe (2003) applied a value of 20 % for invertebrates and fish less than 200 g in weight and this matches best to the conditions in the vicinity of the Holly Beach Pit. Applying this value to the calculated lost benthic invertebrate production, the average loss of demersal fish and invertebrate production is estimated at 3,480 kg (0.2 x 17, 402 kg) over an 11-year recovery period. On an annual basis the average demersal fish and invertebrate production lost would be 316 kg yr^{-1}. The average annual estimate of lost demersal fish production is relatively small (316 kg yr^{-1}) when one considers the harvest levels of many of the commercially important species in the area. For example, the harvest of penaeid shrimp from Louisiana coastal waters (including the continental shelf) has averaged around 115 million lbs (52 million kg) over the last 25 years (National Marine Fisheries Statistics). Nevertheless, this approach provides a much-needed quantitative measure of impacts to higher trophic levels, which ultimately is the most important biological impact of dredge pits. This approach may also be applied to determine the cumulative impact of dredge pits on a species of interest by tracking the impact of all dredge pits within different regions of the OCS.

Although the bioenergetics approach is imperfect, and there are several assumptions that need to be made based on limited information, it represents a relatively cost-effective approach of quantifying the primary impact of dredging – initial defaunation and lost production during the pit infilling and benthic community recovery period.

An evaluation of the key potential impacts (i.e. loss of prey base, degradation of nursery or spawning areas and hypoxia/anoxia impacts) should be completed on a more site-specific for each pit considering the habitat and the local species.

4.5.1 Pits in Muddy Seafloor Settings

Specific issues associated with the three main impacts to higher trophic levels noted at the beginning of Section 4.5 are discussed for pits in muddy seafloor settings.

For pits in muddy settings, the bioenergetics approach for evaluating impacts to prey base as presented above and described in detail in Section 3.2.4 will be conservative as it assumes the demersal and invertebrate species are food-limited. In other words, the loss of benthic prey species will result in a direct loss of higher trophic level production. This is more likely to be an appropriate assumption for unique habitat types and the muddy seafloor setting is not unique for most the western Gulf of Mexico coast.

Impacts to spawning/nursery grounds are difficult to assess for many taxa because significant gaps exist in our knowledge of the early history of many fish – particularly those of limited commercial or recreational value. Several flounder and eel species would also be expected to use offshore sand/mud habitat as nursery grounds; consequently, their potential impact under the spawning/nursery ground category is ranked as medium to high.

The majority of fish identified as likely to occur in areas of non-topographic features along the inner shelf were judged to have fairly low susceptibility to the direct impacts of low dissolved oxygen.

4.5.2 Pits in Sandy Seafloor Settings

The bioenergetics approach could also be applied to sandy seafloor settings to quantify the impact of lost prey base on higher trophic levels. The primary difference would be that the impacts to production of higher trophic levels might be permanent in cases where the pit does not fill in, or fills in only partly with finer sediment.

Impacts to spawning/nursery grounds may be important for some sandy areas. Although, as with muddy settings, wide expanses of sandy seafloor may not represent particularly unique habitat.

In general, as discussed in Section 4.3, the impact of depletions to dissolved oxygen levels (and subsequent impacts to higher trophic levels) is of less concern in sandy seafloor settings owing to the shallower pits (for the same dredged volume) and reduced availability of organic material for deposition in the pit.

4.5.3 Recommendations

With respect to the potential impact to the prey base, a key mitigation strategy would be to choose (where possible) borrow deposits in areas where the habitat type is not unique regionally; this strategy will result in the likelihood of less impact to higher trophic levels (due to the fact higher trophic levels are less likely to be food-limited in these common habitats). Studies that examine the value of unique versus less unique habitat types should be conducted to examine the rigor of this argument with particular focus on whether, and to what extent, higher trophic levels are food-limited.

In order to apply the bioenergetics approach to evaluate the impact of reduction in prey base on higher trophic levels in a predictive mode (i.e. to evaluate *potential* impacts of a project), it is necessary to predict the impact to benthic production resulting from a dredge pit. This prediction requires a better understanding of the impact of pits on benthic communities. The Holly Beach Dredge Pit benthic sampling provides some initial information on this impact, more data is required. In the meantime, a conservative approach is to assume that no recovery of the benthic community occurs within the pit until it has filled and returned to pre-existing substrate sediment conditions.

A better understanding of the appropriate ecological efficiency in transfer of production to higher trophic levels would also improve the bioenergetics approach.

The cumulative impact to both benthic production higher trophic levels should be monitored for all OCS dredging projects in different regions using the results of the energetics approach and considering the time-limited impacts where pits eventually infill completely.

5.0 GUIDELINES FOR EVALUATING AND MITIGATING IMPACTS OF DREDGE PITS

This section provides guidelines for evaluating possible impacts of dredge pits and for mitigating impacts. The discussion is subdivided into six sections on: Guidelines for Regulating Dredge Pits in Offshore Areas from Other Countries (5.1); Morphologic Evolution of Pits (5.2); Impacts on Waves and the Shoreline (5.3); Impacts on Benthic Communities (5.4); Impacts on Mobile Invertebrates and Fish (5.5); and Summary of Considerations in the Development of Pit Design (5.6). Under each of these sub-topics, distinctive characteristics of pits in muddy and sandy seafloor settings are addressed.

No blanket guidelines are offered such as restricting pits to a certain maximum depth or size. These types of guidelines are becoming outdated in other jurisdictions owing to the advancement of capabilities to predict physical and biological impacts of dredging on a case-by-case basis, and the recognition that impacts are often very site-specific.

It is noted that this investigation and this summary focus exclusively on the impacts associated with the creation of pits during the dredging operation. Other impacts associated with the dredging operation are discussed in several other MMS publications and related papers including Nairn *et al.* (2004).

5.1 Guidelines for Regulating Dredge Pits in Offshore Areas from Other Countries

Van Rijn *et al*. (2005) provide a summary of the guidelines for offshore dredging from selected European Community countries (i.e. UK, the Netherlands, Denmark, Italy, Norway and France) as part of the SANDPIT project report. Included in this summary are:

1. Future demands for sediment;
2. Purpose of mined sediment;
3. Overview of existing and future mining;
4. Overview of monitored mining pits and studies completed;
5. Authorities and legal aspects involved;
6. Consultation procedure;
7. Hydrodynamic and morphologic evaluation procedures (i.e. physical impacts);
8. Method of ecological evaluation;

9. Type of regulations and criteria; and

10. Existing experience (lessons learned).

For the purposes of this study, Items 7 to 10 from the above list will be reviewed. For more detailed discussion of the other items, refer to Van Rijn *et al*. (2005). The requirements of the different countries must be considered in relationship to the current (2005) demand for offshore sand in each country: UK – 14 million m^3/year; the Netherlands - 32 million m^3/year; Denmark – 8 million m^3/year; France - 3 million m^3/year; Italy and Norway - minimal. For the UK and France about half those amounts are gravel, for the other countries it is almost all sand. Most countries project that the annual rates of extraction will be somewhere in the range of the same to double current levels over the next 50 years.

The physical impacts assessment of Item 7 covers most of the concerns summarized in Section 4 above. The UK requires an evaluation of: 1) possible drawdown and permanent trapping of beach sediments into the pit; 2) the potential impact of sand moving onshore being trapped and intercepted by the pit; and 3) the impact of the loss of any bars or banks that may protect the coast. The Netherlands requires modeling (and experience) to assess the impact to waves and currents and the morphologic evolution of the pit. Denmark has similar requirements to the UK. Although there are no specific requirements in France, studies typically involved literature/data surveys on local conditions, an assessment of changes to wave conditions, and the resulting impact on longshore/cross-shore sand transport and shoreline change. The requirements for Italy and Norway where the demand for offshore sand is much less are not well defined.

Ecological evaluations (Item 8) also vary considerably in scope between the countries, with the more detailed requirements being associated with the countries where demand and operations related to offshore sand are greatest. For the UK, the Environmental Assessment includes an evaluation of the impact of the sediment plume and associated sedimentation on the associated biological communities. Cumulative impact assessment is also required for multiple dredging operations (nearby or in time). The Netherlands have similar requirements but also single out the need to evaluate the re-colonization process for the benthos. The Danish requirements cover the same topics as the combined requirements of the UK and the Netherlands. France has a protocol that defines the surveys required before and every 5 years after dredging, including: 1) methods for bathymetry, 2) acoustic imagery; and 3) sampling (grain size and benthos).

The UK has the following regulations:

1. Dredging must be in depths greater than 30 ft (10 m) below low water and more than 0.37 miles (600 m) offshore as this is believed to be the limit for onshore-offshore sediment transport and thus the limit for beach drawdown effects;

2. Gravel is unlikely to be mobile for depths greater than 60 ft (18 m) and this should be considered in assessment of impacts (i.e. pit may not fill/change, with filling depending on supply of finer sediments);

3. On the possible impact of changing waves that reach the shore, the old rule of thumb was that dredging could not occur in depths less than 46 ft (14 m), but now refraction studies are preferred.

The Netherlands has the following regulations:

1. No dredging inshore of the 65 ft (20 m) depth contour;

2. The current regulation is that pits may not be deeper than 6.5 ft (2 m). However, the general view is this restriction will be revised to allow much deeper dredging (depths of 30 to 100 ft (10 to 30 m) below the seafloor) in the next few years;

3. An area mined cannot be mined again.

There are no specific limits associated with the regulations on dredging in Denmark. However, a recent change to the regulations in January 2007 will specify conditions on offshore dredging including: type of dredge to be used (trailing or cutter suction); reporting requirements, management of impacts to fisheries; and maximum pit depth (typically less than 10 ft (3 m)).

France also has not fixed limits, and each project is investigated individually.

In Italy, offshore dredging must be further than 3 miles (4.8 km) offshore and for some conditions in depths greater than 164 ft (50 m).

In summary, after discussions with local managers and technical experts in several of these countries, it was apparent that the regulations to manage impacts of offshore dredging in the European countries had developed mostly through local experiences, and they were not based on a comprehensive assessment of impacts and scientifically justified responses. The above noted SANDPIT project was intended to provide the basis for more scientifically justified evaluations of the physical (and to a lesser degree, biological) impacts of dredge pits.

5.2 Morphologic Evolution of Pits

The central requirement for evaluating the impact of dredge pits associated with buried channels and non-topographic features is the need to predict morphologic evolution. The manner in which the pit morphology evolves determines to a large extent the duration and extent of the physical and biological impacts. Without a prediction of dredge pit evolution it would be impossible to quantify the physical and biological impacts.

Pits in muddy seafloor settings will infill with clay and silt. It has been shown that the infilling process can be predicted relatively accurately using average annual parameters for wave height, tidal current speed and background suspended sediment concentration. One simple analytical approach for estimating the rate of pit infilling is provided in Section 3.2.1.2.2 and is covered in more detail in Nairn *et al.* (2005). The Nairn *et al.* (2005) report also provides a series of generic predictions of infilling rates and pit margin erosion for different combinations of pit size/depth, water depth and environmental variables. Hydrodynamic and morphologic models (2D or 3D) are required for the prediction of pit evolution if there are specific concerns, particularly with respect to pit margin erosion and dredge disposal mound evolution.

Dredge disposal mounds are created during the stripping operations to remove the unsuitable fine sediment to uncover the sandy borrow sediment. As the disposal mounds erode they provide a source of sediment for pit infilling, and thus help accelerate infilling. Therefore they should be located along the main axis of flow (such as the tidal current direction) and within 330 to 650 ft (100 to 200 m) of the edge of the pit to promote the transfer of sediment from the mounds back to the pit through natural processes. To the extent possible, the last (and lowest) dredge cut of the stripping operation should be placed in a separate area; otherwise, if it is placed over muddy sediment, it will act as a lag deposit and protect or reduce the rate of disposal mound erosion.

Pit margin erosion occurs around pits in muddy seafloor settings. In cases where there is sensitivity to the impact of pit margin erosion, either to nearby infrastructure or to benthic communities around the pit, the extent of this erosion can be roughly estimated using simple analytical techniques or predicted with more accurate numerical models of hydrodynamics and morphologic evolution (see Nairn *et al.* (2005)).

For pits in sandy settings, the pits can migrate during the infilling process. Also, under some instances the pits may not fill at all. Simple and more advanced methods of predicting sandy pit evolution are given in Nairn *et al.* (2005) and in Van Rijn *et al.* (2005). A distinct impact of sandy pit is the change in sediment characteristics at the base of the pit from sand to fine sediment. This may occur where the pit infilling is slow or not occurring at all.

As part of the assessment of the impact of dredge pits and the development of a mitigation plan, it would be advisable to consider the advantages and disadvantages of shallow pits with a large footprint, versus deep pits with a small footprint, within the constraints of the geologic features being mined. Shallow pits have a greater area of impact but will fill in faster. This assessment is complicated by the fact that the infilling rate is not linear, as shown in the Holly Beach Dredge Pit assessment, the pit was half full in less than a third of the projected time to infill, and the final third of the infilling is projected to take more than half the total infill time.

5.3 Impacts on Waves and the Shoreline

Dredge pits have a significant influence on waves around the pit as the waves transform over the side slopes of the pit. Wave heights are increased on either side of the pit and this likely contributes to pit margin erosion in the case of pits in muddy seafloor settings. It is necessary to apply an appropriate wave transformation model to evaluate the potential for the pit to have a significant influence on waves that reach the shoreline. Clearly, beach nourishment projects, which rely on sand from dredge pits, will be unsuccessful if they mitigate erosion at one location (with placement of the sand) and increase erosion at another location (with the possible impact of changes to waves at the shoreline due to wave transformation processes over the pit). Where there is any concern regarding shoreline impacts, the wave transformation model should be linked to a morphologic evolution model. One-line models are routinely applied to evaluate possible shoreline change impacts, and more recently, 2D models of nearshore morphology and shoreline change are becoming the standard approach for evaluating the impact of changes to waves on shoreline evolution.

In order to assess the impact of the pit on wave transformation, any of the most recently applied models in MMS investigations (including STWAVE, SWAN and WABED) are suitable for evaluating the far-field effects (i.e. potential shoreline impacts) providing that the input waves are described with directional and frequency spectra.

At the Holly Beach Dredge Pit it was determined that the zone of far field influence, in terms of significant change to wave heights, did not extend more than four times the width of the pit (measured perpendicular to the wave direction) inshore of the pit. It is likely that some generic ratio of pit width to distance from shore could be used to define the inshore extent of significant impact of pits on waves (such as the rules of thumb for breakwater impacts on the shoreline related to the ratio of breakwater length to distance from shore). However, the development of such a ratio would require recorded wave data offshore, and at several locations inshore, of a pit to confirm the validity of the numerical models. Unvalidated numerical model results completed for this study found that shallower and shorter pits cause less disturbance to the near-field wave conditions. Recovery distance appeared to be independent of the pit width. Therefore to minimize the impact to the wave field wide and short dredge pits are more desirable than square or narrow long pits.

Near-field wave transformation consisting of the focusing and scattering of waves around the pit margin will be important to predict where a detailed evaluation of pit margin erosion is required (i.e. where there is nearby oil and gas infrastructure or where impacts to benthic communities from pit margin erosion is a critical issue). The near-field transformation processes are relatively well represented by models that describe wave refraction and shoaling, although where accurate predictions are required the secondary processes of diffraction, reflection and non-linear wave interactions should be considered (i.e. with a phase-resolving Boussinesq model).

When pits are dredged in sandy seafloor settings, there is a need to evaluate the possible impact of the pit on sand transport pathways and the related stability of the nearshore profile (and shoreline position). While this is generally not a concern for OCS borrow deposits owing to the distance from shore (more than 3 miles (4.8 km)), it is a possible impact that nonetheless must be considered.

5.4 Impacts on Benthic Communities

Dredging results in complete defaunation within the area of the dredge pit. For muddy seafloor settings there will also be destruction of benthic communities through burial under dredge disposal mounds and possible alteration to benthic communities within the pit margin erosion zone (either due to the erosion process itself or to the coarsening of sediment in this zone).

To quantify the impact to benthic communities, it is first necessary to sample and define the structure of the benthic communities at and around the proposed dredge site. The baseline sampling plan design for pits in muddy settings should include samples taken from three zones: 1) the proposed surface area of the pit; 2) the estimated pit margin erosion zone (estimated as described under Section 5.1); and 3) outside of the influence of the pit margin erosion zone. For sandy pits the only difference to the sampling plan would be that pit margin erosion zone samples are replaced by samples in the zone of expected pit slope change and migration.

The loss of benthic community is then estimated as the total defaunation over the surface area of the pit plus any alterations/losses associated with changes in the pit margin erosion zone for muddy pits or in the pit slope adjustment/migration zone for sandy pits.

The key question in the case of muddy seafloor settings is the time for the pit to fill and the benthic community to recover completely. While some limited initial recovery of the most sedimentation-tolerant benthic species occurs during the infilling process, substantial recovery will not occur until the pit is full or at least until it is almost full (when sedimentation rates become very low). Therefore, the time to recovery is calculated as the time to infill plus the time for the sediment in the pit to return to pre-existing grain size plus the time for the benthic community to recover after infilling becomes sufficiently slow. This probably amounts to 1 to 3 years after the pit is 80 to 90 % full; however, this is only an estimate as the Holly Beach Dredge Pit was still infilling at the conclusion of this study.

For sandy pits that are stable (or evolve slowly) and are susceptible to infilling with fine sediment, the loss or alteration of the benthic community may be permanent.

A final consideration is the potential for anoxia/hypoxia to develop within the pit. It may be possible to predict the potential onset of hypoxic conditions using an ecological model, although this was not tested in the Holly Beach Dredge Pit evaluation of this study. It is also necessary to consider the regional patterns of dissolved oxygen depletion. If there is frequent or extensive hypoxia regionally, the impact of local development of hypoxia or anoxia in the pit will be less important to consider. As a conservative approximation, as noted above, any recovery of benthic communities within the pit prior to full infilling may be ignored, in which case the impact of anoxia/hypoxia can also be ignored.

Based on these considerations the total loss of benthic community and the loss per year can be quantified.

As explained further in Section 5.6, the design of the dredge pit should consider the goal of minimizing the impact to the benthic community in addition to the other key criteria (i.e. addressing the total sand quantity required, working to the geologic configuration of the sand deposit, minimizing the cost of dredging and potential pit margin erosion influences such as undermining oil and gas infrastructure). Minimizing the impact to benthos will be achieved by finding the best balance between a large surface area (with large initial defaunation) but rapid recovery (due to faster pit infilling), versus a small surface area (with less defaunation) and a deeper pit with slower recovery. These tradeoffs can be quantified through the results of morphologic modeling of different alternatives.

5.5 Impacts on Mobile Invertebrates and Fish

A general review of Atlantic and Gulf coast demersal fish and mobile invertebrate species was completed to evaluate the significance of dredge pit impacts. It was determined that the most important impact of dredge pits on higher trophic levels was through the loss of prey base. An evaluation of the key potential impacts (i.e. loss of prey base, degradation of nursery or spawning areas and hypoxia/anoxia impacts) should be completed on a more site-specific for each pit considering the habitat and the local species.

As a conservative method of quantifying the impact of lost prey base to higher trophic levels, the bioenergetics approach described may be applied (e.g. the approach of French McCay and Rowe, 2003). This approach has the advantage of quantifying impacts in terms of lost demersal and mobile invertebrate production, which in turn can be compared to harvest levels for commercially important demersal and mobile invertebrate species. Also, the impact of individual projects can be accumulated in order to evaluate cumulative impacts with time for OCS dredging projects in different regions.

Section 3.2.4 of the report provides the methodology applied to determine the lost prey base associated with pit dredging and estimated time to recovery for the Holly Beach Dredge Pit. The calculation of the decrease in production at the invertebrate and demersal fish level requires the following inputs: 1) surface area of the pit; 2) lost benthic production (determined from biomass, growth and mortality rates using information from benthic samples beyond the influence of the pit); 3) time to recovery for the benthic communities; and 4) an ecological or trophic transfer efficiency.

For pits in muddy settings, the energetics approach as presented above and described in detail in Section 3.2.4 will be conservative as it assumes the demersal and mobile invertebrate species are food-limited. In other words, the loss of benthic prey species will result in a direct loss of higher trophic level production. This is more likely to be an appropriate assumption for unique habitat types and the muddy seafloor setting is not unique for most the western Gulf of Mexico coast.

The bioenergetics approach could also be applied to sandy seafloor settings. The primary difference would be that the impacts to production of higher trophic levels might be permanent in cases where the pit does not fill in, or fills in only partly with finer sediment.

The most specific and important step to take in mitigating impacts to higher trophic levels is to achieve the objective, to the extent possible considering tradeoffs of other objectives, of minimizing impact to the benthic community as explained under Section 5.4 above. A general mitigation strategy for impacts to higher tropic levels consists of selection of borrow deposits with habitat that is not regionally unique for local fish species (i.e. such as a muddy seafloor setting in an area where this is the dominant seafloor condition).

5.6 Summary of Considerations in the Development of Pit Design

Section 5.6.1 provides a checklist of the key considerations for pit design development that will help ensure that the objective of mitigating physical and ecological impacts are considered together with economic and technical (sand quantity and quality) objectives. In addition, a final discussion of the relative merits of dredging buried channel deposits versus surface deposits (on non-topographic or topographic features) is provided in Section 5.6.2.

5.6.1 Checklist for Dredge Pit Design Development

A list is provided below of the key issues and steps that need to be considered in the layout of a pit in a muddy seafloor setting and particularly the location, length, width and depth of the pit. A similar list for pits in muddy seafloor settings is provided below the first list. This list of considerations is developed from the findings of this project and those presented in Nairn *et al.,* (2005). These considerations assume that the general location of the pit has already been determined through a consideration of a list of other more regional factors.

1. The quantity of sand required for the project must be determined; for the points below it has been assumed that this quantity is fixed (e.g. a smaller surface area is compensated with a deeper pit to extract the same quantity of sand).

2. The form and orientation of the target geologic deposit will often be the over-riding factor in determining pit shape, and possibly pit depth.

3. In order to complete this evaluation, the following oceanographic data is required at the site for the period of at least one year: current speed and direction and distribution through the vertical; wave height, period and direction (including spectral parameters); and suspended sediment concentration, salinity, temperature and dissolved oxygen through the water column.

4. Stripping and the related cost to the dredging project will be greater for a pit with a larger surface area. It follows that there will be more dredge spoil disposal for a pit with a larger surface area.

5. Complete an assessment of morphologic evolution using analytical techniques where only pit infilling rate is required or a hydrodynamic/morphologic model where pit margin erosion and/or dredge spoil mound evolution must be predicted.

6. Pit infilling will be somewhat faster for a pit with a larger surface area providing some critical pit depth is achieved to maximize sedimentation (this critical depth can be determined using the methods recommended in this report and is a site-specific value dependent on orientation of the pit, flow speed, width of the pit and background suspended sediment concentration, among others).

7. Pit infilling is faster with higher background concentration of total suspended sediment.

8. Pit infilling is faster (for the same surface area) when the direction of primary flow is perpendicular to the long axis of the pit.

9. Pit margin erosion will extend further from the pit for pits with larger surface areas.

10. Pit margin erosion will extend further from the edge of the pit in the long axis of the pit and/or along the axis of greatest flow speed.

11. Pit margin erosion stops when an underlying sand layer is uncovered. Sediment grain size in the pit margin erosion zone may change in this case.

12. Wave focusing on the sides of the pit, which likely contributes to increasing pit margin erosion, will be minimized with wider, shorter pits (with the width measured parallel to incident wave crests).

13. Far field wave impacts are also reduced for wider, shorter pits, but note that they are temporary. If necessary, predict shoreline change with 1D or morphologic model.

14. For pits in muddy seafloor settings, there will be no impact to sand transport pathways and the littoral sediment budget.

15. The benthic community for the surface area of the pit, the pit margin erosion zone and control areas beyond the pit margin erosion zone should be defined by benthic sampling prior to dredging.

16. Defaunation (due to dredging) and burial and destruction (due to deposition of stripped material) of benthic communities will be greater for pits with larger surface areas.

17. Possible impacts to benthic communities in the pit margin erosion zone should be considered, particularly if there is a change in grain size of the substrate.

18. The impact of benthic community loss (or reduction) will be shorter in duration for shallower pits.

19. Depletion of dissolved oxygen in the base of the pit can be ignored as a conservative assumption providing no partial recovery of the benthic community on the floor of the pit is considered in the evaluation of the loss of benthic communities.

20. Depletion of dissolved oxygen may not be an important factor if regional hypoxia is a frequent occurrence.

21. The impact of the loss of benthic communities on higher trophic levels may be quantified using a bioenergetics approach based on an understanding of the linkage between demersal fish and mobile invertebrates and their specific prey. This will provide a conservative estimate of the impact to higher trophic levels as the bioenergetics approach assumes a food-limited condition that is likely not the case for broad areas of very similar habitat such as muddy seafloor settings.

22. The estimated loss of production at higher trophic levels may be added to the loss from other OCS dredging projects to determine cumulative impact and then compared to harvest levels for commercial species to evaluate the magnitude and acceptability of the impact.

23. Impacts to higher trophic levels associated with the destruction or alteration of spawning/nursery grounds due to dredging or the development of anoxia/hypoxia should be evaluated on a site-specific basis.

24. Pit design could be modified to reduce impact to benthic communities and higher trophic levels if it was determined to be unacceptable.

For pits in sandy seafloor settings the checklist below applies.

1. The quantity of sand required for the project must be determined; for the points below it has been assumed that this quantity is fixed (e.g. a smaller surface area is compensated with a deeper pit to extract the same quantity of sand).

2. The form and orientation of the target geologic deposit will often be the over-riding factor in determining pit shape, and possibly pit depth.

3. In order to complete this evaluation the following oceanographic data is required at the site for the period of at least one year: current speed and direction and distribution through the vertical; wave height, period and direction (including spectra); and suspended sediment concentration, salinity, temperature and dissolved oxygen through the water column.

4. Complete an assessment of morphologic evolution using analytical techniques where only pit infilling rate is required or a hydrodynamic/morphologic model where the migration of the pit may be an important consideration (e.g. potential impact to nearby oil and gas infrastructure).

5. Sandy pits fill primarily through a bed load process and therefore, shallow pits with a larger surface area (and perimeter) will fill faster.

6. Pit infilling is faster for areas with larger waves and stronger currents.

7. Pit infilling is faster (for the same surface area) when the direction of primary flow is perpendicular to long axis of the pit.

8. For pits that are stable or evolve very slowly there may be potential for infilling with finer sediment, changing the grains size of the pit floor.

9. There will be a greater area of erosion impact through pit slope adjustment for deeper pits.

10. Pits will migrate where there is a residual sand transport direction due to currents and/or waves.

11. Far field wave impacts are also reduced for wider, shorter pits, but note that they may be permanent. If necessary, predict shoreline change with 1D or morphologic model.

12. Potential impacts to sand transport pathways must be considered.

13. The benthic community for the surface area of the pit, the pit slope adjustment/migration zone and control areas beyond the pit impact zone should be defined by benthic sampling prior to dredging.

14. Defaunation due to dredging will be greater for pits with larger surface areas.

15. The impact of benthic community loss (or reduction) will be shorter in duration for shallower pits.

16. Depletion of dissolved oxygen in the base of the pit can be ignored as a conservative assumption providing no partial recovery of the benthic community on the floor of the pit is considered in the evaluation of the loss of benthic communities.

17. Depletion of dissolved oxygen may not be an important factor if regional hypoxia is a frequent occurrence.

18. The impact of the loss of benthic communities on higher trophic levels may be quantified using a bioenergetics approach based on an understanding of the linkage between demersal fish and mobile invertebrates and their specific prey. This may provide a conservative estimate of the impact to higher trophic levels as the bioenergetics approach assumes a food-limited condition which may not be the case if and where the sandy setting consists of broad areas of very similar habitat such as expansive non-topographic sand sheets.

19. The estimated loss of production at higher trophic levels may added to the loss from other OCS dredging projects to determine cumulative impact and then compared to harvest levels for commercial species to evaluate the magnitude and acceptability of the impact.

20. Impacts to higher trophic levels associated with the destruction or alteration of spawning/nursery grounds due to dredging or the development of anoxia/hypoxia should be evaluated on a site-specific basis.

21. Pit design could be modified to reduce impact to benthic communities and higher trophic levels if it was determined to be unacceptable.

5.6.2 Comparison of Impacts for Dredge Pits in Sandy and Muddy Seafloor Settings

Dredge pits in muddy seafloor settings have two important general advantages over dredging in sandy seafloor settings: 1) pits in muddy settings will infill relatively quickly owing to the mobility of the finer sediment surrounding the pit, and therefore the recovery time for benthic communities will almost always be finite in time; and 2) more often than not, muddy seafloor settings do not represent unique habitat (this is certainly the case along the western Gulf of Mexico coast), and therefore, impact to higher trophic levels will be less significant as they are not food-limited. Another advantage of pits in muddy settings is that there is little or no chance of impact related to the sediment budget of the nearshore area inshore of the pit (i.e. where sand moving shorewards may be intercepted by a pit or where sand from the nearshore profile may move offshore to fill the pit).

In contrast, pits in sandy settings may not fill in at all, or fill very slowly. Also, there is greater likelihood that the substrate will be finer in the pit that the surrounding sandy substrate. Therefore, changes to habitat may be permanent in nature. Whether this results in a net positive or negative change to production at higher trophic levels will be very difficult to determine. Therefore, if nothing else, there is much more uncertainty in determining the impact of pits in sandy settings, where the pit does not infill. In addition, any impacts associated with changes to waves that reach the shore or through diminished dissolved oxygen levels in the pit will be permanent, or of much greater duration, where pits in sandy settings do not fill in, or fill in very slowly, respectively. Finally, recovery time for benthic communities associated with sandy sediment has been found to be longer than for muddy sediments.

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Appendix

APPENDICES

APPENDIX A:
REPORTS ON GEOLOGY AND GEOMORPHOLOGY

Appendix

APPENDIX A.1:
REPORT ON THE ATLANTIC COAST DEPOSITS, RPI LOUISIANA

Lowstand Valleys and Sand Sheets – East Coast of USA

HAYES, M.O.

FINAL REPORT:

TITLE: Lowstand Valleys and Sand Sheets – East Coast of USA

DATE: 22 November 2005; Revised 12 September 2007

BY: Miles O. Hayes, Research Planning, Inc., Columbia, South Carolina

GOALS OF PROJECT

The primary tasks are to review and assemble information on the nearshore shelf area of the eastern United States as it relates to sand sheets and "buried channels."

Two major topics were covered in this review:

1) With regard to the sand sheets, determine whether sand pathways are disrupted and to what extent in these areas will pits fill in with fine sediments. Thus, adjacent subsurface conditions should be considered.
2) With regard to the buried lowstand valleys, what is the range of thickness of the overlying cap and how does it vary (with respect to its geotechnical properties)? Also, where are the valleys located?

First, a comment on the terminology used in this report. With regard to the term "buried channels," most practicing geologists exploring for oil-and-gas deposits in ancient deposits of this type refer to them as paleo-valleys. Canyons, arroyos, and valleys are formed by downcutting associated with stream erosion, but aggraded valleys are filled with a variety of sediments, some of which are deposited as point bars on meandering channels, some in braided channel sheet sands, some in tidal inlet and tidal-delta deposits, and so on. The major features that show up on the numerous seismic traces in the many references under discussion here are valleys, not individual river and tidal channels. Some of the best seismic traces do show individual channels, but they are usually more subtle than the boundaries of the valleys, which produce very distinct reflectors. These clearly defined surfaces of the valley boundaries are referred to as the "lowstand surface of erosion" or sequence boundary one by stratigraphers. Entire books have been written on valley deposits in the rock record, because they are favored as exploration targets by oil-and-gas explorationists. Unfortunately, these features are sometimes referred to as "incised valleys" (as if they could be formed in any other way). Anderson, in his excellent report that is part of this study (see Appendix A.2), also referred to the so-called "buried channels" as valleys (Trinity, Sabine and Rio Grande Valleys, etc.). During our training courses for the oil-and-gas industry, we have for many years referred to these features as lowstand valleys (with reference to their formation during lowered sea levels) and that is the term used in this report.

SEDIMENT CHARACTERISTICS OF LOWSTAND VALLEYS (GENERAL DISCUSSION)

As a generalization, the typical, medium to large scale lowstand valleys that occur on the continental shelf along the southeast and east-central coast of the USA were initiated by downward erosion by major streams when the base levels for those streams were lower than they are today. This maximum lowering of base level occurred most commonly when sea level dropped several hundred feet during the different major Pleistocene glaciations, of which there were at least four.

Figure 1 is an approximation of the sea-level curve for the South Carolina coast during the past 10,000 years. The upper part of this curve, which covers the last 6,000 years or so, is based on detailed, combined archeological and stratigraphical research (Colquhoun and Brooks, 1986). The rest of the curve is somewhat hypothetical, except that it is generally agreed the lowest level during the last major glaciation (the Wisconsin Glaciation), which ended about 10-12,000 years ago, was near 350 feet below the present level. Between 10,000 and 6,000 years ago, the sea level rose at the average rate of a little over one foot per century. As indicated on the curve in Figure 1, however, this rise was not continuous, with several stillstands occurring during the relatively rapid rise. The exact levels of each of the stillstands has not been determined with certainty. The blips on the curve shown in Figure 1 are for demonstration purposes only. This is an important point, however, because during these stillstands, significant sand deposits, such as river deltas and barrier-island chains (with massive tidal-inlet deposits), were formed out on the shelf at elevations lower than sea level is today. Some of these deposits may become important sources for sand in the future.

Our work on the Georgia Bight area over the past 35 years has revealed that there are two end members of lowstand valley types in that area with regard to the nature of the sediments preserved within them:

1) Those valleys formed by rivers that drain the Piedmont and southern Appalachian Mountains, called piedmont or "red-water" rivers. These rivers carry a large sandy sediment load to the coast, forming the only major river deltas on the east coast. The four rivers of this class, which are located on Figure 2, are the Pee Dee, Santee, Savannah, and Altamaha. The valleys of these rivers are illustrated in Figure 3. The image of the continental shelf given in Figure 4 shows at least one river delta at the edge of the continental shelf formed by the combined Santee and Pee Dee Rivers during one or more of the major lowstands of sea level during the Pleistocene Epoch. These two rivers carry the largest freshwater discharge of any of the rivers between Cape Hatteras and Cape Canaveral. The presence of the lowstand delta indicates that large volumes of sediment, including sand, were carried the entire 60 miles across the area now occupied by the continental shelf during the lowstands.
2) Those valley formed by rivers that are located within the confines of the Coastal Plain, called coastal plain or "black-water" rivers. Unlike the piedmont rivers, these rivers, which drain the flat topography and sedimentary rocks of the Coastal Plain, contain very minimal sandy sediment loads. The major coastal plain rivers in South Carolina are indicated on Figure 2 and some of the major valleys are illustrated in Figure 3.

In order to illustrate the differences between these two lowstand valley types, two hypothetical river systems, based on actual studies by the author and his students at the University of South Carolina (e.g., McCants, 1982; Hayes and Sexton, 1989), as well as several RPI projects (e.g., Hayes, 1994; Sexton and Hayes, 1996), are illustrated in Figures 5 and 6.

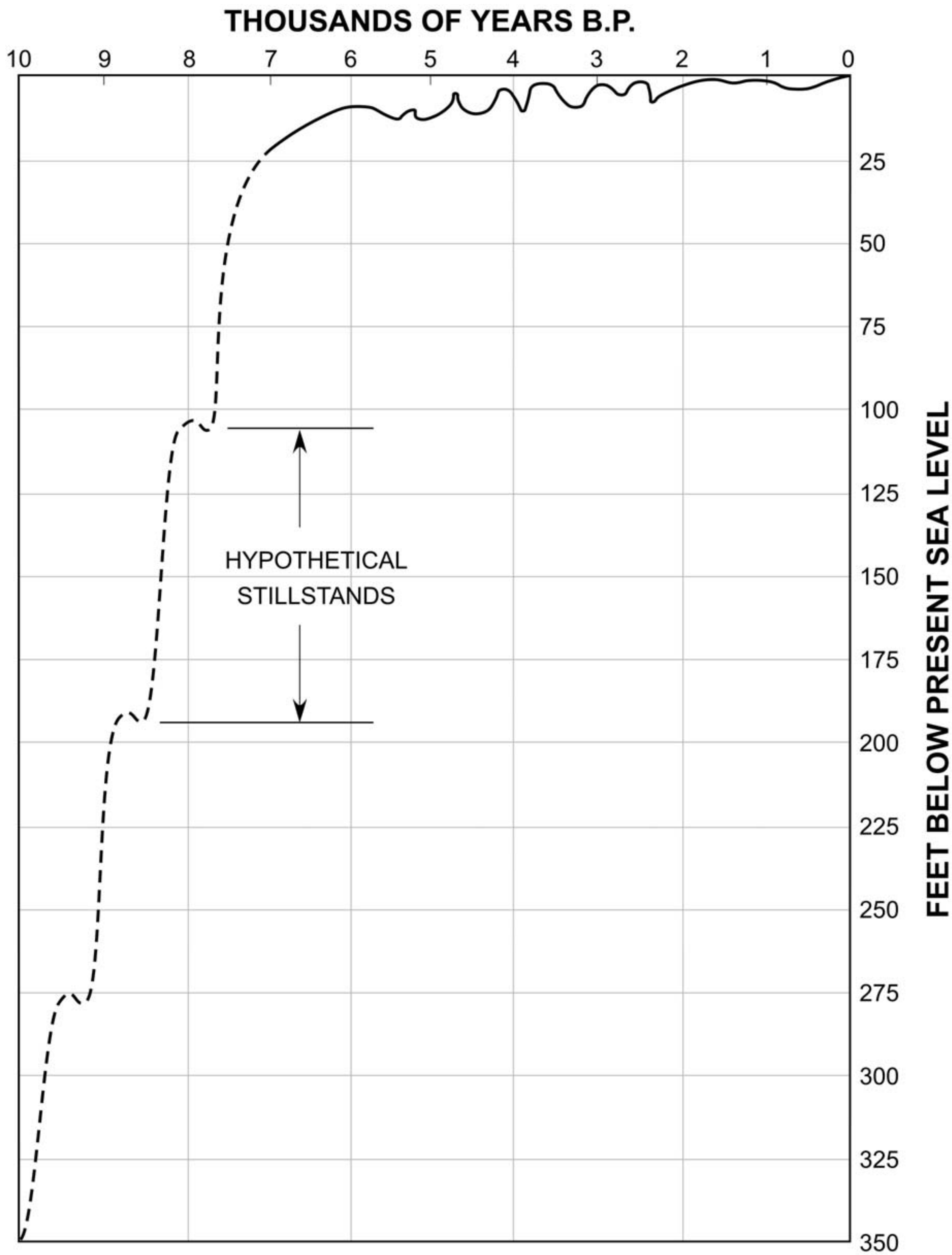

FIGURE 1. Sea level curve for the South Carolina coast for the past 10,000 years. The past 6,000 years is based on Colquhoun and Brooks (1986). The rest of the curve is hypothetical except for the ultimate level (~350 feet) at 10,000 years B.P. (before present).

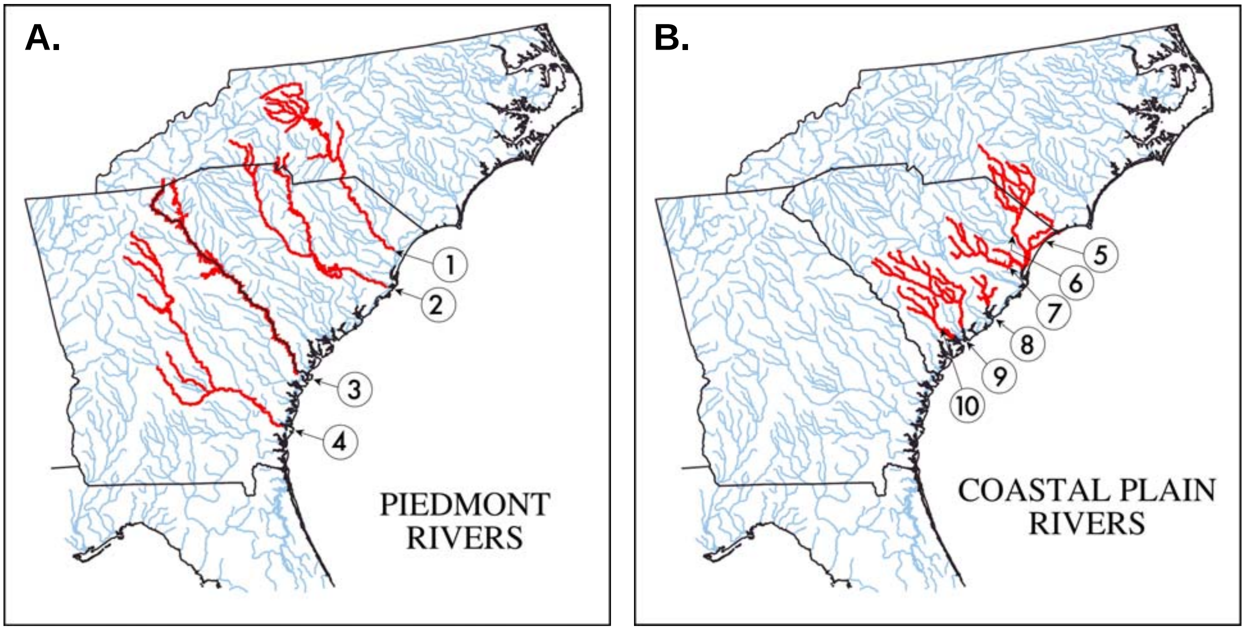

FIGURE 2. Major piedmont and coastal plain river systems occurring within the Georgia Bight region. (A) Piedmont Rivers – Pee Dee (1), Santee (2), Savannah (3), and Altamaha (4). (B) Coastal Plain Rivers – Waccamaw (5), Little Pee Dee (6), Black (7), Cooper (8), Edisto (9), and Combahee (10). Coastal plain rivers in Georgia are not named.

Figure 5 shows the two types of valleys at maximum lowstand. Note that a delta is actively forming at the end of the eroded valley of the piedmont river, but none is present off the coastal plain river. These same valleys under present sea-level conditions are illustrated in Figure 6. Two topographic cross-sections of each valley type are illustrated in Figure 7, and cross-sections of the sediment types that filled them as sea level was rising and during the present stillstand are given in Figures 8 and 9.

Valleys formed by piedmont rivers typically went through the following evolutionary cycle:

1) While sea level was low (during one of the glaciations), a valley as much as 100 feet deep was carved (as is illustrated in Figure 7). Very little sediment carried by the river was being deposited and retained within the valley during that period.
2) With the early rise of sea level resulting from the melting of the glaciers, the river located within the valley began to deposit a flood plain in its lower reaches. If the stream was braided in this earlier phase, and we have every reason to believe most of them were, a sheet-like deposit of coarse-grained sediments would have filled the lower portions of the valley (see stratigraphic cross-sections in Figure 8). The presence of braided channels is probable in the earlier phases of valley fill, because of the relatively steep gradient of the stream. Studies of ancient alluvial valleys in the Cretaceous sediments of western Canada (RPI, 1981), as well as of cores drilled in the Congaree Valley in South Carolina (Hayes and Sexton, 1989), indicate that this is commonly the case. Because of the steep gradient of the stream during this early time interval, fine-grained sediments would have been carried further seaward.

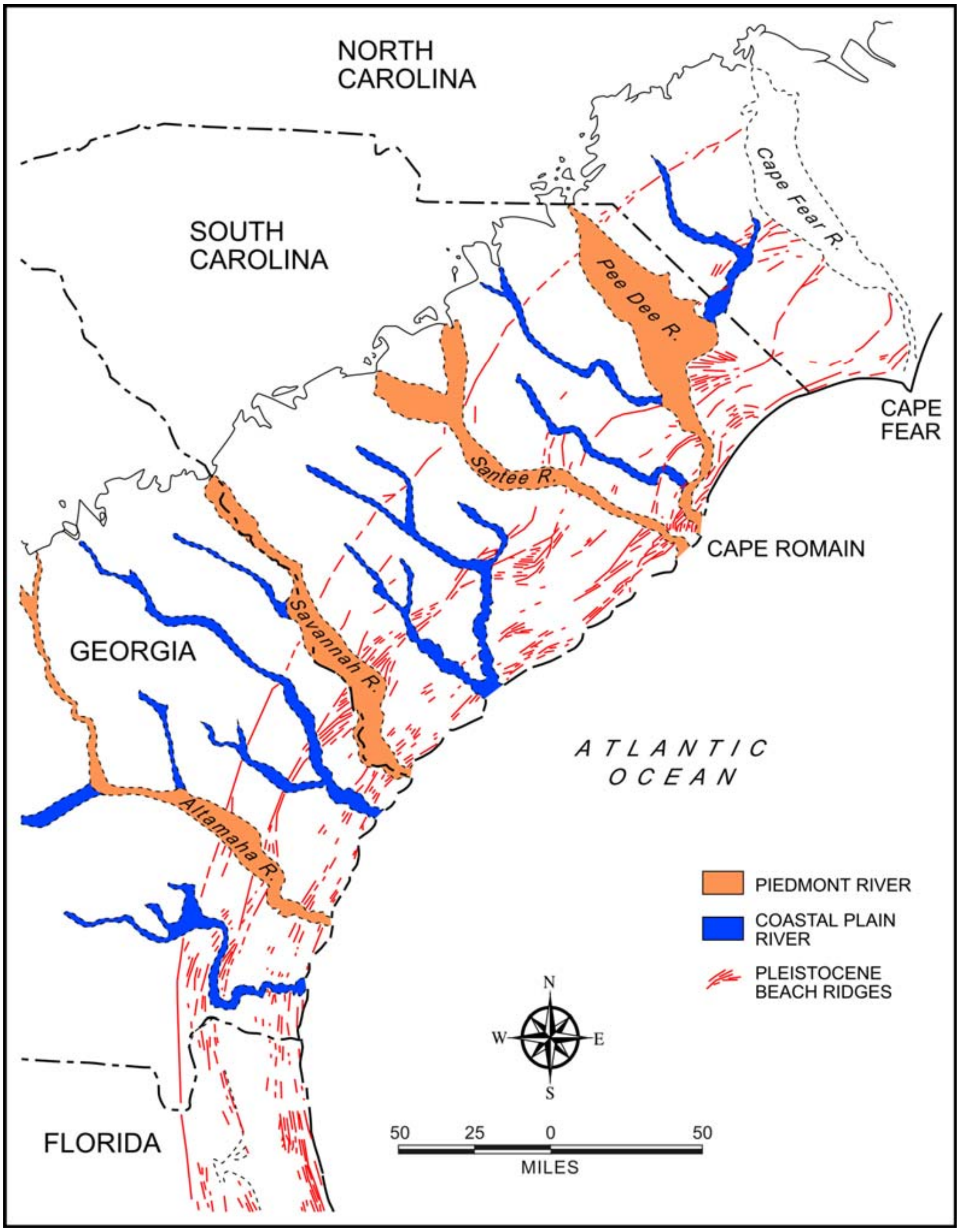

FIGURE 3. Major lowstand valleys of the coastal plains of South Carolina and Georgia. The valleys were carved when sea level was lowered during the major glaciations of the Pleistocene Epoch. The bulk of the sediments composing the flood plains that now occupy these valleys were deposited during the last major rise in sea level, which started about 10,000 years ago. The valleys of the four piedmont, or red-water, rivers (Pee Dee, Santee, Savannah, and Altamaha), are shown in orange, and those of the major coastal plain, or black-water, rivers are shown in blue. The red lines indicate the position of beach ridges formed when highstands of sea level occurred between the major glaciations. Highly modified after Winker and Howard (1977).

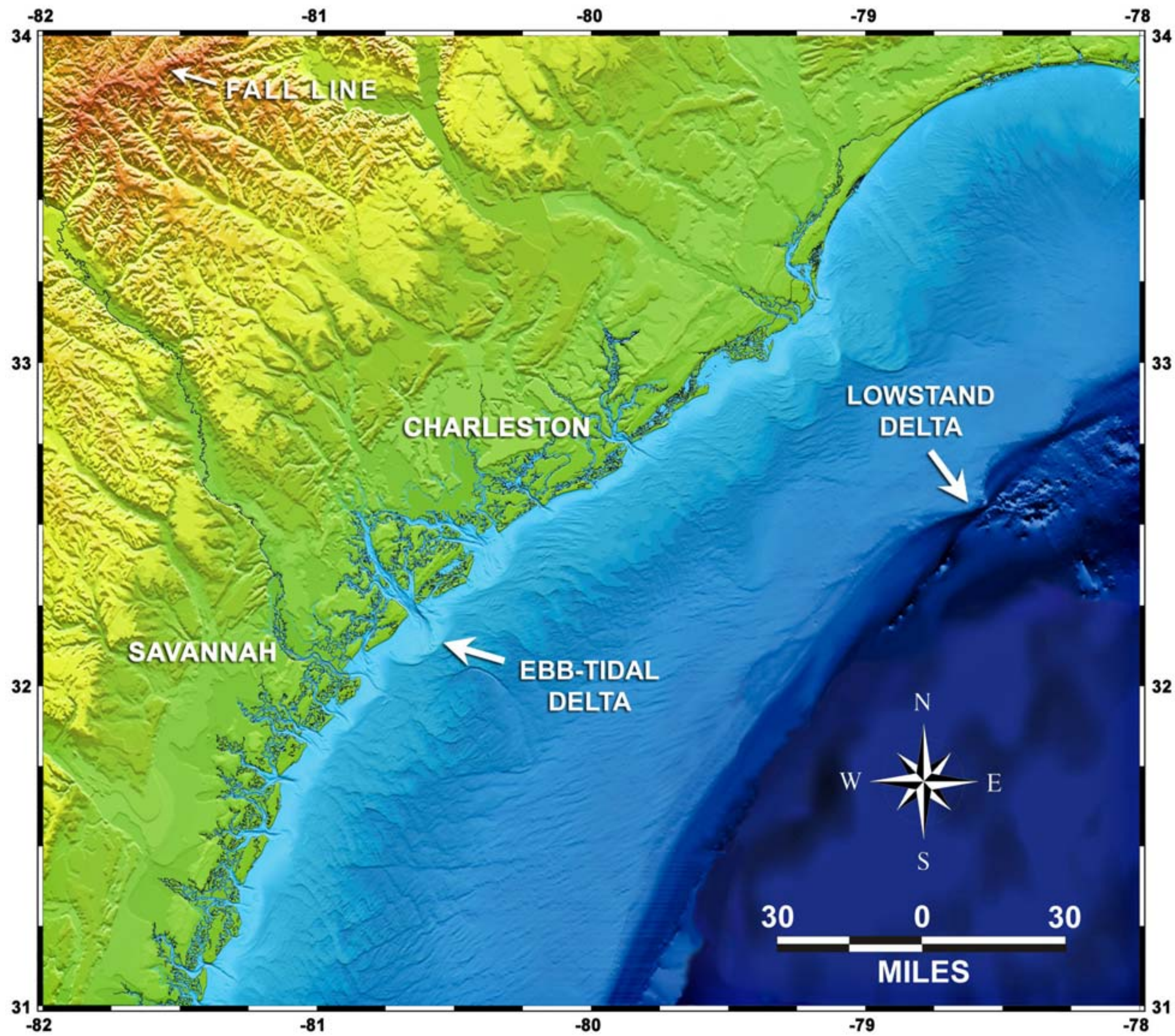

FIGURE 4. Bathymetry of continental shelf off the South Carolina and Georgia shorelines. Note the lowstand delta at the edge of the continental shelf (arrow), as well as the numerous relict deltas further landward on the shelf, off the present mouths of the Santee and Pee Dee Rivers. The massive ebb-tidal delta off Port Royal Sound (arrow) is also clearly shown. From the National Geophysical Data Center (Coastal Relief Model).

3) As the stream developed a flatter gradient later in the episode of rising sea level, the stream channel most probably changed from braided to meandering, in which case the sand would have been deposited in the form of point bars along the meander bends of the channel. The point-bar deposits would not be as laterally continuous as the braided stream sediments lower down in the valley deposits. During floods, some fine-grained sediments would be deposited on the parts of the flood plain not associated with the main channel. These overbank sediments, deposited at the same time as the coarser-grained point-bar deposits, would limit the lateral continuity of the

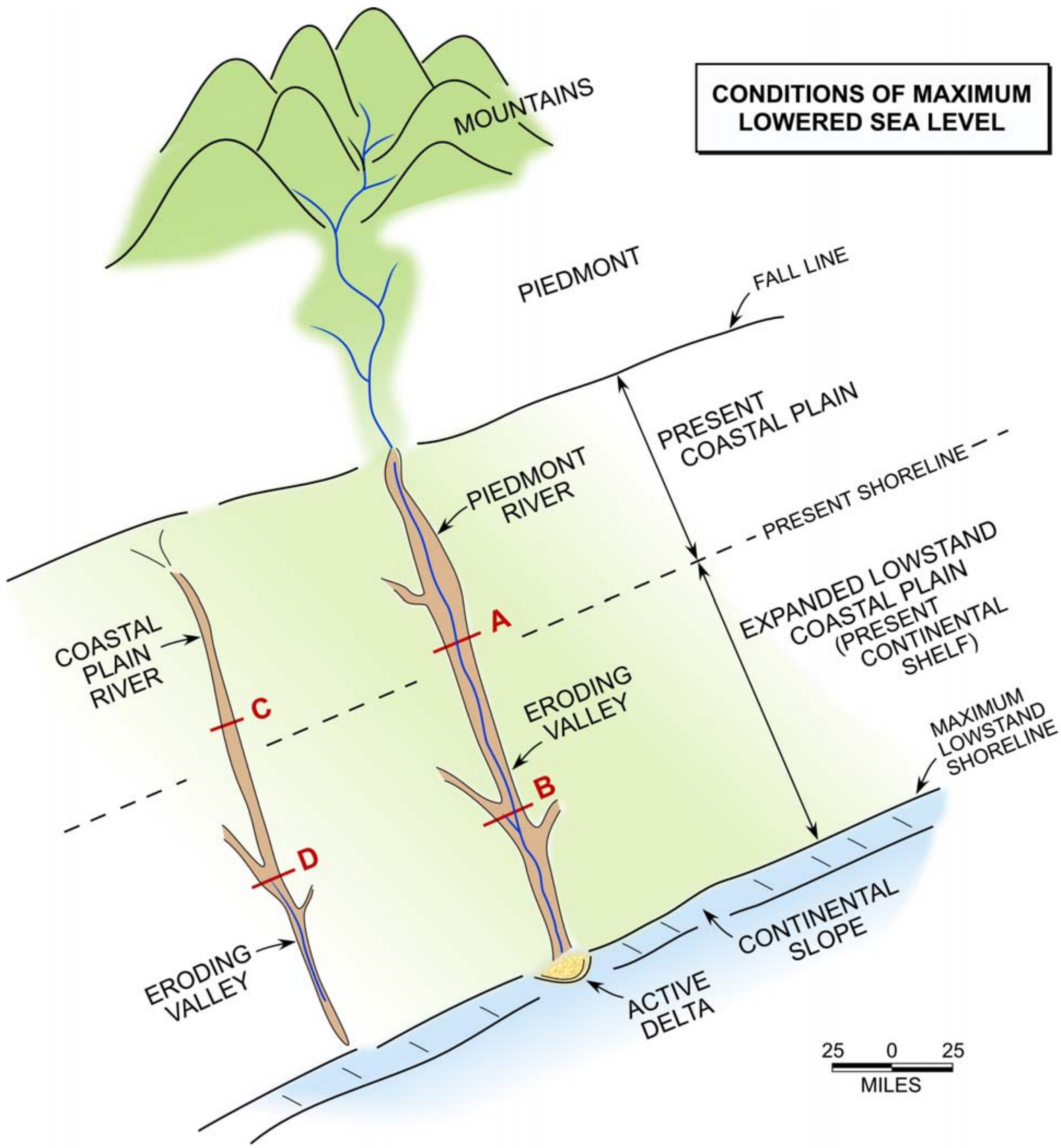

FIGURE 5. Hypothetical illustration of conditions on the continental shelf of the southeastern USA at times of maximum lowered sea level during the Pleistocene Epoch.

sand deposits. Again, numerous examples of this depositional pattern have been recognized in the rock record (Hayes and Kana, 1976). Needless to say, the finer-grained overbank, flood-plain deposits would make poor beach fill material. The point bars, however, which could be as thick as 40 feet or so, would typically make excellent beach sand. Exploring for the point bar sands is much more difficult than exploring for the deeper, laterally continuous braided stream deposits, because of the relatively random distribution of the point bars throughout the valley fill.

4) As the valley fills and the stream gradient decreases even more, extensive, muddy flood-plain sediment would be deposited within the valley.
5) A possible last stage would be the flooding of the valley with marine waters forming an estuary, resulting in the deposition of abundant estuarine muds. With a prolonged stillstand of sea level, however, a coarse-grained river delta could fill in the estuary, as has happened with the Santee River in South Carolina (Hayes and Sexton, 1989).
6) As sea level continued to rise, the so called “ravinement surface,” or “transgressive surface of erosion,” would advance landward and some of the sediments in the upper valley fill would be eroded away (see the stratigraphic sections in sections B in Figure 8 and D in Figure 9). However, any valleys deeper than about 30 feet, the maximum potential depth of ravinement erosion along the east coast (Swift, 1975; Hayes, 1994), would retain some of the sediment even after the shoreline had passed further landward, because the valley-fill deposits could be as much as 100 feet thick.

In general, then, lowstand valleys formed by rivers of the piedmont type should be excellent targets for exploration for sand. Also, the valley would typically become filled with sediments that are coarser-grained near the base and somewhat muddier in the upper portions in flood-plain and delta-plain environments. Because all of the valleys in question on the continental shelf have been “transgressed,” a significant portion of the muddy sediments should have been eroded away.

On the other hand, those lowstand valleys formed by coastal plain rivers should be poor targets for sand exploration. As shown by the stratigraphic cross-sections in Figure 9, the valleys formed by coastal plain rivers are filled mostly with mud. The upper portion of the valley fill would be composed of mud-dominant flood-plain deposits. A few sandy point bars may be present in these sediments, but they would not be numerous enough to provide enough sand for serious exploitation. The lower portion of the valley fill would be composed of muddy estuarine sediments.

One possibility for sand deposits in valleys formed by coastal plain rivers not shown on the cross-sections in Figure 9 is the deposition of tidal-inlet sediments. Large tidal inlets with huge tidal deltas are typically located in the valley entrances during stillstands (Hayes, 1994). The sand that makes up these tidal inlet deposits is brought to the site by longshore sediment transport, not be the river that carved the valley (Pierce and Colquhoun, 1970; Moslow, 1980; and Hayes, 1994). To find these deposits, one would have to determine the locations of the shorelines during the stillstands.

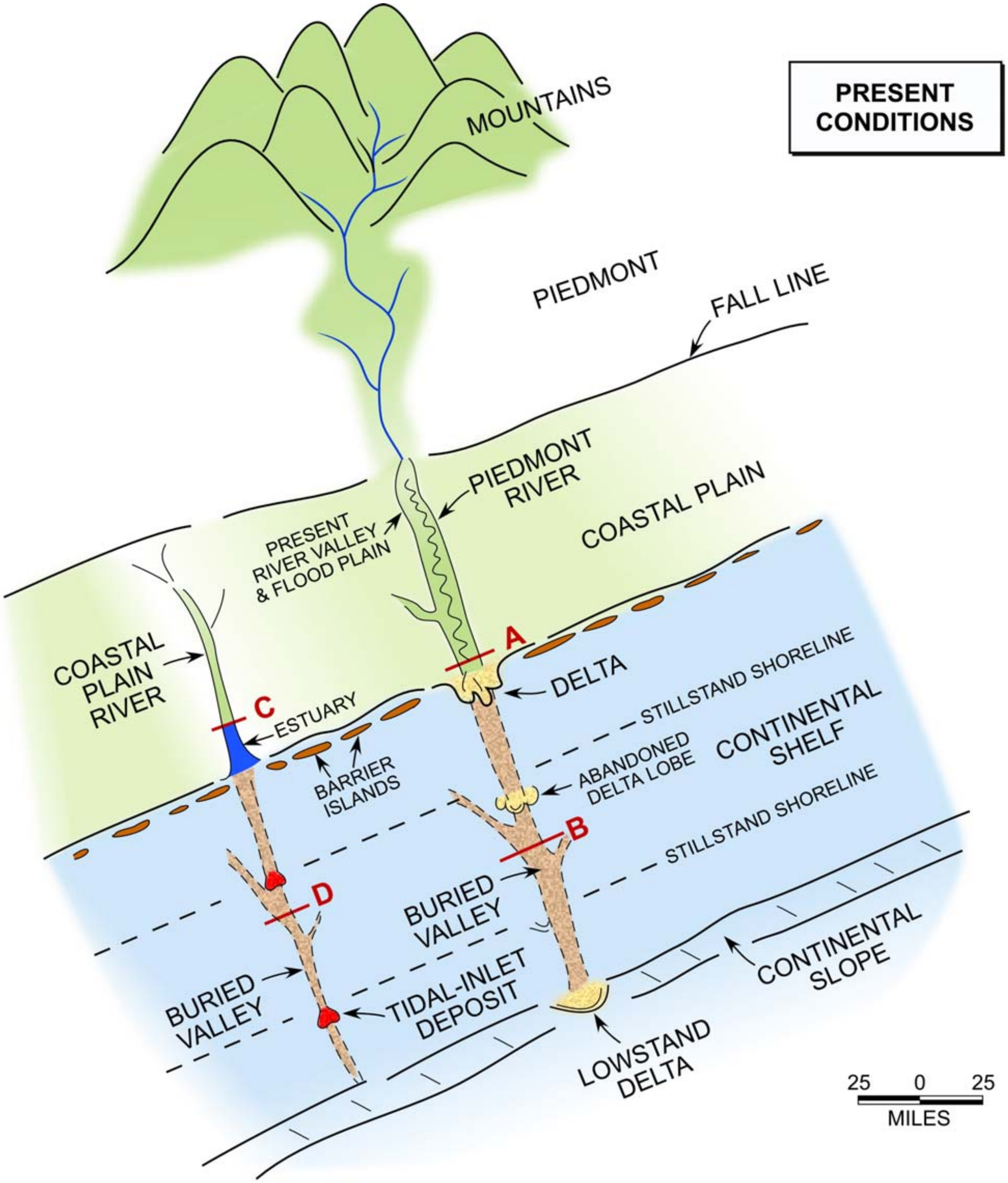

FIGURE 6. General configuration of the shoreline and continental shelf of the southeastern USA during the present highstand of sea level. The locations of the stillstand shorelines are hypothetical. Letters A-D denote locations of topographic and stratigraphic cross-sections given in Figures 7-9. Compare this diagram with the image in Figure 4.

The general model of the two lowstand valley types presented in Figures 5-9 should be applicable for most of the valleys from Florida to New Jersey. However, the further north the valleys are located, the more likely they are to have received some sandy sediments brought south by the glaciers during the Pleistocene Epoch. Also, the associated change in the climate may have increased the potential for some of the rivers in the north to carry more sandy sediment during the glaciations than they do today.

The sediments within some of the lowstand valleys may be more complicated than the general patterns shown in Figures 8 and 9 for another reason. Many of the valleys were eroded during at least four different glaciations when the sea level was lowered significantly. After the first glaciation, the valley became filled with sediments as the sea level rose. During the next lowering of the sea, some of that sediment may have somehow escaped erosion. This process could have been repeated as many as three more times. Therefore, it is possible that the sandy sediments now preserved within a single valley could have been deposited during up to four different time intervals (highstands), making the final preserved sand "target" fairly complicated. We know that the valley fill of the Congaree River in South Carolina is complicated in this way, because the valley migrated to the south throughout the Pleistocene Epoch as a result of uplift on the Cape Fear Arch. Consequently, all of the sediment deposited during a previous highstand was not eroded out during the succeeding lowstand, because the erosion process was focused on the south side of the valley, leaving some of the highstand deposit on the northern side of the valley preserved (Hayes and Sexton, 1989).

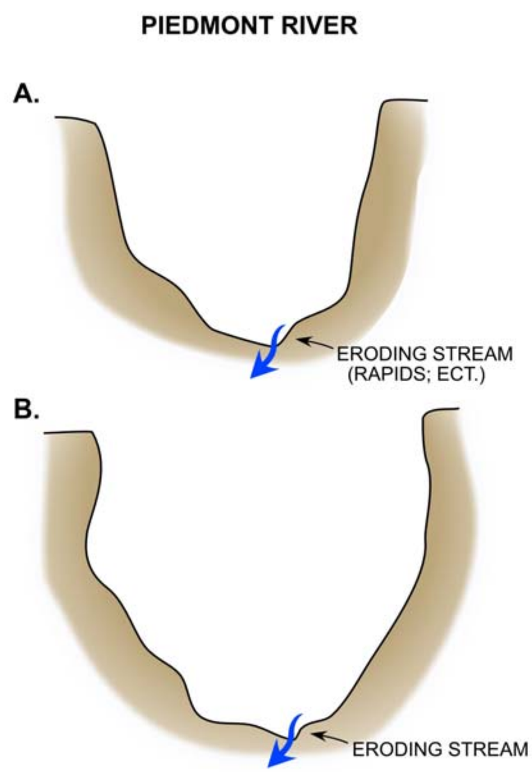

FIGURE 7. Topographic cross-section of the lowstand valleys shown in Figure 5 (during periods of maximum lowered sea levels).

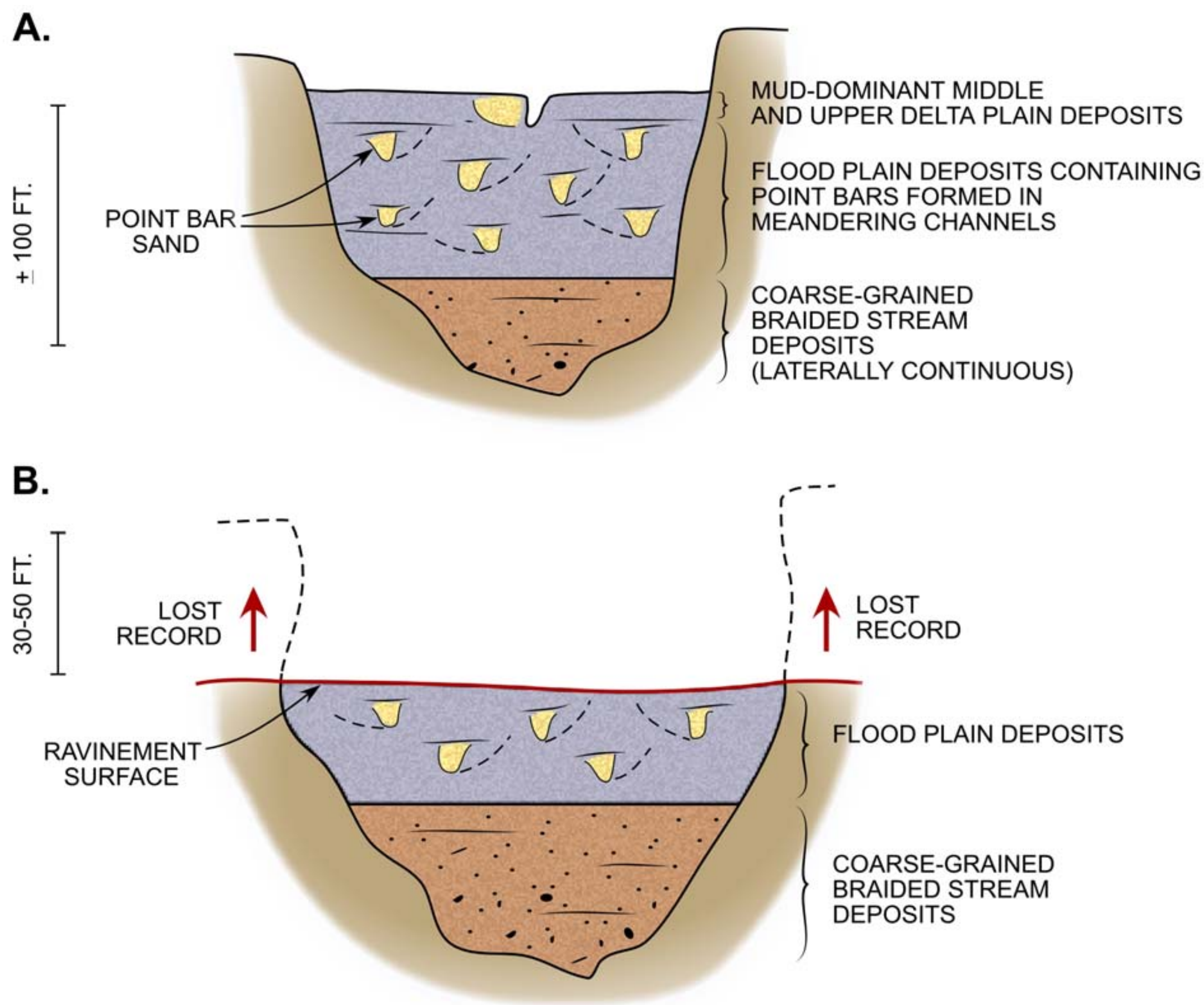

FIGURE 8. Stratigraphic cross-sections for the lowstand valley of the piedmont river illustrated in Figure 6 (during present highstand of sea level).

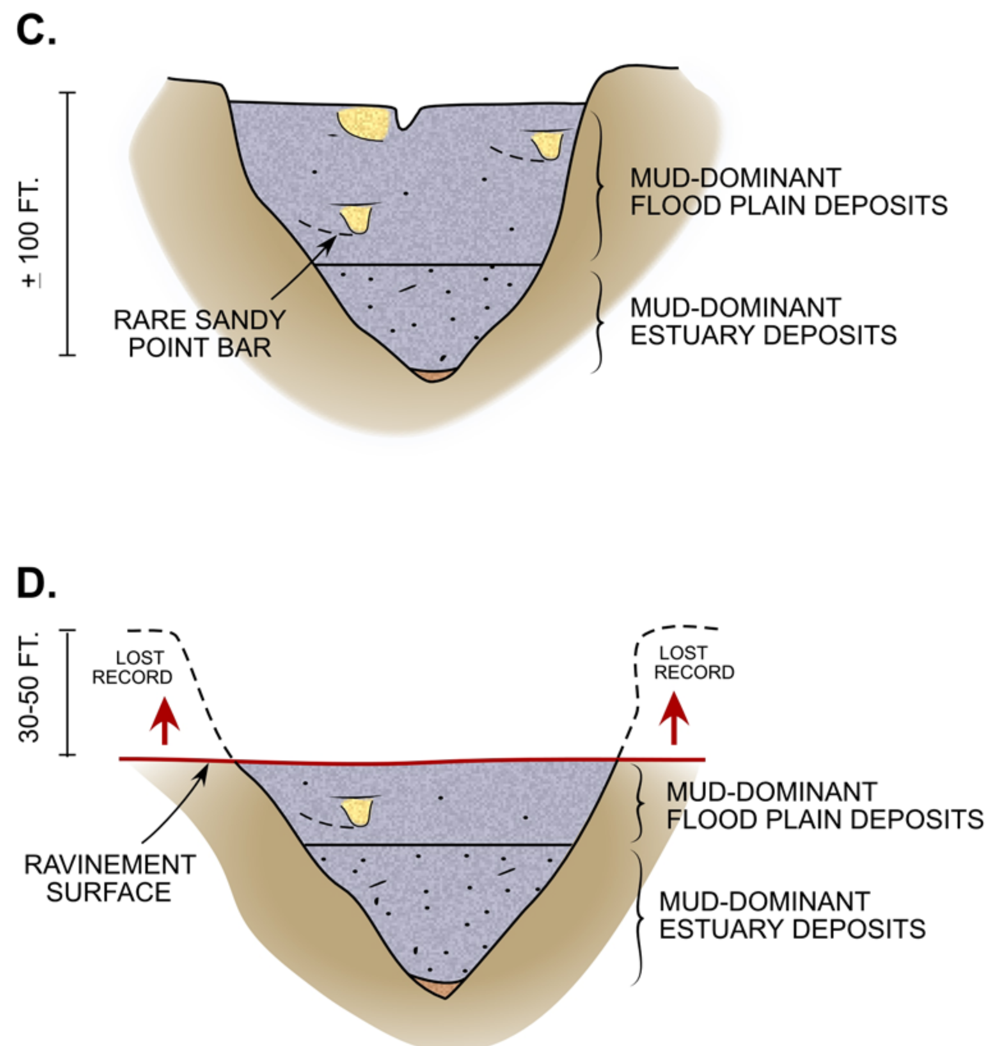

FIGURE 9. Stratigraphic cross-sections for the lowstand valley of the coastal plain river illustrated in Figure 6 (during present highstand).

REVIEW OF STUDIES BY STATE

The following is a brief discussion of the lowstand valleys on the continental shelves adjacent to the states from Florida to New Jersey. The states in New England were not considered, because of two factors: a) the Pleistocene glaciers brought coarse sediments into the coastal area; and b) the effect of glacial rebound on sea-level changes. These two issues make the New England area significantly different from the areas further south with regard to sand deposits in lowstand valleys. A discussion of that completely different area is beyond the scope of this study.

Florida

General Discussion – There are likely few buried lowstand valleys on the continental shelf of eastern Florida because there are few major river systems in that area. Exceptions would be the St. Marys River on the Georgia/Florida border and the extension of the mouth of the St. Johns River at Jacksonville. No references to valleys in those areas were found. Such valleys are no doubt present, but the rivers that carved them were coastal plain rivers (probably with mud-dominant valley fill). However, inlet-fill deposits are possible sand sources in those valleys.

In Florida, OCS sand shoals have been the major source of Federal sand for coastal restoration projects.

Maps of Lowstand Valleys – None were located.

Sediment Characteristics of Lowstand Valleys – Unknown.

Summary – No studies of lowstand valleys on the OCS of the east coast of Florida were identified. The dominant sources of OCS sand are shoals.

Georgia

General Discussion – Information on the inner shelf of Georgia regarding the use of sand sources from sand sheets and lowstand valleys for beach nourishment has not been located. Where Georgia beaches have been nourished, most of that sand came from the huge ebb-tidal deltas and estuarine entrance shoals that occur on that shelf.

Maps of Lowstand Valleys – Henry and Idris (1992), reporting on a minerals assessment study of the Georgia continental shelf, stated that "the seismic records illustrate numerous incised valleys" but they did not reconstruct what they termed "Quaternary paleodrainage networks." Henry et al. (1981), reporting on an earlier shelf survey, noted that "subsurface data show evidence of two possible fluvial erosion surfaces inferred to have been cut during sea-level lowstands in the Pleistocene and Pliocene. Large paleochannels incise to depths of –40 m MSL."

Sediment Characteristics of Lowstand Valleys – Unknown.

Summary – The presence of lowstand valleys in the Georgia OCS has been established, but detailed data on their sedimentary fill is lacking.

South Carolina

General Discussion – Baldwin et al. (2006) gives a thorough coverage of the lowstand valleys in the OCS of the northern third of the South Carolina coast. Some of the most important observations in that paper include:

1) Seven major "paleochannel groups" (presumably lowstand valleys) occur in this area from the present mouth of the Pee Dee/Waccamaw Rivers to the North Carolina border, a distance of approximately 56 miles.
2) Over time, from the late Pliocene to present, the valleys have been displaced to the south. Two possible reasons are suggested in the paper: a) Forcing the stream outlets to the south as a result of southerly longshore sediment transport; and b) Continuous elevation of the Cape Fear Arch, which is located several miles north of the South

Carolina border. The authors favor option a, but option b may be more appropriate, because of evidence of the impact of the rising arch on flood-plain geomorphology of several major rivers to the south of it (Hayes and Sexton, 1989).

3) Generally speaking, the “paleochannel groups” range from about 18-72 feet deep and have widths between 0.6-7.5 miles.
4) These valleys show up clearly on the seismic panels.
5) They say the “channel group contains one or more main channel trunks, which are the deepest and widest incisions within the network.” Interestingly, “shallower, narrower incisions represent smaller localized channels, including tidal inlets, swashes, and backbarrier creeks.” These valley fills are exposed at the surface in places and buried by “surficial sediments” in others, presumably by modern shelf sedimentation, which tends to be relatively thin and sandy in this area. This is an important observation regarding mud cap thickness. Apparently, the upper mud layers have been eroded away in the valley fills “exposed at the surface.”

Several other papers, notably Donovan-Ealy et al. (1993), Putney et al. (2004), and Harris et al. (2005) give additional details on the sediments and geomorphology of the OCS in South Carolina.

Maps of Lowstand Valleys – Figure 10, from Baldwin et al. (2006), is a map showing the location of the lowstand valley systems along the northern one third or so of the South Carolina OCS.

Sediment Characteristics of Lowstand Valleys (In South Carolina) – Based on a conversation with Wayne Baldwin, the senior author of the 2006 paper discussed above, lowstand valley sediments on the OCS of the northern third of the South Carolina coast consist of:

1) Homogeneous sand near the bottom of the valleys. (Note: It is important to point out that the river that presumably formed these valleys, the Pee Dee River, is a piedmont river. See Figures 2, 3, 6, and 8.).
2) The top of the valley fill typically has “sand interbedded with organic clay.”
3) The valleys to the south within their study area typically contain a thicker mud cap than those to the north, probably because of the uplift on the Cape Fear Arch to the north, which allowed the erosion during the transgression to cut deeper into the valley sediments (this is my interpretation). Another possibility is that the longer reaches of the valleys to the south were not completely filled in with coarse sediment by the time of the present stillstand (about 4,500 years ago), whereas the shorter reaches to the north were. This hypothesis assumes that all of the valleys were carved by ancestral Pee Dee River systems as is suggested by Baldwin et al. (2006). The Pee Dee River typically carries a significant load of coarse-grained sediments. Possibly a combination of these two suggested hypotheses, the uplift plus the diminishing supply of sand, explains the increase in the thickness of the mud cap toward the south.
4) The sea bottom in the open shelf areas adjacent to the valleys in the northern area is covered by only a thin veneer of sand or patches of mud in places (up to about 3 feet). Bare rock outcrops are also present in some areas.

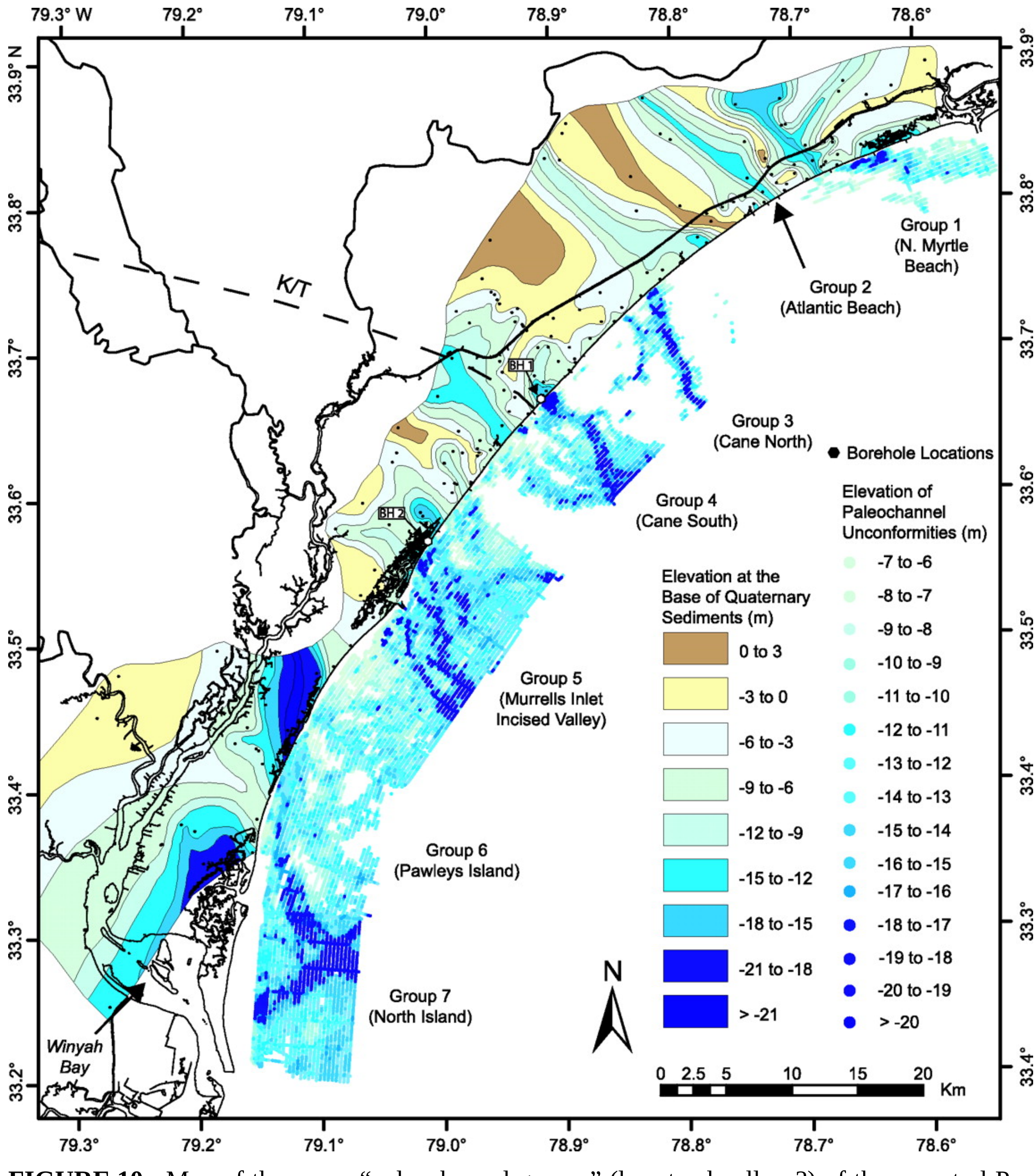

FIGURE 10. Map of the seven "paleochannel groups" (lowstand valleys?) of the ancestral Pee Dee River identified beneath the Grand Strand and Long Bay inner shelf, South Carolina. Onshore contours represent the elevation (in meters relative to mean sea level [msl]) of the unconformity at the base of Quaternary sediments and were constructed from borehole data. Offshore elevations (in meters relative to msl) of "paleochannel" unconformities were interpreted from seismic-reflection profiles. From Baldwin et al. (2006), Figure 4.

Although Baldwin says they have no vibracores of the valley fills in the Myrtle Beach area, other studies have taken sediment samples and cores from the South Carolina shelf (e.g., Gayes and Donovan-Ealy, 1995: Alpine, 1986). Matching their core data with lowstand valleys has been difficult. However, a more detailed study might be able to make that correlation with more certainty.

Based on seismic investigations of the lowstand valleys off Myrtle Beach by Alpine (1986), a study by the U. S. Army Corps of Engineers (1990) identified the lowstand valleys as potential sites for beach-fill material. According to Baldwin, lowstand valley sediments have been used twice for beach nourishment projects at Myrtle Beach.

Summary – The abundance of seismic and boring data on the lowstand valleys in the northern OCS area of South Carolina has located several lowstand valleys that are potential sources for beach nourishment. In fact, lowstand valley sediment has been used already as a source for beach sand at Myrtle Beach. The mud cap over the sandy sediments in these buried valleys is quite thin (only a few feet in the northern section), probably because of: 1) the tectonic uplift of the Cape Fear Arch; 2) the abundance of coarse sediments provided by the Pee Dee River (a piedmont river), and 3) the generally mud-starved nature of the continental shelf between Charleston, South Carolina and Chesapeake Bay. The mud cap apparently thickens in some of the valleys to the south (near the present mouth of the Pee Dee River), but no data to verify the thickness of the mud cap in that area have been found.

Presumably, the search for sand in lowstand valleys has focused more in the northern sector of the OCS of South Carolina than elsewhere, because of the abundance of large ebb-tidal deltas (see Figure 4) and other types of sand shoals on the shelf in the southern sector.

The report by Anderson (Appendix A.1, this report) shows an abundance of relatively thick modern muddy sediments that cap many of the buried lowstand valleys on the OCS of Texas, no doubt because of the heavy load of muddy sediments carried by the large rivers of the Gulf Coast. General tectonic downwarping in that area may also be a factor. These two variables, modern rivers carrying heavy loads of muddy sediment and tectonic downwarping, are not nearly as dominant along the mid-Atlantic coast.

North Carolina

General Discussion – The OCS off the east coat of North Carolina has a considerable amount of information available regarding lowstand valleys. Studies discussed by Hine and Synder (1985), Riggs et al. (1995), Boss et al. (1999), Boss and Hoffman (2001), and Thieler et al. (1995; 2001) are particularly noteworthy. The North Carolina/MMS Sand Resources Task Force has focused its efforts on the offshore area extending from Oregon Inlet to Duck, recently completing a seismic stratigraphic characterization of that survey area. Approximately 56 new vibracores and 338 square nautical miles of seismic data have been analyzed.

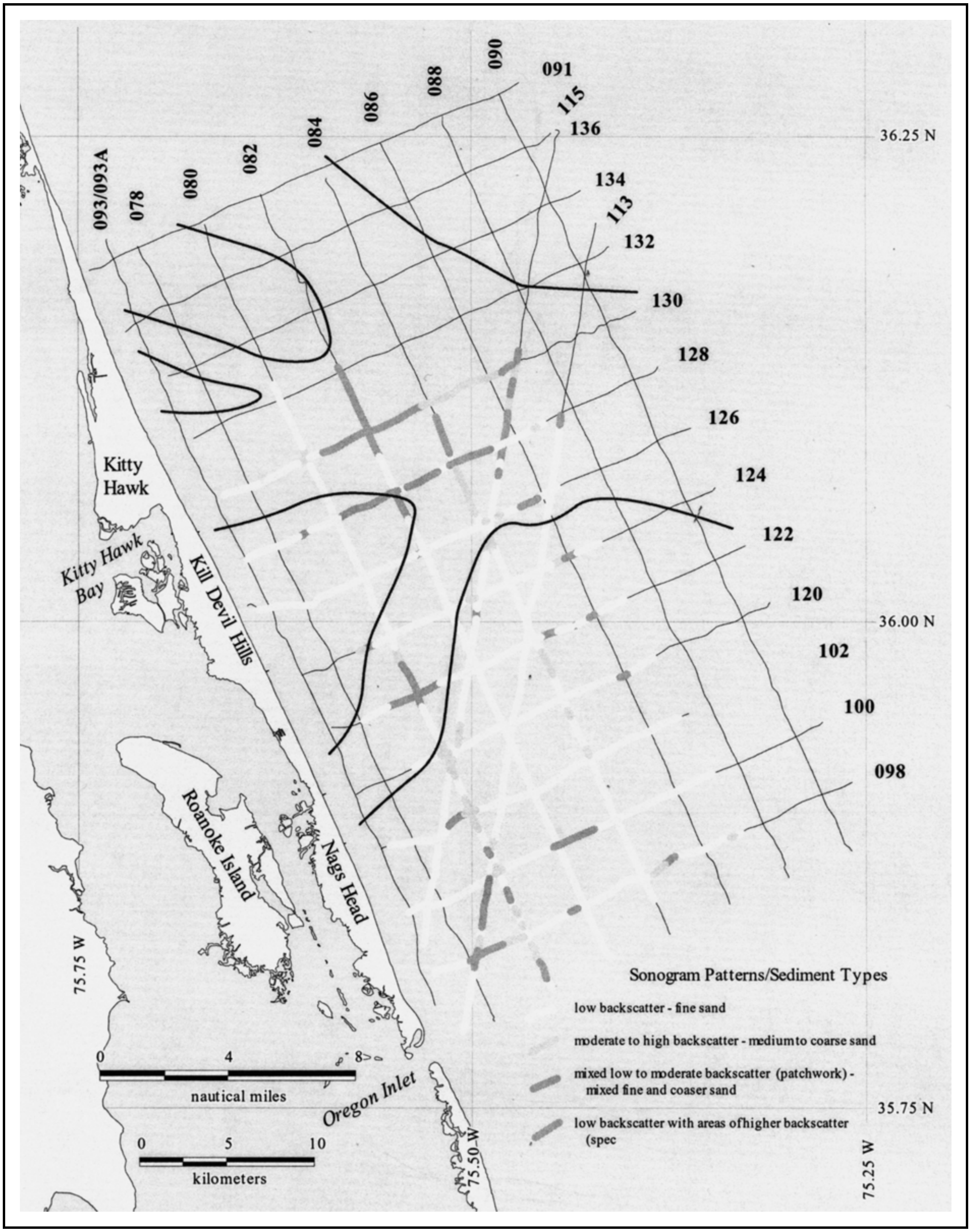

FIGURE 11 Distribution of the main side-scan sonar signatures seen in a portion of the inner continental shelf in the Kitty Hawk, NC area. The heavy lines in the upper half of the diagram locate the boundaries of a major lowstand valley. From Boss et al. (1999).

Maps of Lowstand Valleys – One of the most inclusive earlier references on the regional geomorphological setting of the North Carolina coast, particularly with regard to the presence of lowstand valleys, is Riggs et al. (1995). Their map in Figure 2 in Boss and Hoffman (2001) gives the general location of these valleys, or what they call “valley-fill systems.” From north to south, these systems are: Roanoke/Albemarle Valley Fill; Neuse/Pamlico Valley Fill; White Oak/New River Valley Fill; and Cape Fear Valley Fill. Figure 14 in Boss and Hoffman (2001) gives a map showing the plan-view outline and location of the largest of these systems, the Roanoke/Albemarle Valley Fill, which is located in the Kitty Hawk area. Their map is included as Figure 11 in this report. Thieler et al. (2001) discussed some lowstand valleys located further to the south (off Wrightsville Beach), which are illustrated in Figure 12.

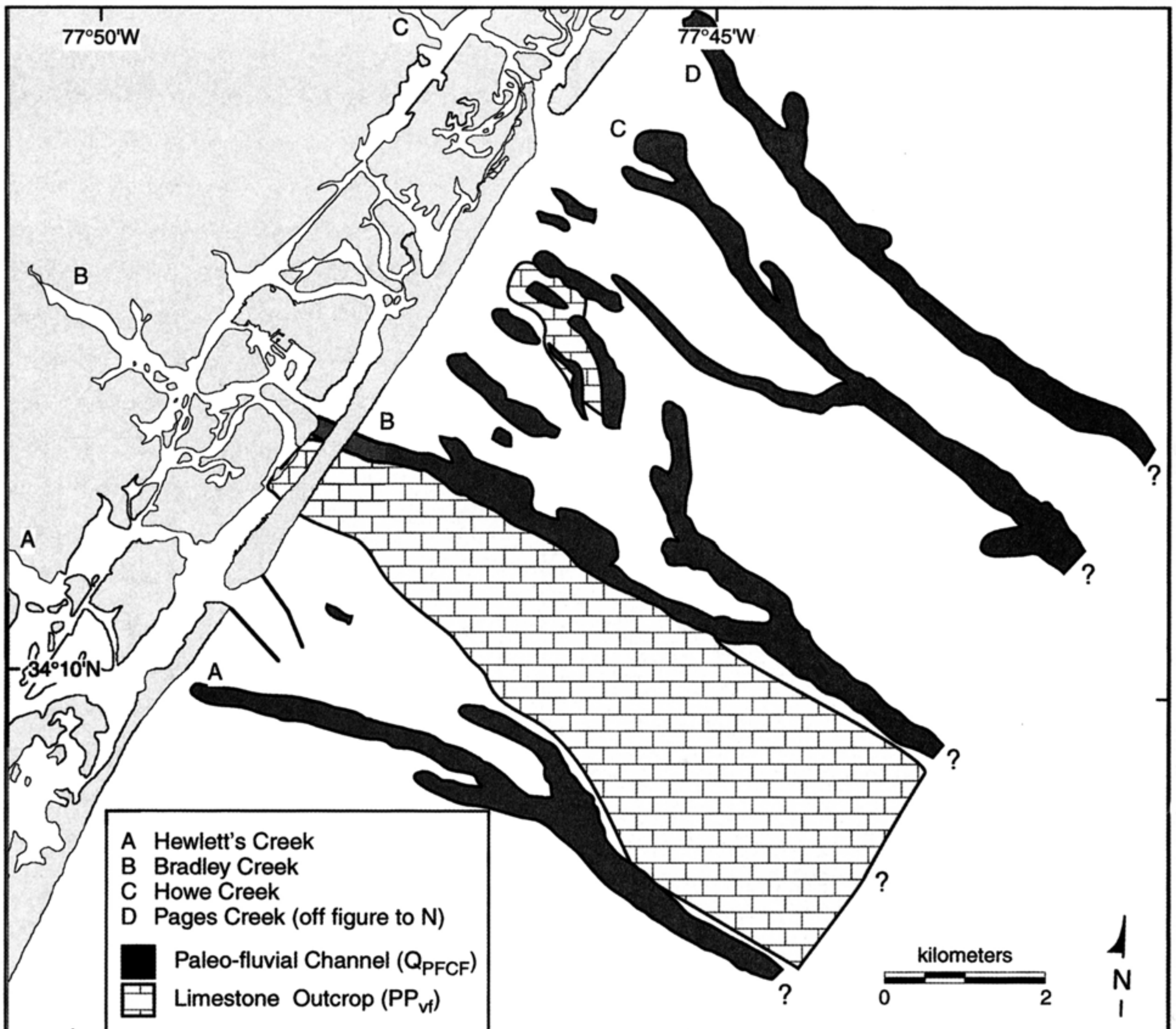

FIGURE 12. Lowstand valleys in the Wrightsville Beach, NC area. From Thieler et al. (2001).

Sediment Characteristics of Lowstand Valleys – Some of the most useful information on the sediment characteristics of the lowstand valley fill on the OCS of North Carolina was presented by Boss and Hoffman (2001). Some of their discussion of the major lowstand valley off Kitty Hawk, illustrated in Figure 11, follows:

1) "The uppermost seismic stratigraphic unit (unit S1) represented sedimentary deposits resulting from extensive fluvial incision of the continental shelf during an episode (or episodes) of lowered sea-level. Fluvial processes during development of unit S1 were responsible for extensive erosion, reworking and re-deposition of sediment throughout most of the northern half of the study area."
2) "During each regressive interval, fluvial systems re-established, and incised into coastal plain and continental shelf sediments, and eroded sediments resulting from previous depositional episodes. During subsequent transgression, fluvial valleys were inundated by rising sea-level and the locus of fluvial sedimentation stepped landward many tens of kilometers, creating estuarine systems dominated by deposition of organic-rich mud and coastal barrier island and shallow marine shelf environments dominated by fine to medium sand reworked from fluvial deposits."
3) The basal reflector of unit S1 "was observed to truncate a number of deeper parallel to sub-parallel reflectors … throughout the northern half of the study area and was interpreted to be the deepest erosional surface developed within a complex series of nested fluvial channels that meander across the continental shelf. Individual seismic profiles in the northern portion of the study area …reveal remarkable detail of multiple channel incisions within unit S1."
4) "The largest trunk channel appears to be that associated with the ancestral Albemarle River, which crosses the continental shelf west-to-east from Kitty Hawk Bay."
5) The maximum observed relief within the channel system (lowstand valley) is on the order of 90 feet.
6) The cores they took only penetrated to "very shallow depths within the sediment package."
7) They describe two basic sediment types in the cores: Type I – mostly sand; Type II – generally muddy.
8) "The relation between paleofluvial channels, high mud content, and Type II cores, became apparent when core locations were plotted on seafloor maps - the paleofluvial valley fill was mud prone, and the bathymetrically high areas (shoals – linear sand ridges presumably) were sand-prone." The fact that the valley fill is mud prone is very significant, because it points out the fact that the river that carved the valley (presumably the Albemarle River) did not carry enough sand to fill in the valley with material useful for beach nourishment. In other words, this river was most likely a coastal plain river that responded in the fashion illustrated in Figures 5-9.

Summary – The Roanoke/Albemarle Valley Fill near Kitty Hawk is probably not one of the better places to look for beach nourishment sand, unless tidal-inlet sand deposits are present. Boss and Hoffman (2001) state clearly that the valley sediments that they cored are "mud-prone." Their explanation of this fact is that "these sediments formed primarily as back-filling estuarine deposits during transgressions," a process discussed earlier when considering the valley fill for coastal plain rivers (outlined in Figure 9). If we assume that cores of the Type II subfacies, which is mud prone, were taken mostly from the valley fill, some thicknesses of the mud cap can be determined. Based on 24 such cores, the maximum depth penetrated was about 18 feet. Average depth of penetration was about 15 feet and the average percent mud by weight was 42 % (maximum value was 71%). None of these cores reached sand at depth. Therefore, the mud cap was at least 15 feet thick and possibly much thicker.

The features off Wrightsville Beach referred to as "Quaternary fluvial channels" by Thieler et al. (2001), shown in Figure 12 in this report, are as much as 30-60 feet deep. Whereas a considerable amount of data was collected on the shoreface sediments in that area, some of which were of beach-nourishment quality, the valley sediments were not cored to any significant depth. Therefore, it is not clear if they are mud-filled or not.

It is unknown at this time how many valleys on the OCS of North Carolina have relatively thick mud caps like the major one off Kitty Hawk. The potential for abundant sand within mud-prone lowstand valleys would be greatly increased if: 1) the ravinement surface has eroded away the mud, or 2) processes, such as ridge-and-swale topography on the shelf or tidal-inlet sedimentation within the valley, have formed some sand deposits that either bury the valley fill or partly fill in the valley (in the case of tidal-inlet fill).

Virginia

General Discussion – Apparently, no significant effort has been made to find potential sand sources from buried lowstand valleys on the Virginia OCS**.** However, Colman et al. (1990), Chen et al. (1995) and Foyle and Oertel (1997) discuss the valleys in that area in some detail.

Maps of Lowstand Valleys – Figure 8 in the Colman et al. (1990) paper, included as Figure 13 in this report, shows show that two buried lowstand valleys underlie the Delmarva Peninsula area. Although the authors of that paper do not discuss the lowstand valleys on the OCS, they do show two seismic cross-sections located in the landward area of the peninsula as well as give descriptions of the valley-fill sediments. These two valleys range from about 1-2 miles in width and both are around 150 feet deep.

Sediment Characteristics of Lowstand Valleys – Colman et al. (1990) described the sediments in the lowstand valleys in the Chesapeake Bay area as follows: "The lower channel-fill unit of each paleochannel is a fluvial deposit, typically consisting of coarse sand and fine gravel. The upper unit of each paleochannel fill, in contrast, was deposited in river-estuary to open-bay environments or in nearshore-marine environments at the bay mouth. These units are finer grained than the lower, fluvial units, and the lithologies are commonly complex, consisting of interbedded muddy sand, silt, and peat, especially near the bay mouth. The estuarine units become finer grained both landward and toward the tops of the units." This trend for the sediments to get finer toward the top of the valley fill is consistent with many of the other valley fills discussed earlier. Therefore, the mud caps in the nearshore region of the Delmarva Peninsula have the potential of being rather thick.

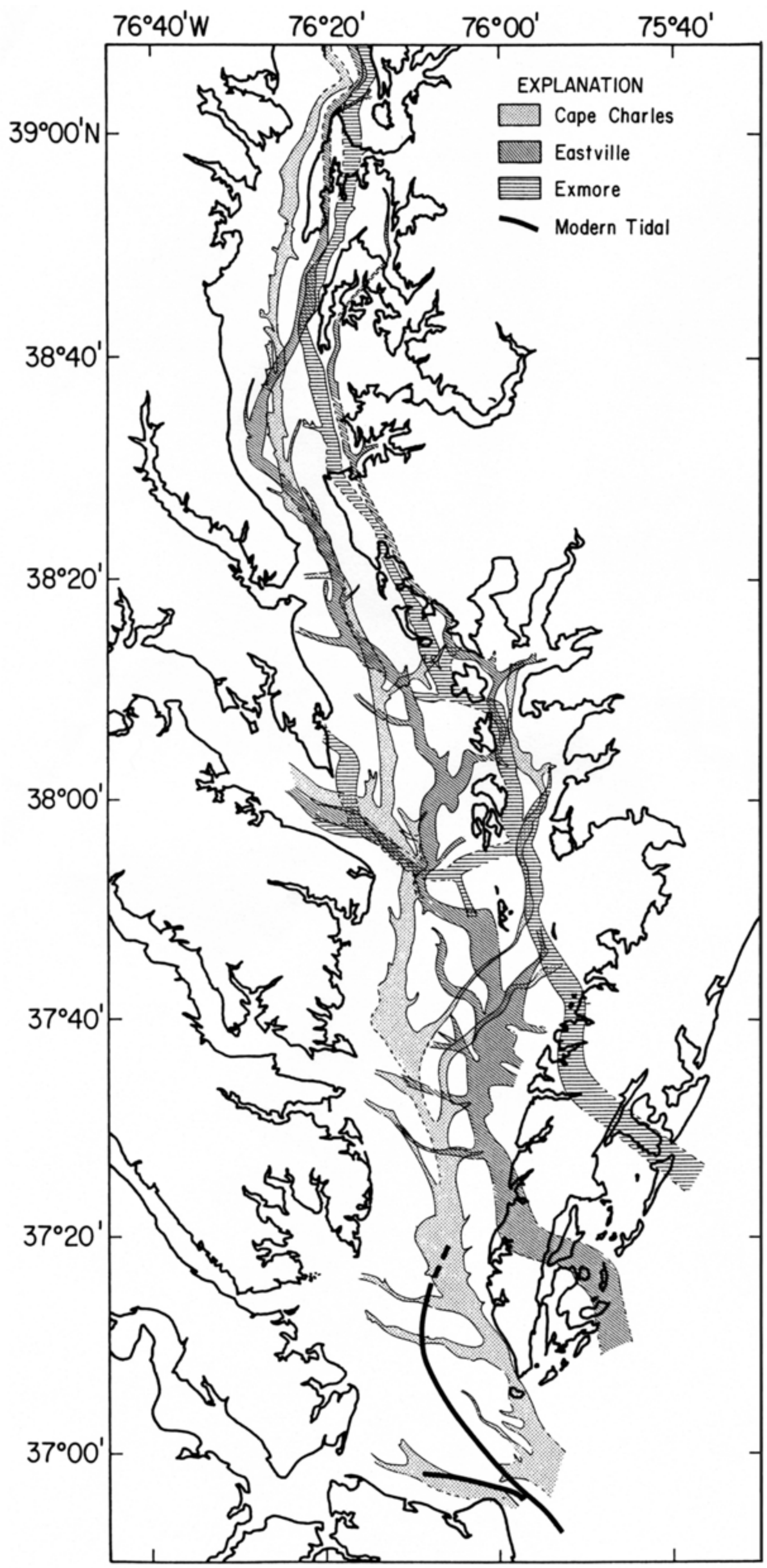

FIGURE 13. Map of the three major Quaternary lowstand valleys of the Susquehanna River beneath the Chesapeake Bay and the Delmarva Peninsula. From Colman et al. (1990).

Foyle and Oertel (1997) observed that the lowstand valleys of the Virginia OCS are up to 3 miles wide, with up to over 100 feet of relief and thalweg depths of up to 120 feet below modern mean sea level. They state further that "these valleys were cut through underlying Pleistocene and Mio-Pliocene strata in response to drops in base level on the order of 300 feet," and that "fluvially incised valleys were significantly modified during subsequent marine transgressions as fluvial drainage basins evolved into estuarine embayments (ancestral generations of the Chesapeake Bay)." Complex incised-valley fill successions are bounded by, or contain, up to four stacked erosional surfaces (basal fluvial erosion surface, bay ravinement, tidal ravinement, and ebb-flood channel base diastem) in vertical succession. The focus of this paper is on unraveling stratigraphic sequences, with little detail given on the sedimentary content of the paleovalleys. However, they do recognize an upper sequence of shelf and shoreline deposits (presumably sand rich) that overlies estuarine deposits (presumably mud rich). Another key point they make is that parts of the valleys are filled with estuarine entrance sediments, which could be sandy. Their comments may be disclosing a general trend, namely that the further offshore one goes in this particular area, the more likely it is that the muddier sediments of the upper valley would be eroded away by the advancing ravinement surface and that sandy estuarine-entrance sands may be present. Ravinement erosion in this area was discussed at some length by Oertel et al. (1991).

Summary – Despite the potential for beach nourishment sand to be present in the lowstand valleys on the OCS of Virginia, it is not possible to give exact numbers on the thickness of the mud cap of these lowstand valleys because of their complex variety. This complexity is caused, at least in part, by their association with an ancestral Chesapeake Bay entrance area.

Maryland

General Discussion – MMS, working in cooperation with the Maryland Geological Survey, has discovered significant volumes of sand on the Maryland OCS, mostly in the form of sandy linear ridge-and-swale topography. A few lowstand valleys are present, but they are limited in size, and are usually buried under significant thickness of overlying sediment.

Maps of Lowstand Valleys – None were located.

Sediment Characteristics of Lowstand Valleys – Unknown.

Summary - Without much supporting information, this shelf appears to be similar to Virginia and New Jersey.

Delaware

General Discussion – Searches for sand for beach nourishment on the Delaware OCS have primarily focused on linear sand ridges (ridge-and-swale topography) and ebb-tidal delta shoals. However, studies reported by McKenna and Ramsey (2002) show that a network of buried lowstand valleys **(**they sometimes refer to them as channels within the paleovalley) underlie the continental shelf off Delaware.

Maps of Lowstand Valleys – Figure 14, from McKenna and Ramsey (2002), shows the location of the principal lowstand valleys on the Delaware OCS. According to McKenna and Ramsey, "the Delaware River paleovalley is a distinct bathymetric low that trends from northwest to southeast from the mouth of Delaware Bay to the continental shelf. It is flanked on the northeast and northwest by bathymetric highs and is defined as a low with depths greater than 70 feet (all depths are presented below sea level) with maximum depths up to 150 feet. Most of the paleovalley is at depths of 70 to 105 feet. within this area of study." This is one of the largest lowstand valleys on the east coast, because the size of the Delaware River.

Sediment Characteristics of Lowstand Valleys – The McKenna and Ramsey (2002) paper has an abundance of data on the sediments on the shelf off Delaware. The M.S. thesis by Williams (1999) is also an excellent source of information on sediment characteristics. The following discussion from the McKenna and Ramsey (2002) summarizes this information:

> "The paleovalley channels have little or no surface expression on the sea floor, and they range in depths below the seafloor surface between 45 feet and 80 feet. Williams (1999) described two generations of erosion and subsequent infilling of the channels with some channels containing mostly mud and others sand. This study has found no influence of the paleovalley channels on the sediment quality or resource rating of cores, because most of the cores were less than 20 feet in length and the sediments filling the paoleovalleys occur too deep to influence this resource evaluation."

McKenna and Ramsey stated further that "of the 32 cores located within the paleovalley channel boundaries and assigned excellent or good resource ratings, all but one core are assumed to be filled with reworked (Holocene) sediments." In other words, the sediment with "excellent" ratings did not come from the valleys. The quality of sediment more closely corresponds to geomorphic region than to proximity to paleovalley channels or to bathymetry.

In summary, while an excellent source of information on the quality of the sand on the Delaware OCS, these two references do not provide any information on the thickness of the mud cap.

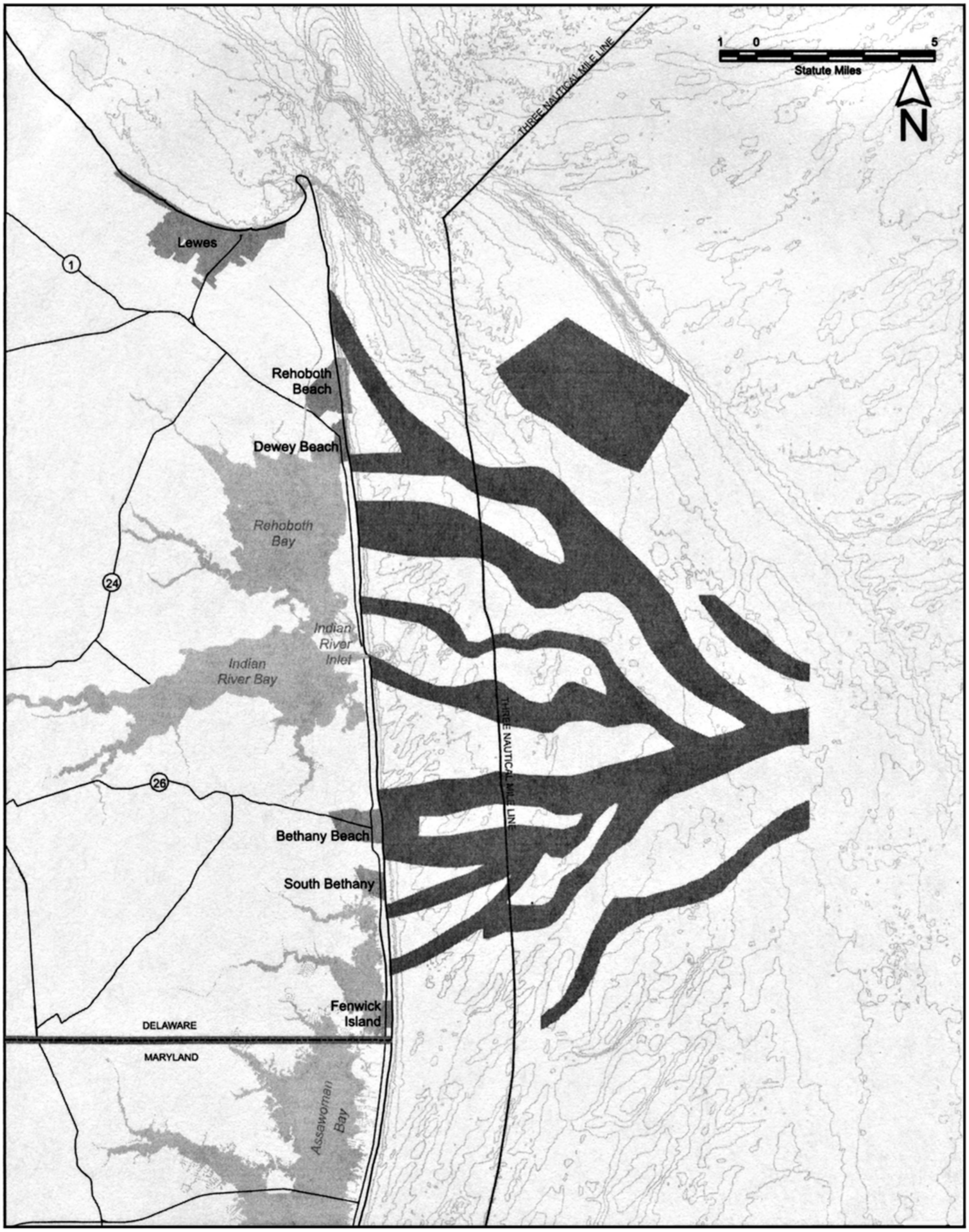

FIGURE 14. Paleovalleys on the inner continental shelf of Delaware [as interpreted by Williams (1999)]. From McKenna and Ramsey (2002).

Summary – The sand and gravel appears to be too deep in the Delaware lowstand valleys to be a good source of sediment for beach nourishment. This probably means that the linear sand ridges and ebb-tidal delta sediments have completely buried and covered the valleys to such an extent that the valley sediment would not be a likely source for beach nourishment sand. This observation illustrates the importance of the erosional nature of the shelf in question. If the shelf is highly eroded and there is little sandy shelf sediment available, such as linear sand ridges and abandoned ebb-tidal deltas, then the lowstand valley sediment may become a meaningful source of beach-nourishment sand. This does not appear to be the case on the Delaware OCS.

New Jersey

General Discussion – Much of the MMS-supported research in the past has focused on linear sand ridges (Byrnes and Hammer, 2001). However, there is also a fairly extensive literature on the investigation of lowstand valleys on the continental shelf off New Jersey. For example, the Institute of Geophysics of the University of Texas has conducted several detailed studies on the outer New Jersey shelf [e.g., Nordfjord et al. (2005); and Goff et al. (1999, 2000, 2004, and 2005)]. Although these studies are informative, this area of study may be too far offshore to provide sand for beach nourishment. Closer-in studies have been completed by Ashley and Sheridan (1994) and Duncan et al. (2000).

Maps of Lowstand Valleys – Nordfjord et al. (2005) gives a number of excellent maps of the valleys (see examples in Figures 15 and 16), but as already noted, these are on the outer part of the shelf.

Sediment Characteristics of Lowstand Valleys – Information on the exact nature of the sediments in the outer shelf valleys studied by Nordfjord et al. (the Goff group) is sparse. However, they hypothesize that the valleys, which had river sediments in their lower parts, turned into estuaries as sea level rose, and that, no doubt, generated some muddy sediments in the upper part of the valley fills.

The following quote from Gaswirth et al. (2002) gives a clue about the nature of the sediments that filled the valleys close to the present shore in New Jersey. “The coarse-grained buried Pleistocene channel deposits and Holocene fine-grained estuarine muds beneath the bay are in contact with the Cretaceous coastal plain stratigraphy. Buried channel deposits have high permeability and are adjacent to the Cretaceous aquifer. Estuarine muds form an aquitard,” etc. Thus, the valleys appear to have significant mud caps, but exact thicknesses are unknown. If some of the valleys were the host of major tidal inlets as sea level rose, they could contain some excellent sand deposits within the upper valley fill. This last statement needs some research, but there certainly may be some of this high-quality sand in at least a few of the valleys.

Summary – The lowstand valleys do not appear to be a premier source of sand for beach nourishment on the New Jersey OCS (unless they contain tidal-inlet fill), especially considering the excellent quality of the linear sand ridges. No specific data are available on the mud cap thicknesses.

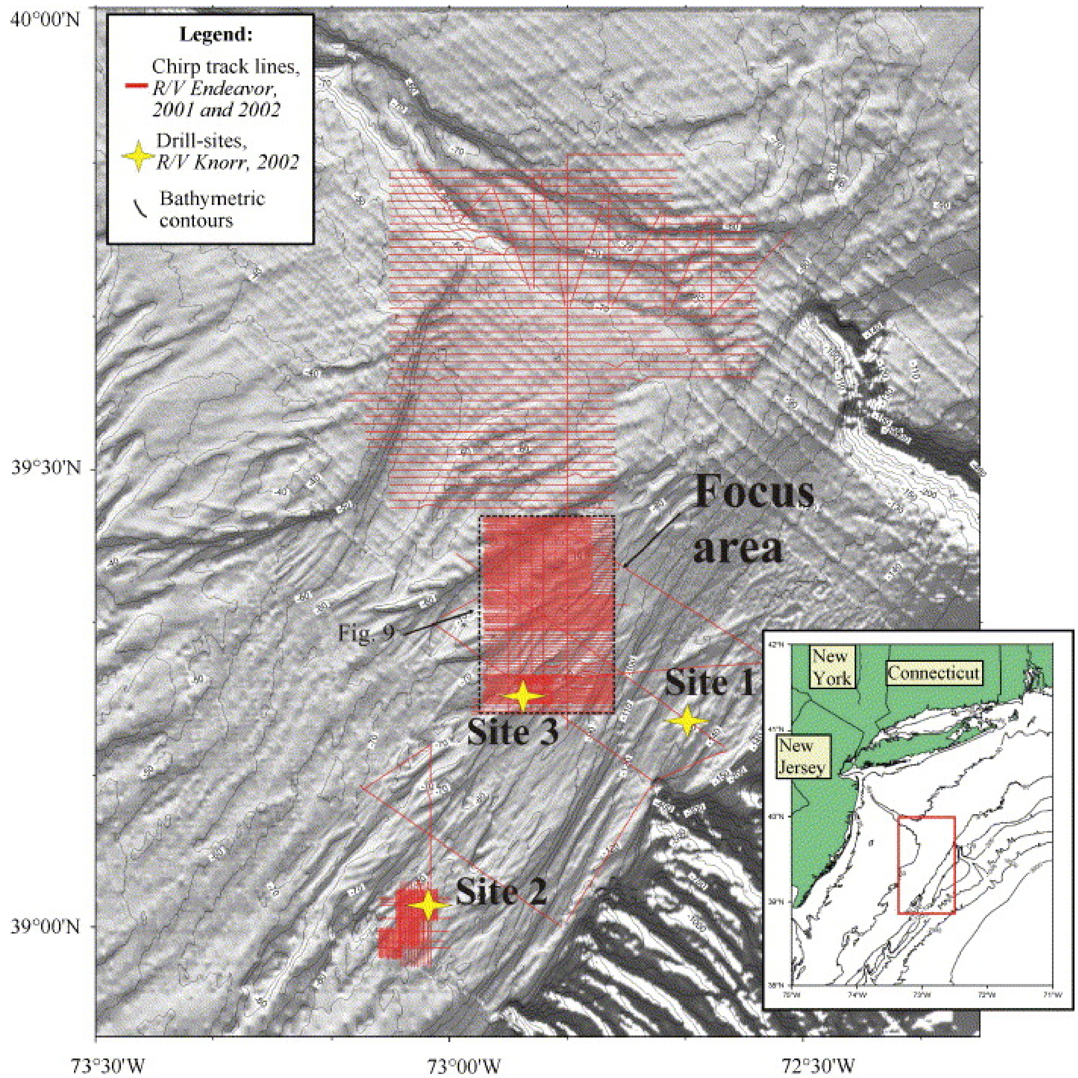

FIGURE 15. Location of deep-towed chirp sonar track lines collected in 2001 and 2002 aboard R/V Endeavor (EN359 and EN370), superimposed on NOAA's bathemetry merged with STRATAFORM swath mapping (Goff et al., 1999) of the New Jersey middle and outer continental shelf. Box shows focus area. 1-3 are boreholes. From Nordfjord et al. (2005).

CONCLUSION ON LOWSTAND VALLEYS

The original assignment posed two questions: (a) what is the range of thickness of the overlying mud cap and how does it vary (with respect to its geotechnical properties), and (b) where are the valleys located?

a) Specific data on the "overlying cap" are limited, but it appears that it is almost universally muddy. Thickness will vary, depending on how much was eroded by the ravinement surface, the depth and general nature of the estuary, where the sediments were deposited, etc. Based on the information at hand, the two places to look for significant sand deposits (i.e., those with minimal thickness of mud cap) in lowstand

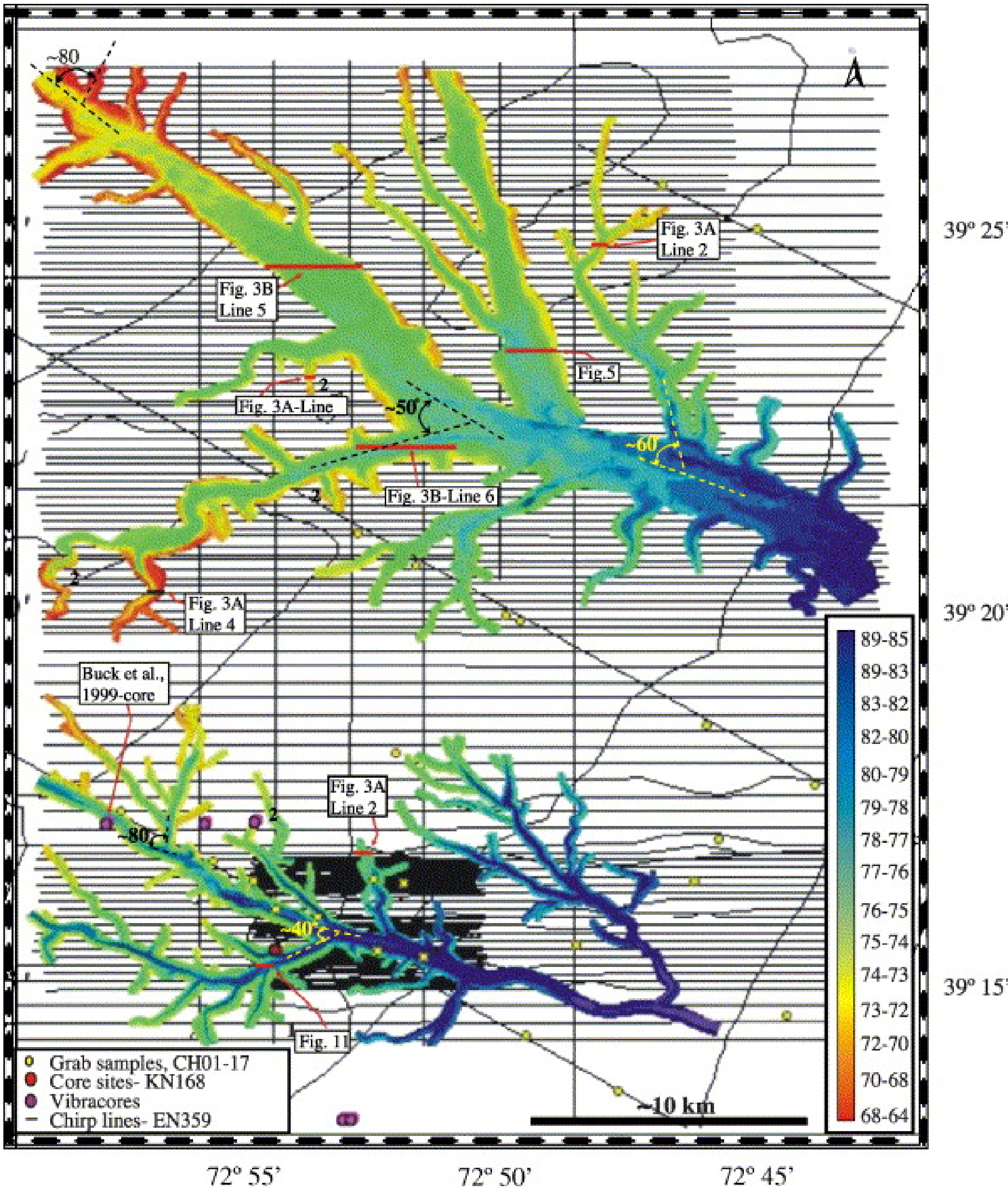

FIGURE 16. Two interpolated, shallowly buried drainage systems mapped beneath the outer New Jersey continental shelf (see Fig. 15 for location of focus area). From Nordfjord et al. (2005).

valleys are: 1) where the shelf is exceptionally erosional, either because of some kind of tectonic uplift (e.g., the Cape Fear Arch) or extensive erosion by the ravinement surface; and 2) where major tidal inlets have occupied the valleys during stillstands within the last sea-level rise.

b) The probability of finding significant sand deposits in lowstand valleys is much greater in the valleys formed by rivers that carried a large, sandy sediment load, such as the piedmont rivers illustrated in Figures 2, 3, 6, and 8. The research for this project has revealed that the only place where lowstand valley sand clearly has been used for beach nourishment is at Myrtle Beach, S. C., and it appears that the river that carved those particular lowstand valleys was a piedmont river (Pee Dee River).

c) Pretty good data are available for the valleys off South Carolina, North Carolina, Virginia and Delaware (and maybe New Jersey). Maps given in Figures 11-17 show some of these valleys.

An important observation shown by this review is that the sediments within the valleys tend to be very complicated. The seismic profile of the major valley off Kitty Hawk, North Carolina given in Figure 17 illustrates this point. This profile, taken from Boss and Hoffman (2001), was run across what they called a "major paleofluvial valley system." This lowstand valley is about 8 miles wide and nearly 100 feet deep. The R1 reflector shown on the profile no doubt marks the eroded bottom of the valley. This seismic panel shows what appear to be individual channel fills within the valley system. Whether these are river channels or tidal channels is unclear. It is also unclear whether these channel fills are sand or finer-grained sediment. This complexity is probably typical of many such valleys, which makes determining average values for mud cap thickness difficult.

A general conclusion based on the information available appears to be that lowstand valleys in the south and central Atlantic are not a very good place to look for sand for beach nourishment at the present time. One problem is that the estuarine mud deposits in many valleys are generally pretty thick (up to 10s of feet). Unfortunately, not enough is know at this time to give averages for "mud cap" thicknesses without more information on the origin of the specific valley in question. Also, the valley deposits are commonly covered with shelf sediments, Therefore, even in those valleys where major quantities of sand are present, they may be at depths too great for recovery. Perhaps some time in the future, however, effective techniques for mining this deeper sand may be developed.

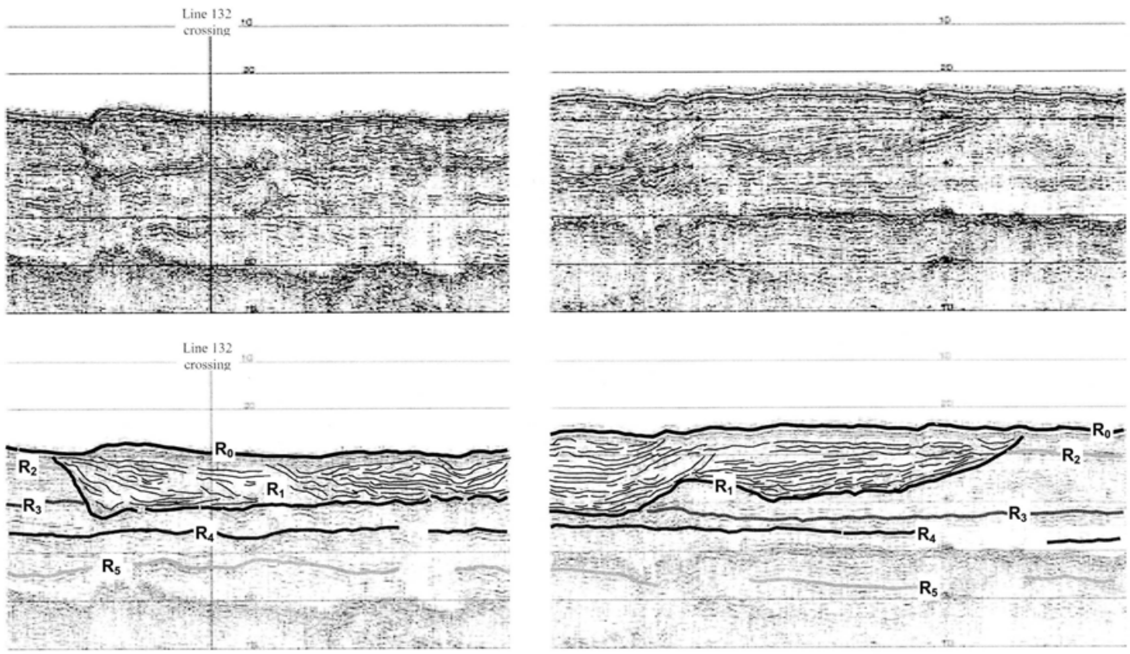

FIGURE 17. Seismic reflection profile across a lowstand valley off Kitty Hawk, North Carolina. The plan view outline of the valley is shown on the map in Figure 11. From Boss and Hoffman (2001).

CONLCUSIONS ON SAND SHEETS

Very limited information on sand sheets has been found. The exact geomorphological definition of these features has also been difficult to determine. They are discussed as follows on the Maryland Geological Survey web site: "Sheet sands are common off the Delmarva coast. These deposits are highly variable in thickness, areal extent and grain size. Such characteristics can make sheet sands difficult to dredge."

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APPENDIX A.2:
REPORT ON TEXAS COAST DEPOSITS, RICE UNIVERSITY

Sand Bodies of the Texas Continental Shelf

Anderson, J., Milliken, K., Simms, A., and Taha, P.

Sand Bodies of the Texas Continental Shelf
John B. Anderson-Project Director
Assisted by Kristy Milliken, Alex Simms and Patrick Taha

During the time period between 1986 and 2001, the Rice University research vessels *R/V Matagorda* and *R/V Lone Star* were used to acquire nearly 20,000 kilometers of high-resolution seismic data from the Texas and western Louisiana continental shelves (Figure 1). These data were augmented by more than 100 vibracores and pneumatic hammer cores and oil company platform boring descriptions to map fluvial channels, deltas and transgressive sand bodies on the continental shelf (Figure 2). The most prominent fluvial valleys include the Sabine, Trinity, Brazos, Colorado, Lavaca, Nueces and Rio Grande alluvial valleys. In this report each valley will be discussed separately, starting with the Sabine Valley.

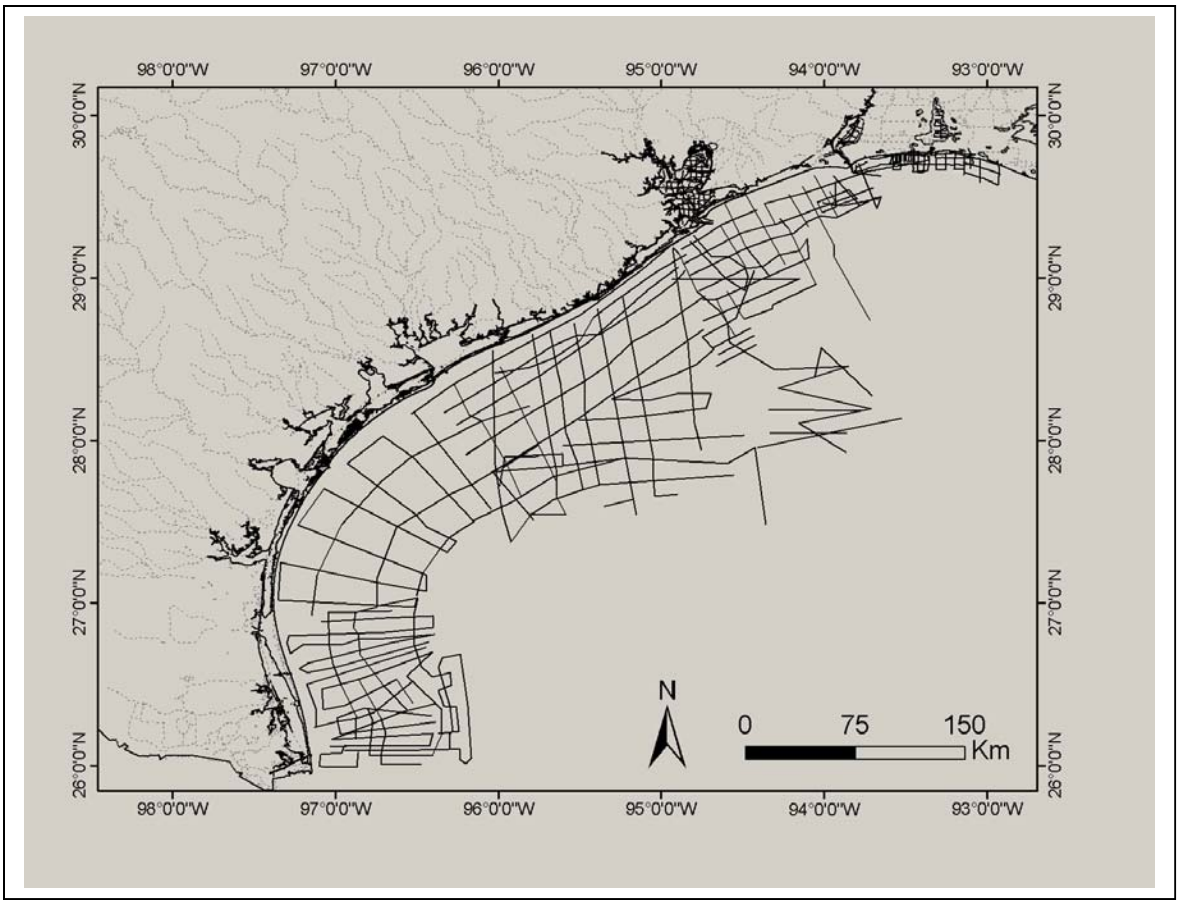

Figure 1. Track lines of high-resolution seismic data used to map fluvial channels on the Texas continental shelf.

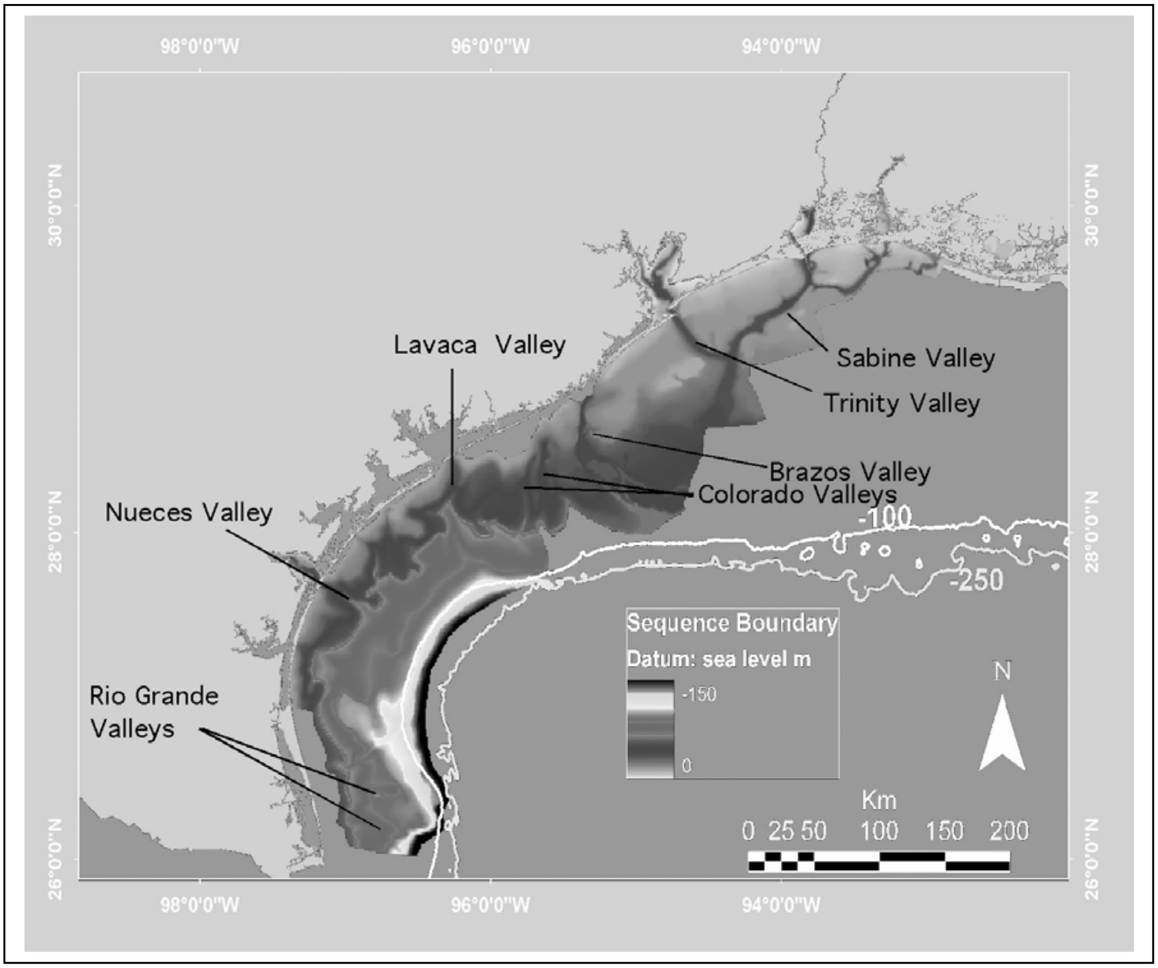

Figure 2. Digital elevation map showing lowstand fluvial channels (from Simms et al., in press).

Sabine Valley

During the last lowstand the Sabine river cut an incised valley that extended offshore and toward the west, merging with the ancestral Trinity River valley approximately 40 kilometers offshore of Bolivar Peninsula (Figure 3). Seismic facies and platform borings indicate that fluvial sands within the valley lie beneath 10 to 20 meters of marine and bay mud (Figure 4).

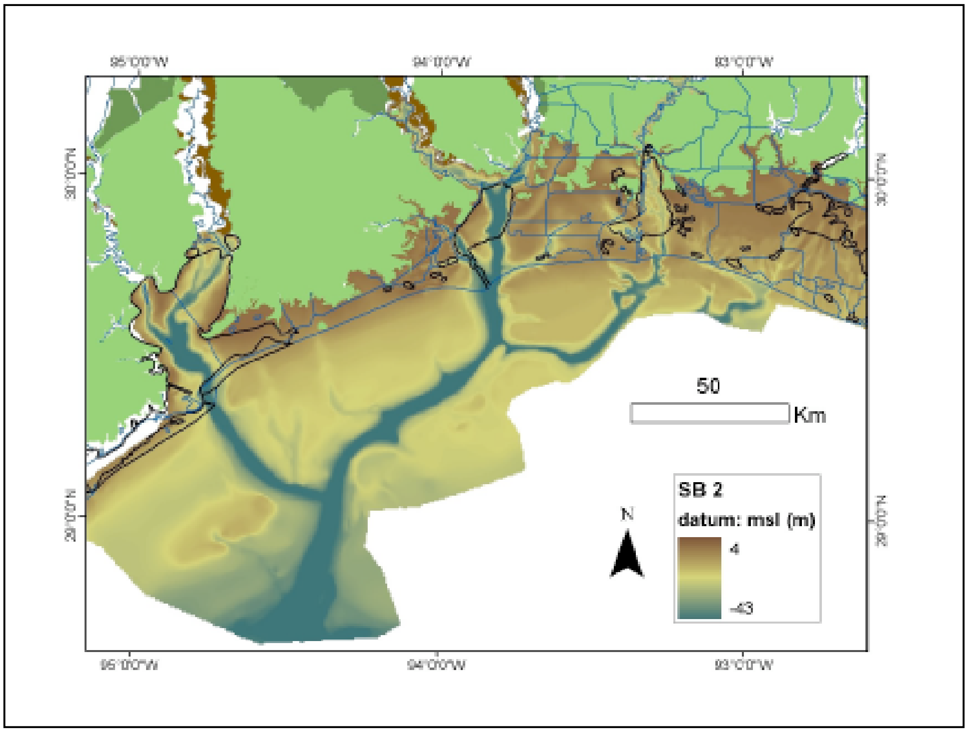

Figure 3. The incised river valleys of the east Texas and western Louisiana continental shelf. See Figure 2 for valley names. (from Simms et al., 2004).

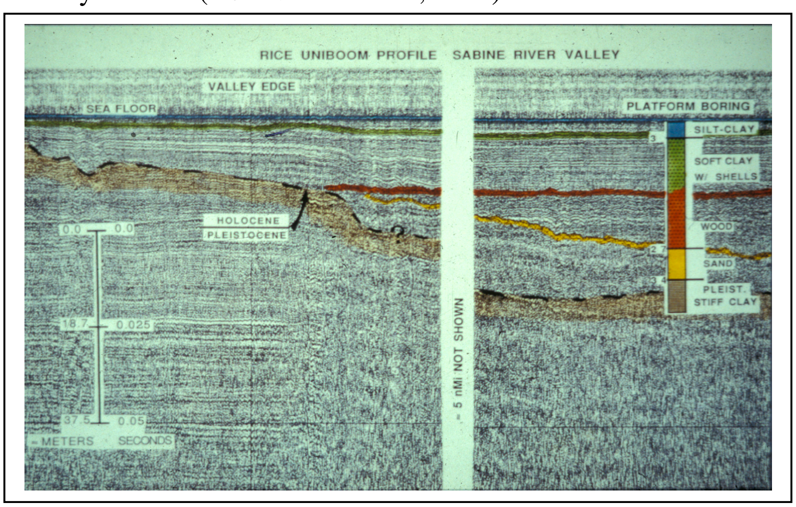

Figure 4. Seismic profile across the ancestral Sabine River valley. The chaotic seismic facies in the base of the valley is fluvial sand and gravel that was sampled by the platform boring shown in this figure.

Trinity Valley

Detailed mapping of the offshore Trinity River Valley was conducted by Thomas and Anderson (1994), including an analysis of the valley fill using seismic data and platform borings. The location of the valley is shown in Figure 3. The valley contains an average of 8 meters of quartz-rich fluvial sand, which is confined to the base of the valley. This sand is overlain by an average of 20 meters of marine and bay mud. Other sand bodies within the valley include tidal inlet and delta deposits, which locally occur within a few meters of the seafloor (Figure 5). Figure 6 shows the locations of these deposits. The platform borings that have sampled these deposits are described as interbedded mud, sand and muddy sand.

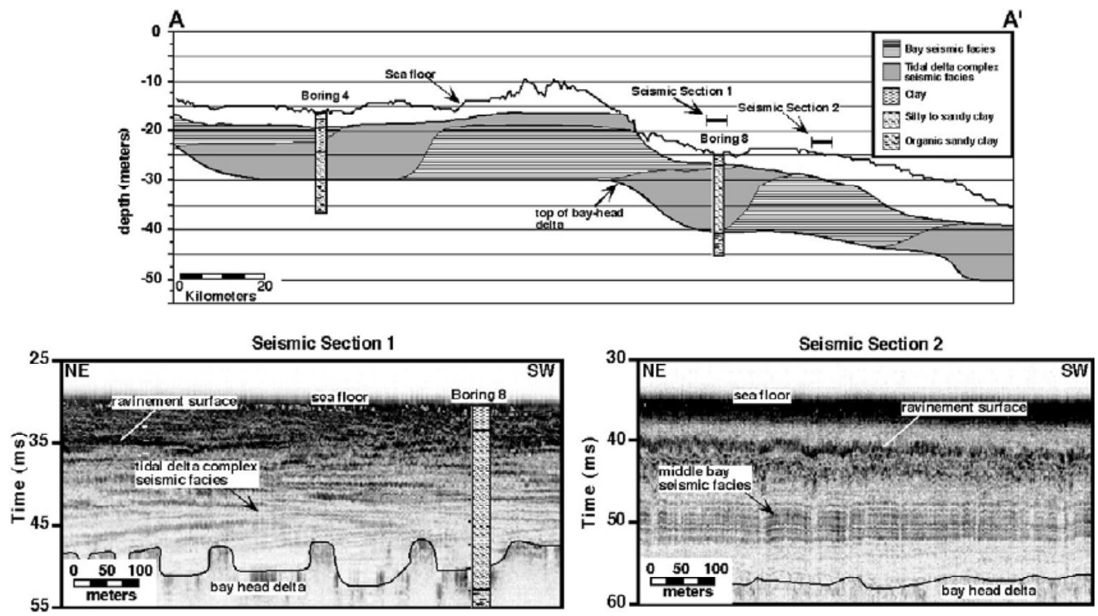

Figure 5. Example of high-resolution seismic data illustrating different seismic facies character between tidal delta deposits (Seismic Section 1) and laminated bay mud (Seismic Section 2). The line drawing at top shows the cross sectional profile of the Trinity valley and illustrates the isolated location of tidal deposits within the valley. See figure 6 for profile location. (from Rodriguez et al., 2004).

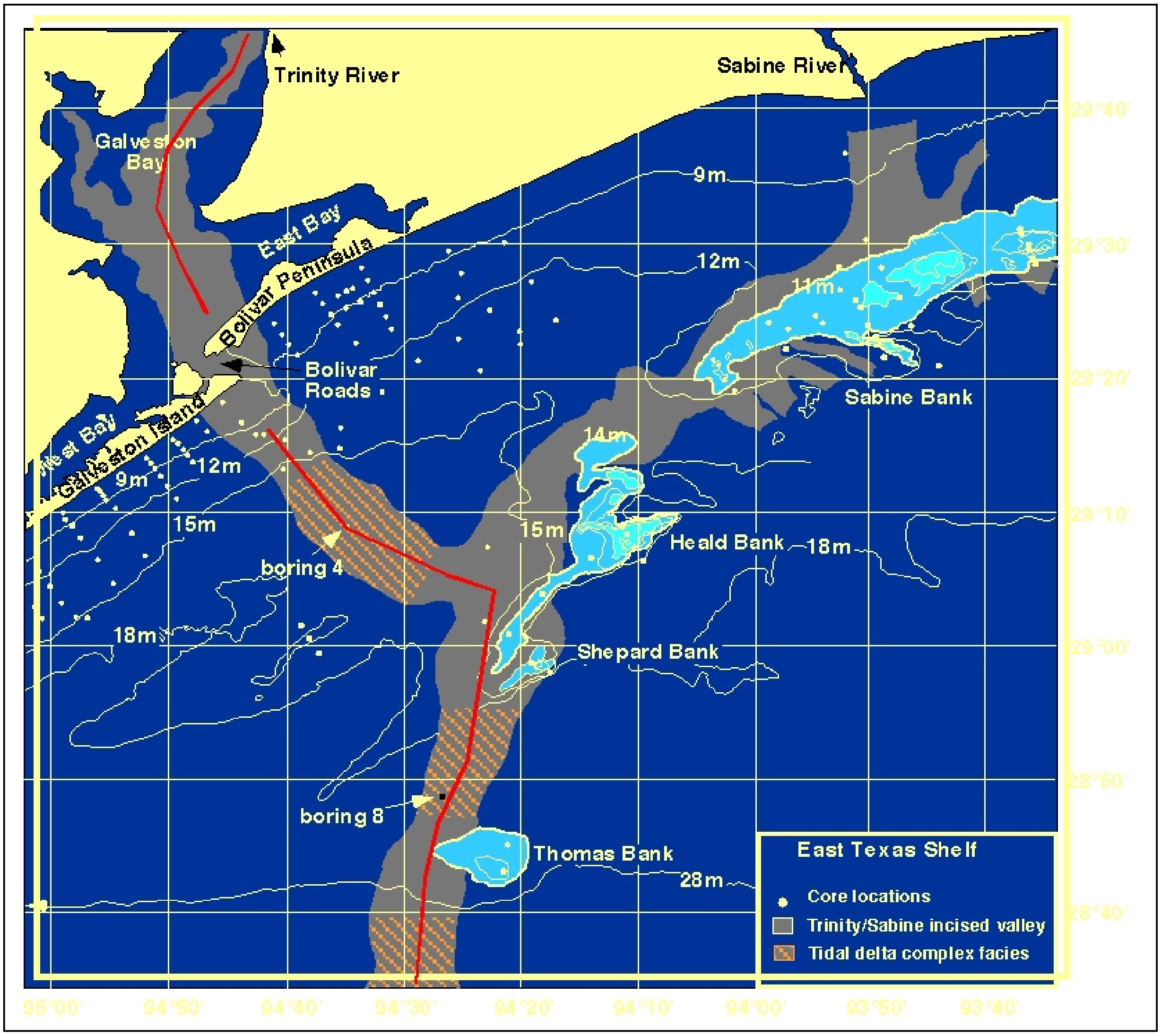

Figure 6. Locations of tidal deposits within the offshore Trinity valley (orange stripes). Also shown are the locations of sand banks, which have been studied in detail by Rodriguez et al. (2000). The red line is the location of the cross section shown in Figure 5. Of these, the inner tidal delta could contain sands that would meet the criteria for offshore sand resources, but additional work is needed to verify that clean sands occur within a few meters\ of the sea floor.

Sand Banks

Figure 6 shows the locations of large sand banks on the east Texas shelf. The two largest banks are Sabine Bank and Heald Bank. There are two smaller banks, Shepard Bank and Thomas Bank, but to date these have not been sampled. These banks are the remains of former barrier islands that were drowned in place by the advancing sea. Detailed studies of Sabine and Heald banks by the Bureau of Economic Geology and by Rice University have shown that they contain significant volumes of sand (Rodriguez et al., 2000; Morton and Gibeaut, 1993) The BEG estimates that the two banks contain 1.8 billion cubic meters of sand. The best quality sand occurs within two meters of the sea floor. The problem with utilizing these banks as sand resources is that they are believed to be unique fisheries habitats (Dr. Bill Jackson, personnel communication).

Sand banks do not occur on the central and south Texas shelf because the shelf because thick Holocene mud of the Texas mud blanket and ancestral Rio Grande delta blanket the shelf.

Brazos Valley

During the last fall in sea level the Brazos River down cut its valley on the Texas continental shelf and extended this valley to the shelf break. Abdulah et al. (2004) mapped the valley in detail. The valley bifurcates on the middle shelf (Figure 7). There is very little actual lithological information for the valley, but the seismic data indicate that fluvial sediments occur within a few meters of the seafloor within the inner shelf valley. Hence, the Brazos valley may contain viable sand resources, but cores are needed to verify that clean sands occur within a few meters of the sea floor.

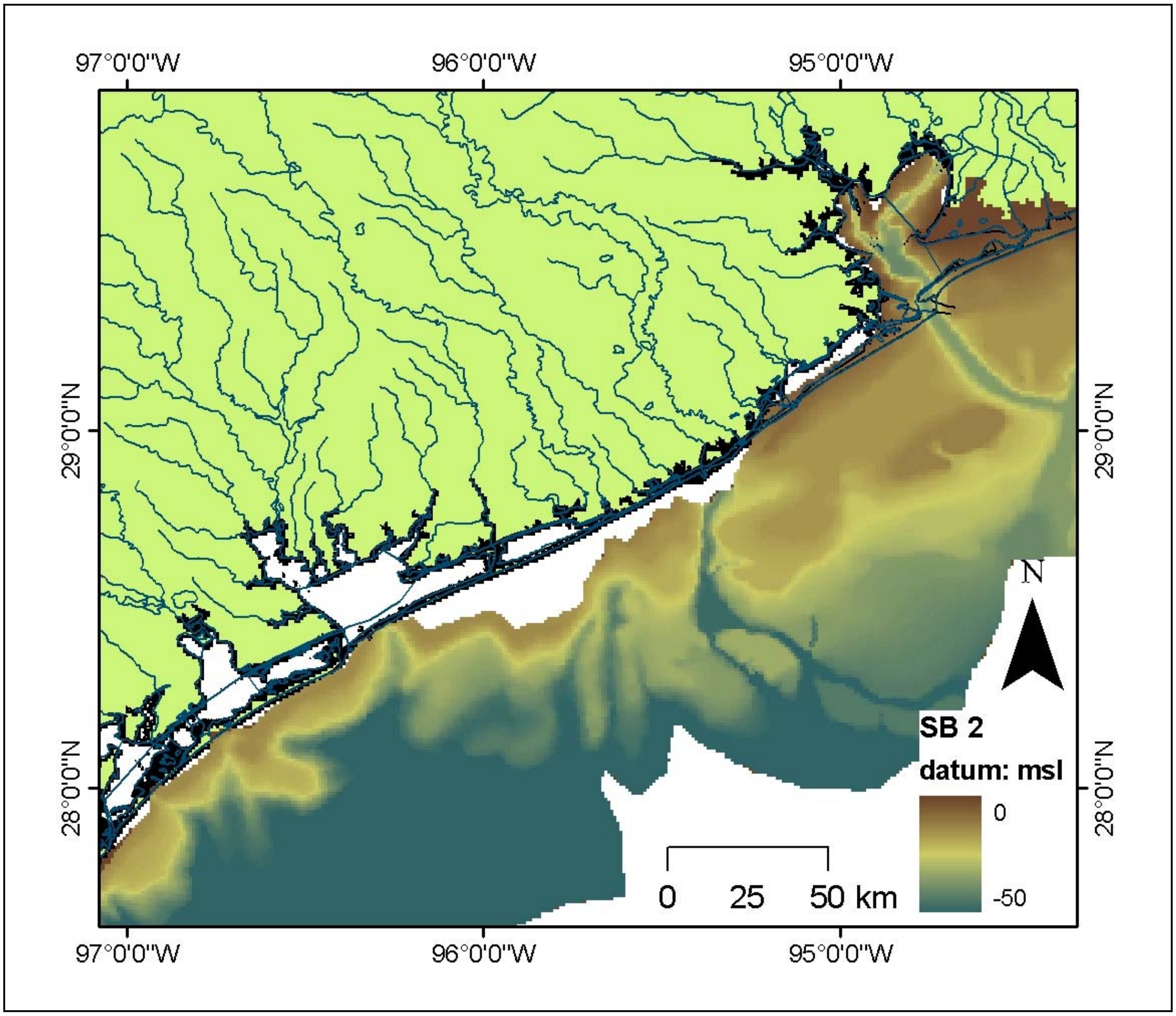

Figure 7. Map showing the locations of the Brazos, Colorado and Lavaca valleys on the continental shelf. See Figure 2 for valley names.

Colorado Valleys and Transgressive Delta

The ancestral Colorado River cut two valleys on the continental shelf (Figure 7). Platform borings and seismic data indicate that both valleys are filled with fluvial deposits that are overlain by marine mud (Abdulah et al., 2004). Thus, the Colorado valley may contain sand resources that meet the criteria for this project. This needs to be confirmed by coring.

During the last transgression the Colorado River nourished a sizable delta on the inner shelf (Figure 8). Sediment cores, platform borings and seismic facies indicate that good quality sands occur at or near the sea floor near the center of the delta. In our opinion, the Colorado delta is the most likely feature to contain good quality sands within a few meters of the sea floor, however, additional cores are needed to confirm this interpretation.

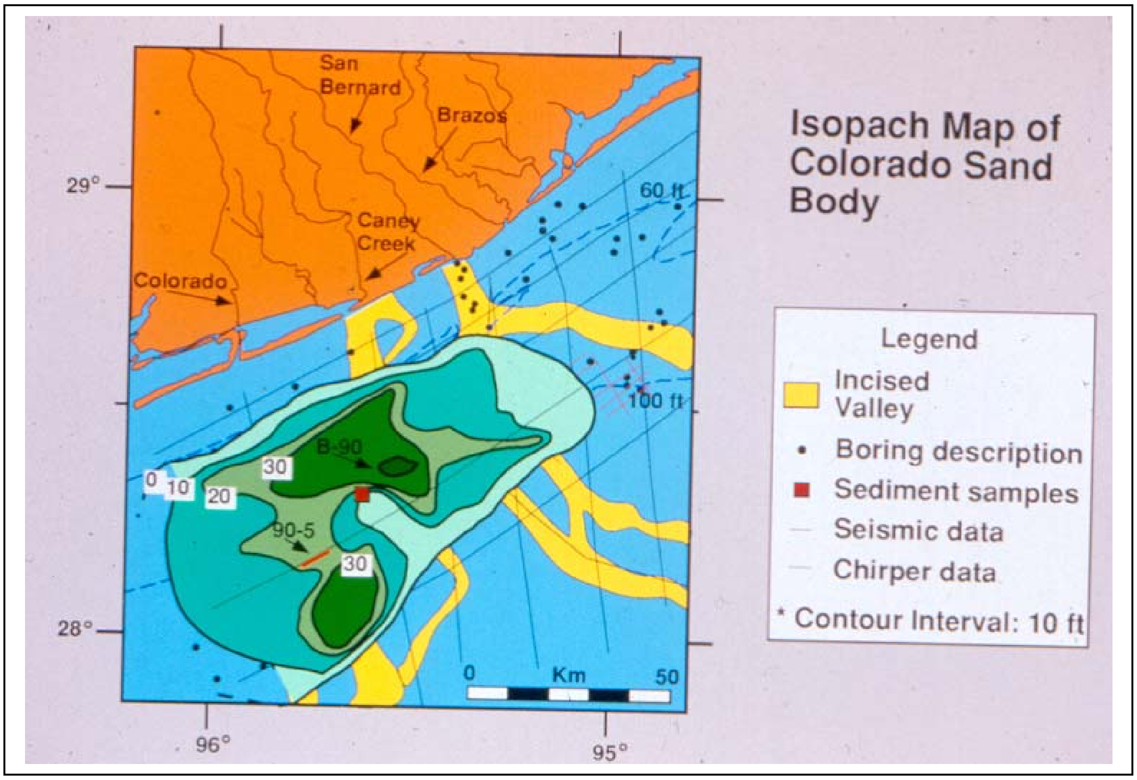

Figure 8. Isopach map (in feet) of the offshore Colorado River delta.

Central Texas Valleys

The inner continental shelf of the central Texas is crossed by valleys of the ancestral Lavaca, San Antonio, Aranses, and Nueces rivers. Only the Nueces valley has been sampled and studied in detail (Simms, 2004). The offshore Nueces is characterized by only a few meters of fluvial sands that are confined to the base of the valley and buried in up to 25 meters of bay and marine mud. In fact, the entire central Texas continental shelf is covered by a relatively think (up to 40 meters) mud drape, which is referred to as the Texas mud blanket. Thus, the offshore fluvial valleys of the central Texas shelf are considered unlikely sources for offshore sand. There are no other known sand bodies in the area.

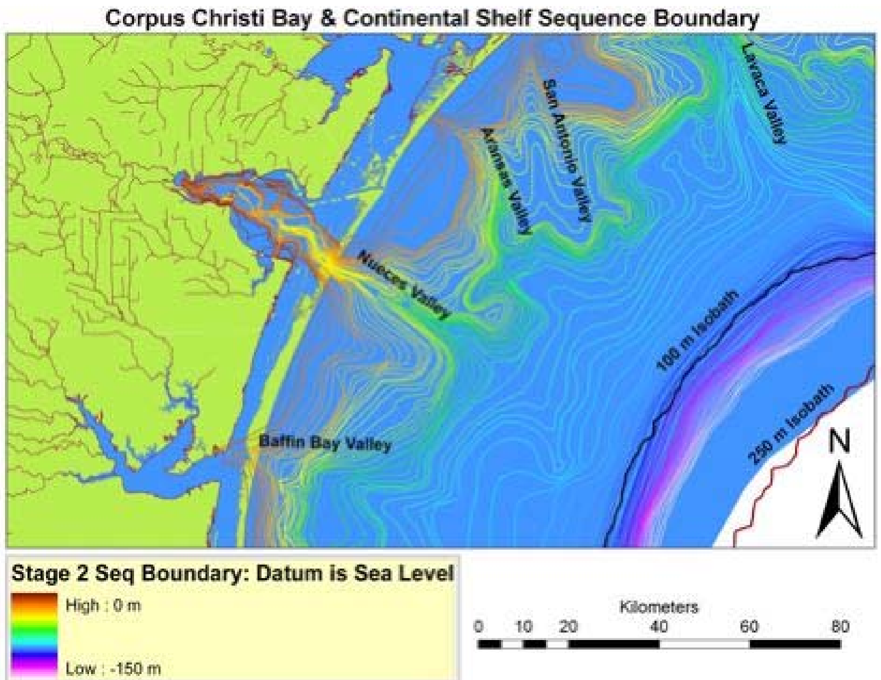

Figure 9. Map showing the ancestral river valleys of the central Texas continental shelf (from Simms et al., in press).

Rio Grande Valley

Detailed seismic analysis of the south Texas continental shelf has revealed two valleys associated with the ancestral Rio Grande River. Neither valley has been sampled, but the seismic data indicate that fluvial sands may occur within a few meters of the sea floor in both valleys (Banfield and Anderson, 2004). The Rio Grande River also formed a large delta during the last transgression, but it is buried beneath several meters of marine mud. More work is need to isolate potential sand resources associated with the Rio Grande fluvial valleys.

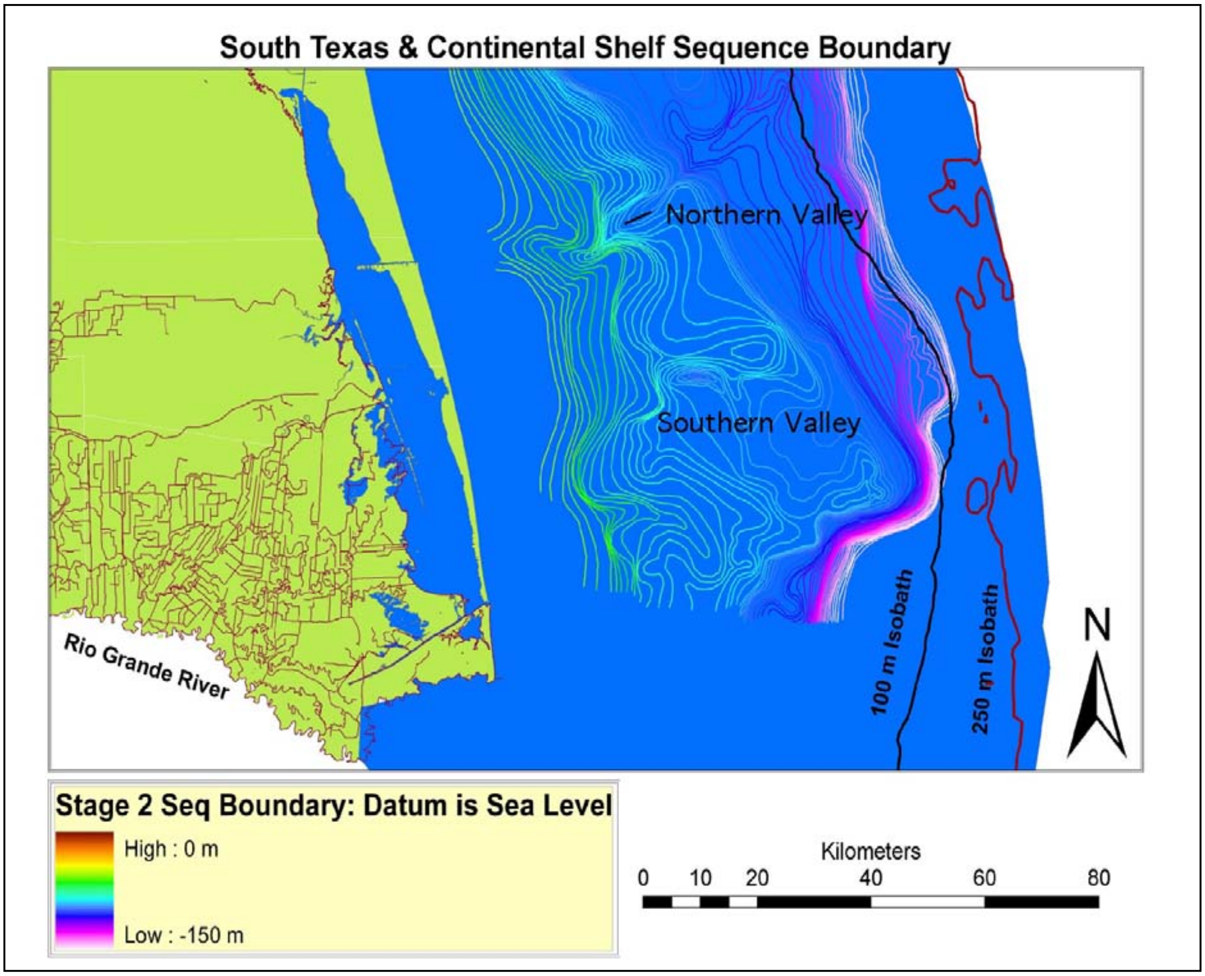

Figure 11. Map showing locations of ancestral river valleys of the ancestral Rio Grande River (modified from Banfield and Anderson, 2004).

Methodology for Generating DEM of Lowstand Fluvial Surface

The stage 22 sequence boundary in high-resolution seismic data is identified as a strong seismic reflector which exhibits truncation of underlying reflectors and onlap of overlying reflectors. This surface, when sampled in cores, exhibits distinctive properties including evidence for soil formation, de-watering, and prolonged exposure.

Multiple graduate students mapped this surface in their respective areas and constructed contour maps that were included in dissertations and theses. These maps were checked for consistency and geo-referenced in ArcGIS. After georeferencing, the contours were digitized as polylines into a seamless map. The digitized polylines were then interpolated in ArcGIS/ArcMap using the Spatial Analyst interpolation toolbox. After the interpolation, the surface was re-checked for consistency and accuracy.

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Appendix

APPENDIX A.3:
REPORT ON LOUISIANA COAST DEPOSITS, UNIVERSITY OF NEW ORLEANS

Stratigraphy and Genesis of Incised Fluvial Channels Across the North-Central Gulf of Mexico

KULP, M.A.

Appendix

Stratigraphy and genesis of incised fluvial channels across the north-central Gulf of Mexico

Final Report for Baird and Associates

Submitted By

Dr. Mark A. Kulp

Introduction

Shoreline retreat and interior wetland loss across the Louisiana Coastal Zone has prompted considerable concern among residents and stakeholders of the region, as well as government agencies that recognize the importance of coastal Louisiana to the nation's socio-economic welfare. This shoreline erosion and the disappearance of interior coastal wetlands along the coastal zone have already contributed toward the degradation of a highly productive ecosystem and a coastal buffer that protects residents and infrastructure against storm surges. Consequently, the state of Louisiana, with some support by federal agencies, has begun implementing coastal restoration and renourishment projects along critical segments of the Louisiana shoreline. The intent of these projects is to reconstruct and replenish fragmented or eroded shorelines through the addition of sandy sediment, thereby rebuilding the ecosystem and storm surge protection elements that are most critical to the regions economy and culture. Although sand-rich sediment is of primary value for these shoreline restoration projects, there is a limited amount of sand-rich strata within the regional, generally fine-grained Holocene stratigraphy (Kindinger et al., 2001).

The limited volume of sand-rich strata necessary for the restoration efforts has resulted in a variety of efforts to develop an in-depth understanding of the distribution, textural character, and volume of sedimentary deposits within the Mississippi River delta plain and Louisiana continental shelf stratigraphy (see summary by Kulp et al., 2005). Although many of these deposits are located within areas governed by the state of Louisiana, a number of potential sediment resources are located on the Louisiana continental shelf within waters that are federally managed by the Mining and Minerals Management Service (MMS). One of these deposits has previously been used along the western Louisiana shoreline at Holly Beach and others, such as Ship Shoal and Sandy Point, are potential borrow targets for Louisiana shoreline restoration projects (Fig. 1). Because these deposits are recognized as potential sites for borrow material the MMS has become increasingly interested in the environmental impact associated with the removal of continental shelf deposits.

The report provides an overview of current knowledge regarding the distribution and sedimentary character of several of these sandy deposits, and their overburden, on the Louisiana continental shelf. The purpose is to provide an understanding of the geologic framework of these deposits and allow for a more in-depth understanding of the physical and biological responses to borrow material excavation in these waters. The strata that are of primary interest are located along the western Louisiana shelf offshore of the Louisiana Chenier Plain and along the south-central shelf offshore of the modern Balize depocenter of the Mississippi River. Herein they are specifically referred to as the Pevoto Beach Pleistocene Channel (PBPC) and the Sandy Point Deposit (SPD), located south of the chenier plain and west of the modern Mississippi River Balize depocenter, respectively (Fig. 1). Although these strata are the result of Late Quaternary deposition (~ last 18,000 yrs) they represent distinctly different styles of formation during different phases of the continental shelf evolution. This difference suggests that they may possess inherently different physical and sedimentological characteristics that should be considered during an environmental assessment of continental shelf sediment excavation.

Late Quaternary Louisiana Continental Shelf Geology

Our current knowledge of north-central gulf stratigraphy derives from more than 50 years of geologic investigations, which have revealed many of the primary details of the Upper Quaternary stratigraphic relationships across the north-central Gulf of Mexico (e.g., Fisk, 1944; Fisk and McFarlan, 1955; Kolb and Van Lopik, 1958; Frazier, 1967; Suter et al., 1986; Anderson and Fillon, 2004). The most regional studies, covering the onshore (delta plain) and offshore (continental shelf) geologic framework of the north-central Gulf, generally date to Fisk and colleagues (e.g., Fisk, 1944; Fisk and McFarlan, 1955; McFarlan, 1961). Many subsequent investigations by Gulf coast workers have been more geographically restricted, for example: 1) Suter (1986) mapped Upper Quaternary stratigraphy on the western shelf south of the chenier plain and Anderson et al. (e.g., 2004) have completed numerous similar studies for the east Texas-western Louisiana continental shelf to provide a good understanding of the stratigraphy and distribution of fluvial systems entering that area of the Gulf during the latest Quaternary. Offshore of Louisiana the continental shelf stratigraphy and evolution has been extensively documented by Coleman and Roberts (1988a,b,c), Kindinger (1988), Sydow and Roberts (1996). Stanley et al. (1996) and Kulp et al. (2002) provided insight to the distribution and thickness of deposits deposited during the Holocene from the direct influence of the Mississippi River and its distributaries. One of the most fundamental results of previous research efforts has been the recognition and verification that Late Quaternary depositional patterns were strongly influenced by: 1) changing sea-level elevations in response to the growth and decay of continental-scale ice sheets, and 2) shifting sites of deposition related to fluvial avulsions and distributary migrations (Coleman et al., 1991).

<u>Depositional Response to Late Quaternary Sea Level Change</u>

Sea-level elevations during the Late Quaternary have varied considerably, ranging between several meters above, to more than 100 m below the present sea-level elevation (Fig. 2). These highs and lows in sea level, referred to as highstands and lowstands respectively, are recorded in the geometry and sedimentology of the regional stratigraphy. For example: physical characteristics of the strata that are diagnostic of sea-level lowstands may include surfaces of erosion and the presence of channels incised into subjacent stratigraphy; whereas highstand conditions can be recognized by the presence of marine flooding surfaces and widespread shelf-phase deltaic deposition with numerous bifurcating fluvial distributaries. During falling and lowstand sea-level conditions of the Late Quaternary, depocenters migrated basinward, whereas rising sea-level forced depocenters landward (Coleman and Roberts, 1988b; Autin et al., 1991). Equivalence in the timing of glacial and non-glacial conditions, indicated by glacial-deposit stratigraphy on the continents and ^{18}O isotope-chemistry changes, to erosional and depositional events recorded in the north-central Gulf strata suggests that glacio-eustatic fluctuations have controlled many regional Late Quaternary sedimentation patterns (Fisk, 1944; Beard et al., 1982; Kindinger, 1988; Suter et al., 1987; Coleman and Roberts, 1988a,b,c; McFarlan and LeRoy, 1988; Stanley et al., 1996; Sydrow and Roberts, 1996).

Falling and Lowstand Sea-level Deposition: Substratum

The most recent sea-level lowstand followed an early Sangamon highstand, culminating at approximately 18,000 yrs B.P. within the late Wisconsinan glacial stage (~28,000 to 12,000 yrs B.P.) at a lowstand elevation of approximately -110 to -120 m (Chappell and Shackleton, 1986; Suter et al., 1987; Fairbanks, 1989; Stright, 1990). Within this timeframe (Sangamon to Wisconsin) sea-level curves indicate a relatively persistent drop in sea level. However, there are multiple, smaller amplitude highstands and subsequent sea-level drops that punctuate this interval of overall falling sea level (Fig. 2). Along the northern Gulf, drainage systems adjusted to this interval of overall falling sea level by extending across the continental shelf, from the previous highstand shoreline, and/or incising into older, underlying sediments (Fisk, 1944; Suter and Berryhill, 1985; Kindinger, 1988; Sydrow and Roberts, 1996). At maximum lowstand during the latest Wisconsin glacial stage the Louisiana shelf was subaerially exposed, creating a considerably expanded coastal plain that forced deltaic deposition to the shelf edge (Suter, 1986; Morton and Price, 1987; Kindinger, 1988; Sydrow and Roberts, 1996; Winn et al., 1998).

Because much of the Louisiana shelf was exposed during the lowstand a widespread and easily recognized unconformity developed, preserved in the subsurface as a highly weathered and oxidized surface referred to as the Prairie surface or late Wisconsin unconformity (e.g. Fisk 1944; Stanley and Warne 1994; Kulp et al., 2002). During lowstand and early sea-level rise shelf deposition was primarily restricted to incised valleys within braided fluvial systems (Fisk, 1944; Fisk and McFarlan, 1955; Coleman et al., 1991). This depositional phase produced a lithologically distinct unit, dominated by gravel and sand-rich sediments, classically referred to as *substratum,* often present within the braided paleo channel trends that incised the underlying Pleistocene strata (Fisk, 1944). Grain-size analysis of multiple lithofacies above the late Wisconsinan unconformity along south-central Louisiana has revealed that substratum sediments contain some of the coarsest sediment available within the latest Wisconsin to modern stratigraphy of the Louisiana Coastal Zone (Kuecher, 1994).

During the late Wisconsin sea-level fall the most prominent incision across the Louisiana continental shelf resulted from basinward extension of the Mississippi River alluvial valley to the shelf edge at the head of the Mississippi Canyon (Fig. 1). At the modern coastline, depth to the base of the excavated alluvial valley is approximately 100 m (Fig. 3). Southward extension of the Mississippi River alluvial valley during this sea-level lowstand resulted in shelf bypassing and funneling of much of the river's sedimentary load to the Mississippi Fan through the Mississippi Canyon (Coleman et al., 1983). Between 18,000 and 12,000 yrs B.P., delivery of sediments to the shelf edge diminished as sea level rose in response to late Wisconsinan deglaciation.

Rising and Highstand Sea Level Deposition: Topstratum

Between 18,000 and 12,000 yrs B.P. sea level began an initially rapid rise in response to late Wisconsin deglaciation. This sea level rise led to marine flooding of previously formed incised valleys and the development of estuarine environments, which are recorded in the accumulation of fine-grained, organic-rich sediment (Coleman et al., 1983). Many of the braided fluvial systems that developed during the earlier sea-level low evolved toward meandering regimes during the subsequent sea-level rise (Coleman et al, 1991). As sea-level rose and estuaries flooded, aggradational deposition within these topographically low areas began as backswamp and floodplain environments matured. Thus, organic-rich sediments of brackish/estuarine stratigraphically above coarse-grained, channel-base sediments typically indicates initial drowning and inception of estuarine environments within the stream valleys flooded by rising sea level (Suter et al., 1987; Sydow and Roberts, 1996). This initial flooding marks a major change in depositional style, generally recorded in the incised valleys as a vertical gradation from gravel-rich sandy sediments to more organic-rich, finer-grained strata. Fisk (1944) referred to the generally fine-grained unit above substratum and interfluves as *topstratum*.

The topstratum sedimentary package reflects marine, deltaic, and low-gradient fluvial deposition within formerly incised valleys, as well as the sediments deposited on the non-incised sections of the continental shelf after marine flooding (Fig. 4). Approximately 7,000 yrs B.P., rates of sea-level rise had slowed enough (Fig. 2) to allow the Mississippi River to prograde beyond its main alluvial valley and to begin forming the Mississippi River delta plain and chenier plain.

Mississippi River Delta Plain

In the last 7,000 years the Mississippi River and associated distributaries have been the primary conduits delivering sediments to the north-central Gulf Coast. Current models describe the growth of the Mississippi River delta plain as a multi-stage process that has been influenced by the interaction between changing sea-level elevations and sediment dispersal paths (Frazier 1967; Boyd and Penland, 1985; Penland et al., 1988). Deltaic plain growth alternates between periods of seaward advancement of deltaic depocenters (regressive deposition) and a subsequent landward retreat of deltaic headlands as depocenters are abandoned, reworked, and inundated by marine waters (transgressive deposition). Assembled as overlapping, stacked sequences of unconsolidated sands and muddy sediments, the Holocene Mississippi River delta plain is composed of four major delta complexes that in turn are built by numerous smaller deltaic lobes (Fig. 5). A wide array of studies, (e.g. Fisk, 1955, 1961; Kolb and van Lopik, 1958; Coleman and Gagliano, 1964; Frazier, 1967) have focused on the regressive phase of Mississippi delta sedimentation.

Regressive Deposition

Regressive depositional episodes are characterized by the seaward advance of distributaries that overlap through time and that can erode into underlying, previously deposited, strata as individual deltaic headlands advance seaward. Regressive deposition is recognized as an important contributing process to the vertically stacked and laterally offset deltaic depocenters preserved within the shallow Holocene stratigraphic framework of the Mississippi River delta plain and adjacent continental shelf (e.g. Scruton, 1960; Coleman and Gagliano, 1966; Frazier, 1967). The presence of distributary channels within the topstratum package records their progradation and ultimately, their abandonment and then burial by subsequent phases of deposition. Beyond the progradational limits of the Holocene deltas or in areas that have been previously abandoned a limited sediment input to the continental shelf is currently creating a mud-rich interval of pelagic deposits that have buried many of these earlier formed depositional systems (Loutit et al., 1988).

Transgressive Deposition

Distributary pathways are ephemeral and their progradation results in lengthened distributary networks, a reduction in their gradient, and ultimately, abandonment of the active distributary networks in favor of shorter, more hydraulically efficient routes. It is during this abandonment phase that a deltaic headland is subjected to marine processes such as wave and tidal currents, which are capable of dispersing sediment laterally and contributing toward the construction and nourishment of flanking barrier islands, beach ridges, and chenier plains (Fig. 6). Many of the Holocene deltaic headlands already have been reworked or transgressed to create barrier islands and shoals along the Louisiana Coastal Zone, for example the Chandeleur Islands and Ship Shoal (Figs. 1 and 6) (Penland et al., 1987).

Subsurface Deposits as Potential Borrow Material Sites

The previous discussion of regional Late Quaternary geologic processes, depositional styles, and evolutionary history provides an important framework within which to better understand the distribution and origin of potential borrow deposits across the Louisiana continental shelf. The following sections provide the current state of knowledge regarding several of these deposits, the geologic processes inherent to their formation, and a perspective for evaluating the potential impact of their removal for shoreline restoration projects.

Stratigraphy of Pevto Beach Channels

The 12 to 20 mile-wide Chenier Plain of southwestern Louisiana extends from Sabine Pass, Texas to Southwest Point Louisiana (approximately 200 km), with elevations that range from between 0 and 6 m (Fig. 1). Overall, the chenier plain shoreline has extremely limited surface geomorphologic features, such as tidal deltas, that can be used for shoreline renourishment projects. Consequently any effort to replenish this section of the Coastal Zone must rely upon deposits located offshore. Detailed seismic mapping of Upper Quaternary stratigraphy has revealed much about the Late Quaternary depositional history in the area as well as the distribution of buried, paleo fluvial trends. Limited deltaic deposition in this area since the Holocene transgression (see Fig. 1) has led to a cover of deltaic deposits less than 10-m thick. Shelf sedimentation through the Holocene has been dominated by fine-grained sedimentation from suspension rather than by direct fluvial input. Consequently the most likely location for sand-borrow sources exists in the subjacent channels that were created by incision into the underlying Pleistocene sediments.

Across the shelf, offshore of the chenier plain, the late Wisconsinan unconformity is a prominent stratigraphic feature and numerous incised channel networks are present (Fig. 7), all of which were formed as the late Wisconsin sea-level fall forced fluvial systems seaward toward the continental shelf edge (Suter and Berryhill, 1986; Suter et al., 1987). Across much of the mid to outer western shelf, late Pleistocene sediments crop out at the seafloor, and the only sediment above the Late Wisconsin exposure surface is the result of fine-grained, hemi-pelagic accumulation (Suter et al., 1987). The most detailed and geographically extensive studies of paleo channels, that incise subjacent Pleistocene strata, were completed by Suter and Berryhill (1986) and Suter et al. (1987). These investigations, although informative, do not provide the level of detail necessary to developing dredging plans for specific borrow areas. Consequently, the stratigraphy of individual channels within these areas, derives from subsequent in-depth studies that focused on the use of incised channel deposits for restoration.

Investigations into the use of incised-channel sediments as borrow material along the Chenier Plain appear to have started in the early to mid 1980's with the inception of Act 41 (Nearshore Sand Resource Inventory) and research conducted by the U.S. Geological Survey's Marine Geology Branch using vibracores and high-resolution Boomer seismic data to map their origin. According to reports by Coastal Planning and Engineering (CPE, 2001; 2002) one of the best potential borrow sites was found to be a set of lowstand fluvial channels that are incised into the underlying Pleistocene strata.

Between 2000 and 2001 CPE conducted an array of research on the geometry, stratigraphy and textural character of a channel offshore of Peveto Beach using jet probes, vibracores, surface samples, and high-resolution geophysical surveying (Fig. 8). On the basis of these data CPE reported that numerous irregularly shaped, subsurface sand bodies were present within the boundaries of a previously identified relict valley (Fig. 9). Figure 10 shows the bathymetry of the area immediately above the identified fluvial valley. Between the sand bodies within the relict valley, CPE (2001) identified areas that they called "sub channels" that contained little to no sand and a lithology dominated by interbedded silt and clay strata. Between the sub channels sand deposits were present below an overburden that consisted of an upper layer of very soft, sometimes silty clay (1-1.5 m thick; 4 to 5-ft thick) and an underlying layer of stiff clay (0.3 to 1.2 m thick; 1 to 4-ft thick). Figures 11 and 12 are east-trending, high-resolution seismic profiles that show the distribution of sand deposits, sub channels and character of overburden across the northern and southern part of the relict valley respectively (cross sections location on figure 9). CPE (2001) interpreted the irregular sand bodies to represent fluvial deposits that were overlain by fine-grained sediment and later incised by subsequent, smaller sized channels carrying a finer-grained sedimentary load.

The 2001 study by CPE identified a nearshore and offshore region of sand deposits, differentiated according to distance from the shoreline and most significantly, the character of the sand deposits within each area. This break between the onshore and offshore area is located approximately 5 kilometers (2.7 nautical miles) offshore where the fluvial valley narrows to approximately 1.2 km (4,000 feet) (Fig. 9). A fundamental difference between these two deposits is the color; whereas the nearshore deposits consist of fine-grained gray sand the offshore deposits contain fine-grained gray and yellowish brown sand. In their 2001 report CPE estimated approximately 2,752,397 m^3 (3,600,000 yd^3) in the nearshore area below 1.5 to 3 m (5 to 9 ft) of overburden and 12,615,155 m^3 (16,500,000 yd^3) in the offshore below 1.5 to 2 m (5 to 7 ft) of overburden. In both areas the overburden generally consists of fine silt and clay.

Characteristics of the Selected Borrow Site

In an attempt to further classify the regional stratigraphic characteristics of the deposits all of the primary sand bodies were subsequently labeled by CPE (2002) as sites A through O (Fig. 13). Because of limitations created by the presence of gas lines, infrastructure, and volumetrically small deposits only 5 of the total A through O sites were subsequently investigated; consisting of sites B, H, and I in the nearshore zone and L and P in the offshore. The second round of coring found that volumetrically significant deposits of sand were not present in the nearshore zone and the CPE (2002) investigation for borrow material then focused on the offshore area.

A total of 32 additional cores were acquired in the offshore, 31 of these cores were concentrated in deposit L (Fig. 13). Within site L several subareas for borrow material excavation were chosen because it had the overall thinnest overburden as well the largest volume of subsurface sand (Fig. 14). Overburden in across site L ranges between 0.5 and 2.5 m (1.6 and 8.2 ft) with an average thickness of 1.2 m (4 ft) of clay, unlike the very stiff clay that is more typical of the rest of the area. Within the finally determined borrow area the sand deposits typically consisted of sediment with: 1) a size between 0.10 and 0.14 mm, 2) 8.8 to 34.5% silt, and 3) a sorting range of 0.73 to 0.84. Figure 14 shows the distribution of all of the suggested targest in site L as well as the depth to the base of the identified subsurface sand body in deposit L. Figures 15 and 16 are two stratigraphic cross sections that show the general lithostratigraphic framework of the borrow site, indicating clearly a substantial thickness of sand underlain by an overburden of clay and silt strata. Figure 17 is a stratigraphic log for core HBVC-01-29, which is the core common to the lithostratigraphic cross sections of Figures 15 and 16. HBVC-01-29 provides a good record of the overall character of the sand-rich sediment in the borrow site as well as the thickness and physical characteristics of the overlying, fine-grained sedimentary units.

Stratigraphy of Sandy Point Borrow Sites

The Sandy Point borrow site is located within Holocene age strata offshore from the western edge of the lower Plaquemines shoreline, proximal to the modern Balize depocenter of the Mississippi River delta complex (Fig. 1). In 2000 much of the continental shelf offshore of the south-central Barataria Bight was investigated for sand resources as part of the Barataria Barrier Island Feasibility Study (see Kindinger et al., 2001). This sand resource evaluation, jointly conducted by the U.S. Geological Suvey, University of New Orleans, and U.S. Army Corp of Engineers provided a regional perspective of the distribution of sand resources on the continental shelf offshore of the Barataria Bight. Because of the large area covered by the investigation the report provided a fundamentally important perspective into the distribution of sand resources but did not provide extensive detail into their character and complete suitability for restoration efforts. During this research the largest nearshore, subsurface sand body, herein refereed to as the Sandy Point Site, was found to exist offshore of Sandy Point of the western Plaquemine shoreline (Fig. 1).

Kindinger et al. (2001) suggested that the Sandy Point deposit consisted of an extensive deposit containing 60 to 80% of fine sand (0.17 to 0.02 mm; 2.5 to 5.5 phi) with a thickness of 6 to 9 m (20 to 30 ft) (Fig. 18), approximately 12 to 15 m (40 to 48 ft) below mean sea level. Further, they noted that the irregular upper surface of the sand body was the result of overlying channels that had incised into the underlying sand. These channels were found to generally consist of interbedded sand and clay; locally, a more sand dominated lithology was suggested to exist at the base of these channels. Across the area the overburden was found to consist of interbedded clay-rich silt.

On the basis of the available cores and high-resolution seismic data Kindinger et al. (2001) interpreted the body to reflect a distributary mouth-bar deposit at the seaward termination of fluvial distributaries that Suter et al. (1991) had previously mapped in the area. These distributaries prograded during the recent development (approximately last 1,000 yrs) of the Plaquemine delta complex and simultaneously eroded into the underlying deposits (Fig. 5). Previously, Fisk *et al.* (1954) and Fisk (1955) had recognized the environment of shallow water, inner-shelf deltas to be one in which sand sheets at distributary mouth bars became fused to create semi-continuous, delta-front sheet sands. Locally, distributary channels that have eroded into the stratigraphically lower deposits interrupt the lateral continuity of these sandy deposits. Although channels created during fluvio-deltaic progradation can contain high proportions of sand, matter in the Sandy Point deposit they were found to typically consist of interbedded silt, clay, and organic. During abandonment these once active distributaries become the site of low energy, fine-grained deposition that typically becomes finer upward.

Subsequent work by CPE (2003) suggested a lesser degree of lateral continuity and textural uniformity of the Sandy Point deposit then had been previously documented. CPE recognized that within the borrow area there was a general increase in sand content toward the more offshore portion of the Sandy Point borrow site. A result of the CPE work was the designation of a Northwest Borrow Area and a Southeast Borrow Area within the overall deposit mapped by Kindinger et al. (2002) (Fig. 19). Both the Northwest Borrow Area and Southeast Borrow are located in water depths of approximately 10 m (35 ft) (Fig. 20).

Northwest Borrow Site

Using vibracores and high-resolution seismic records CPE mapped the thickness of subsurface sand deposits to range between 0 and 7 m (25 ft) with the maximum thickness of 7 m (25 ft) in the northern part of the site (Fig. 21). Texturally the northwest borrow site consists of sand with an average size of 0.11 mm (3.1 phi) and sorting value of 0.72. Figure 22, a seismic cross section with a vibracore, indicates the fundamental geometry of the body in the subsurface, the irregular nature of the upper surface, as well as an indication of the variation in overburden thickness across the area. The overburden ranges between 1.5 and 4.5 m (5 and 15 ft) along the north to approximately 3.0 m (10 ft) in the south with an average thickness of 2.5 m (8 ft) (Fig. 23). Across the site the overburden consists of sedimentary units containing clay laminae or silty sand.

Southeast Borrow Site

Sand thickness in the Southeast Borrow Site ranges between 1.5 and 7.6-m thick (5 and 25-ft thick) with an average of 2.7 m (9 ft) of sand (Fig. 24). In this deposit the mean grain size was found to be 0.12 mm (3.03 phi) with a sorting value of 0.67. Similar to the northeast borrow site the subsurface sand body exhibits considerable irregularity along its upper surface (Fig. 25) as well as variation in the thickness of overburden. Locally, the sand body appears to be a relatively consistent deposit of sandy strata with limited interbedded, fine-grained sediment. An isopach map of the clay-rich overburden indicates that the thickness varies between 0 and 6 m (0 and 20 ft), with an average of 2.7 m (9 ft) (Fig. 26).

<u>Stratigraphy of Ship Shoal</u>

Ship Shoal is a large, asymmetric inner-shelf shoal that formed as a result of an earlier phase of deltaic abandonment and continues to be modified by ongoing marine transgression (for detailed summary see Kulp et al., 2002; Fig. 1). Approximately 50-km long, the shoal is thought to mark the minimum seaward extent of early to mid-Holocene Maringouin deltaic deposition (Fig. 4) (Penland et al., 1987). Across the central part of the shoal the width ranges between 4 and 8 km and between 5 and 10 km on the eastern and western ends. Elevation of the shoal above the surrounding seafloor decreases from approximately 7 m (23 ft) in the west to 5 m (16 ft) in the central and eastern section of the shoal and water depths range between approximately 3 m (10 ft) over the western end to 8 m (26 ft) on the eastern-edge (Fig. 27). Across much of the shoal the thickness is on the order of 4 m or more (13 ft) with decreasing thickness in all directions away from the shoal crest (Fig. 27). The use of Ship Shoal in restoration projects is currently a very real possibility. Although much of the sandy sediment within the shoal is located in the upper shoal and not buried below a substantial fine-grained cap, it is conceivable that upper shoal sediments may in places have to be removed in order to recover subjacent strata. Moreover, because it contains the largest volume of sediment within any sedimentary body located in federal waters it is included in this report for reference.

Building upon the work of others, Williams et al. (1989) mapped seven major lithofacies in the Ship Shoal area using sand content as the basis for their divisions. Fine-grained quartz sand, consistent with the results of Krawiec (1966), was found to be a primary constituent of the surficial sediment with an average, but highly variable, sand content of 54%. Locally, however, much of the shoal contained 90 to 99% sand (Fig. 28).

The crest of the shoal, upper 4 m (13 ft), consists of an east-striking accumulation of sand and shell that has been deposited in response to reworking by wave and tidal processes. This high-energy environment results in current and wave winnowing that sorts the sediment into a uniform grain size. Sediment comprising the shoal crest consists of very well-sorted (0.5 to 1.6), well-rounded, quartz sand (mean of 0.35 to 0.15 mm; 1.5 to 2.7 phi; Cumo, 1984) in very thin parallel, horizontal to subhorizontal beds. In places the crest consists of as much as 99% sand with a high concentration of whole and reworked shells. Along the seaward edge the shoal crest is bordered by the shoal front facies, containing 75 to 95% of moderately sorted (0.5 to 0.9), fine to very fine-grained sand (0.15 to 0.11 mm; 2.7 to 3.1 phi). The base of the shoal is represented by a sedimentary facies of interbedded silty clay and lenticular-to-wavy bedded, poorly sorted (1.2 to 1.5 phiunits), very fine-grained sands (0.11 to 0.08 mm; 3.1 to 3.6 phi), sand content ranges between 50 and 75%. Relative to the Shoal crest the shoal base environment represents a much lower-energy environment in approximately 8 to 12 m (26 to 40 ft) of water.

Conclusions

This report has presented a summary of the geologic framework and formation of offshore sedimentary bodies that have been used or have the potential for use as borrow material along Louisiana's rapidly disappearing and fragmented coastal zone. These borrow targets are located in federal waters and there exists a wide array of interest in the environmental impacts of removing these subsurface sand bodies. Although often containing very similar sand-rich strata the genesis of these sedimentary bodies is distinctly different and there is consequently variation in the fine-grained sediments that overly many of these units.

Along the western Louisiana continental shelf the sand resources available will undoubtedly be associated with late Wisconsin fluvial incisions where rivers deposited a variety of sand-rich bars and sandy deltaic fronts during the most recent sea-level lowstand. The thin Holocene sedimentary cover overlying these sources is fine-grained with very limited to non-existent sand or coarser-grade material, although there may be thin sandy surfaces locally (Fig. 17). Alternatively, fluvial channels at the Sandy Point site are associated with fluvial progradation and delta lobe deposition within the Holocene, specifically the last 1,000 yrs. Because generally finer-grained sedimentation is associated with the Holocene fluvial systems it is expected that the sediment within these borrow sites will be generally finer grained than lowstand-incised channel fills. This reflects both the sediment supply available to each system during their respective periods of formation as well as the type of systems involved, for example lowstand fluvial incisions versus highstand fluvial distributaries. The texture of the overburden appears to be very similar at the Pevoto and Sandy Point site where available data suggest an admixture of clay and silty strata. Available reports indicate the presence of a laterally persistent and compacted clay layer offshore of Pevoto Beach that is locally overlain by very soft clays. Correspondingly, the overburden at Sandy Point is more likely to be softer and more organic-rich sediment because of proximity to the modern river wetlands and marshes, here recent sedimentation by fluvial processes has not resulted in substantially compacted overburden. Nonetheless, in both locations the thin overlying cover of the deposits reflects generally slow rates of sedimentation with likely episodic inputs through storm processes.

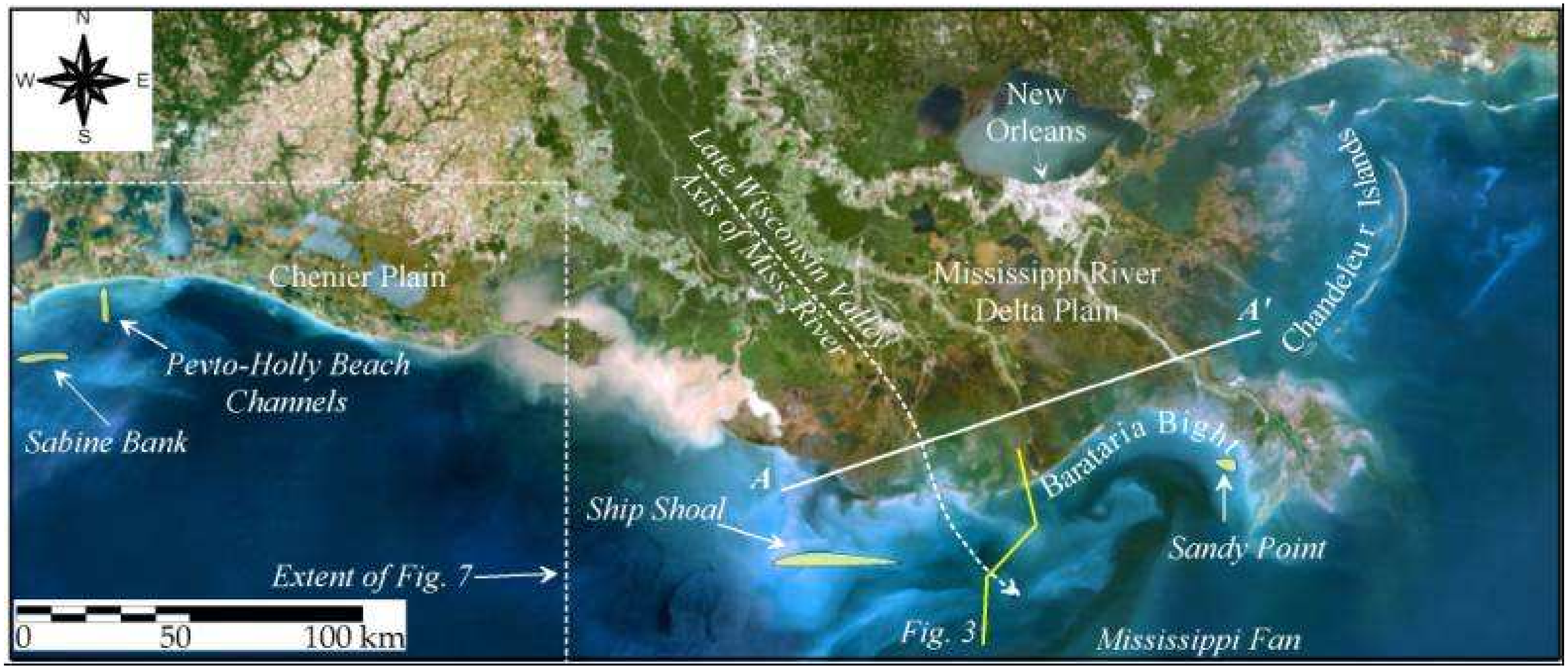


Figure 1. Base map of the Louisiana Coastal Zone that identifies the delta plain and chenier plain. Several subsurface to near surface sand bodies discussed in the text are shown for reference. Additionally shown is the location of lines of cross section, figures, and geomorphic features discussed in the report.

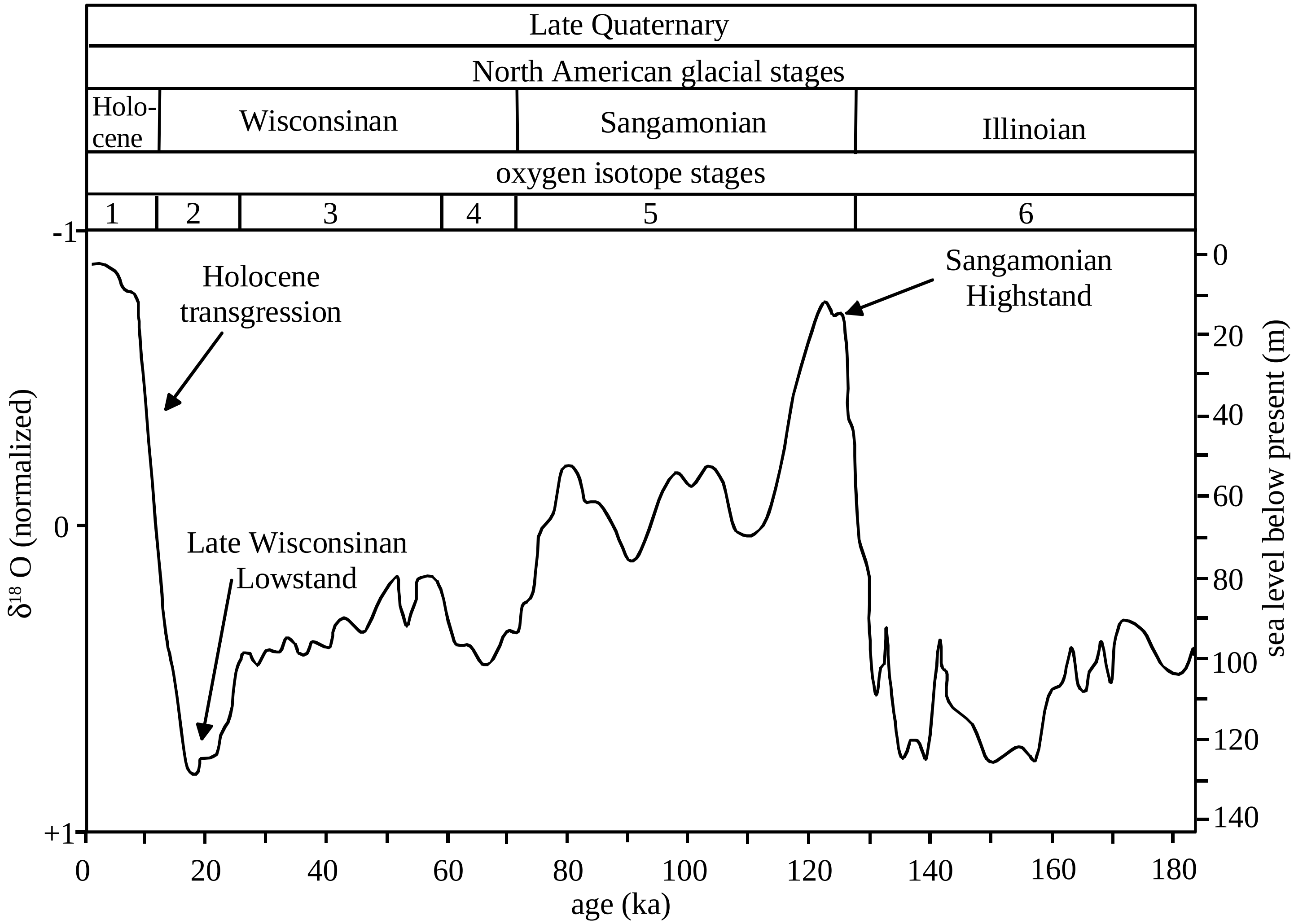


Figure 2. Diagram showing the Late Quaternary correlation between terrestrial glaciations, oxygen-isotope chemistry, and sea-level elevations (modified from Morton and Suter, 1996; oxygen-isotope data from Martinson et al., 1987; sea-level history and approximate correlation to isotope stages from Chappell and Shackleton, 1986).

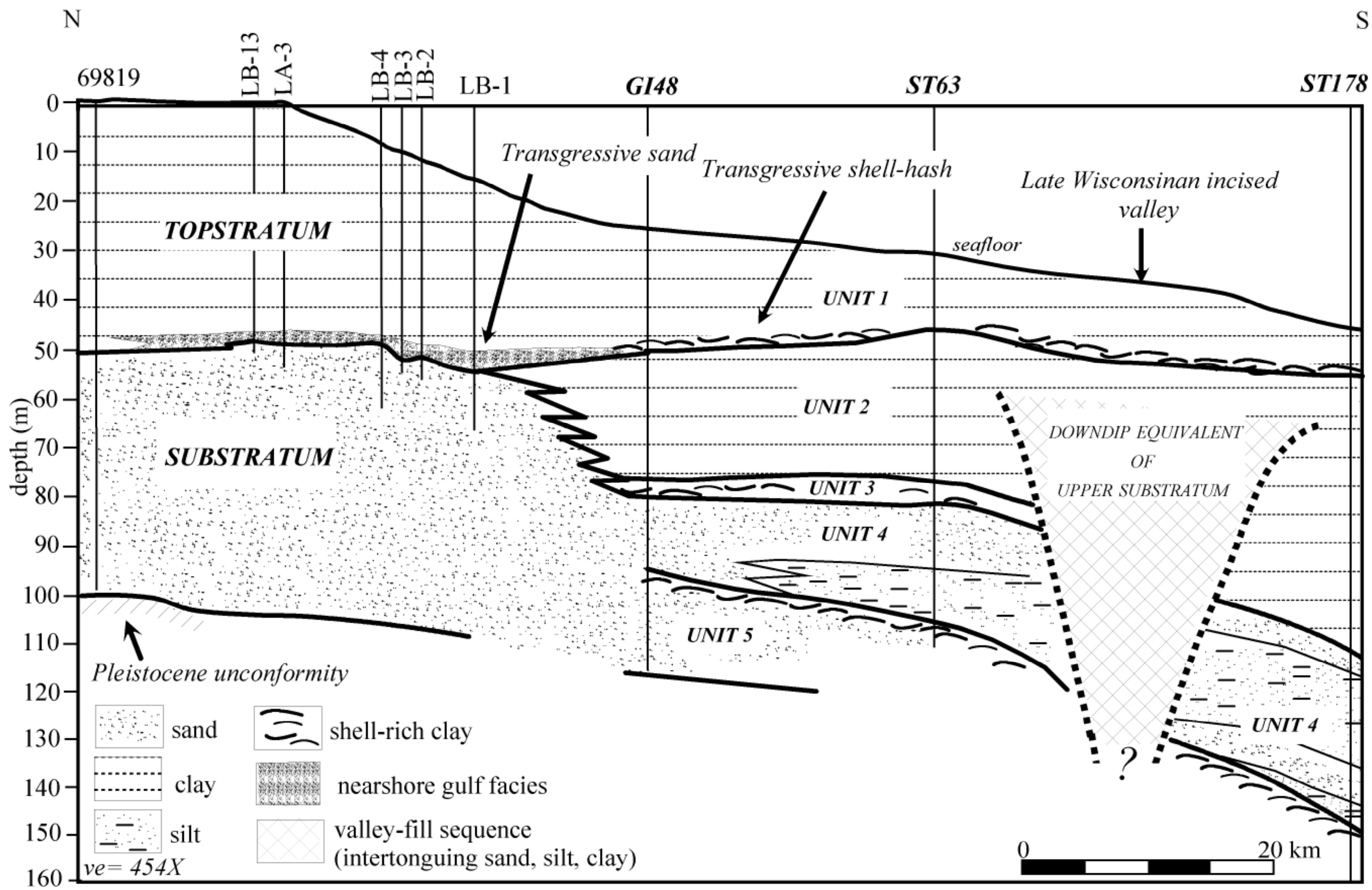


Figure 3. South-trending lithostratigraphic cross section showing the incised alluvial valley of the Mississippi River overlain by generally fine-grained sediments deposited during the Holocene (last 10,000 yrs) rise in sea level to its current elevation (from Kulp, 2000). Note the 100 m depth to the base of the substratum interval. This interval is overlain by topstratum and the facies in the boundary between them records a portion of the Holocene transgression. Trend of cross section is shown on figure 1.

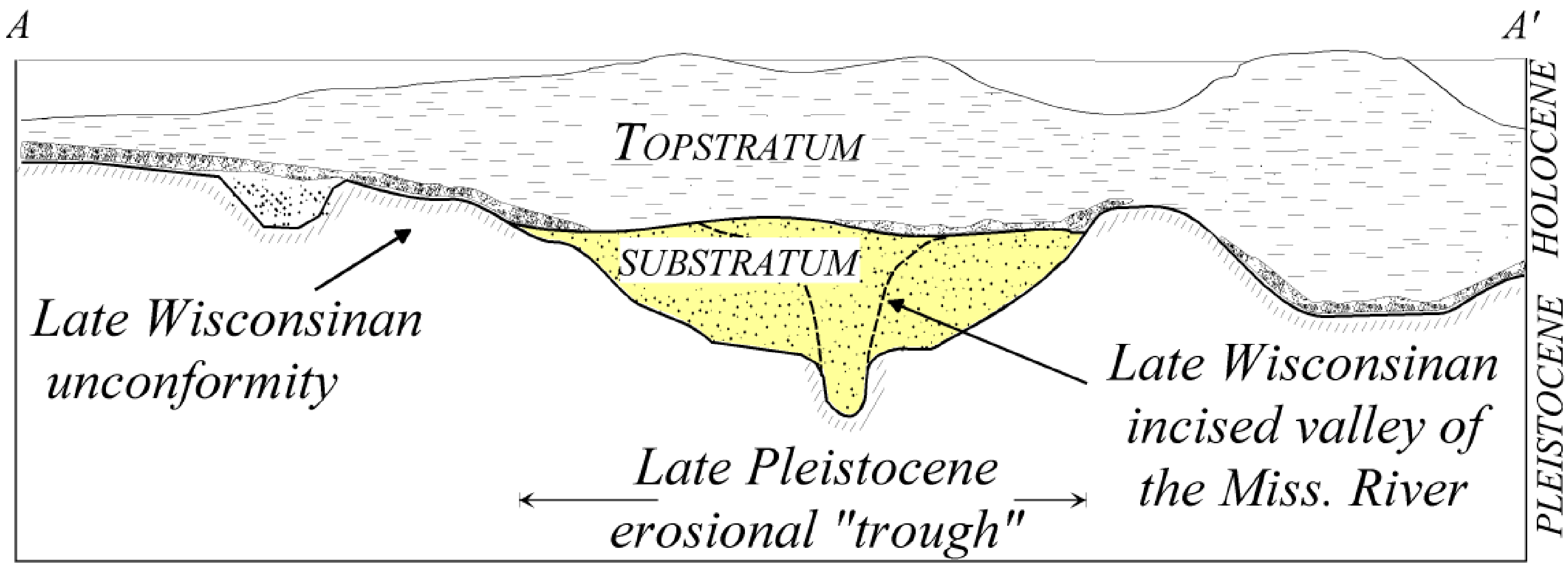


Figure 4. Schematic cross section showing the stratigraphic relationships between the incised valley fills referred to as substratum, the late Wisconsin unconformity, and the generally fine-grained, interval overlying topstratum (from Kulp et al., 2002).

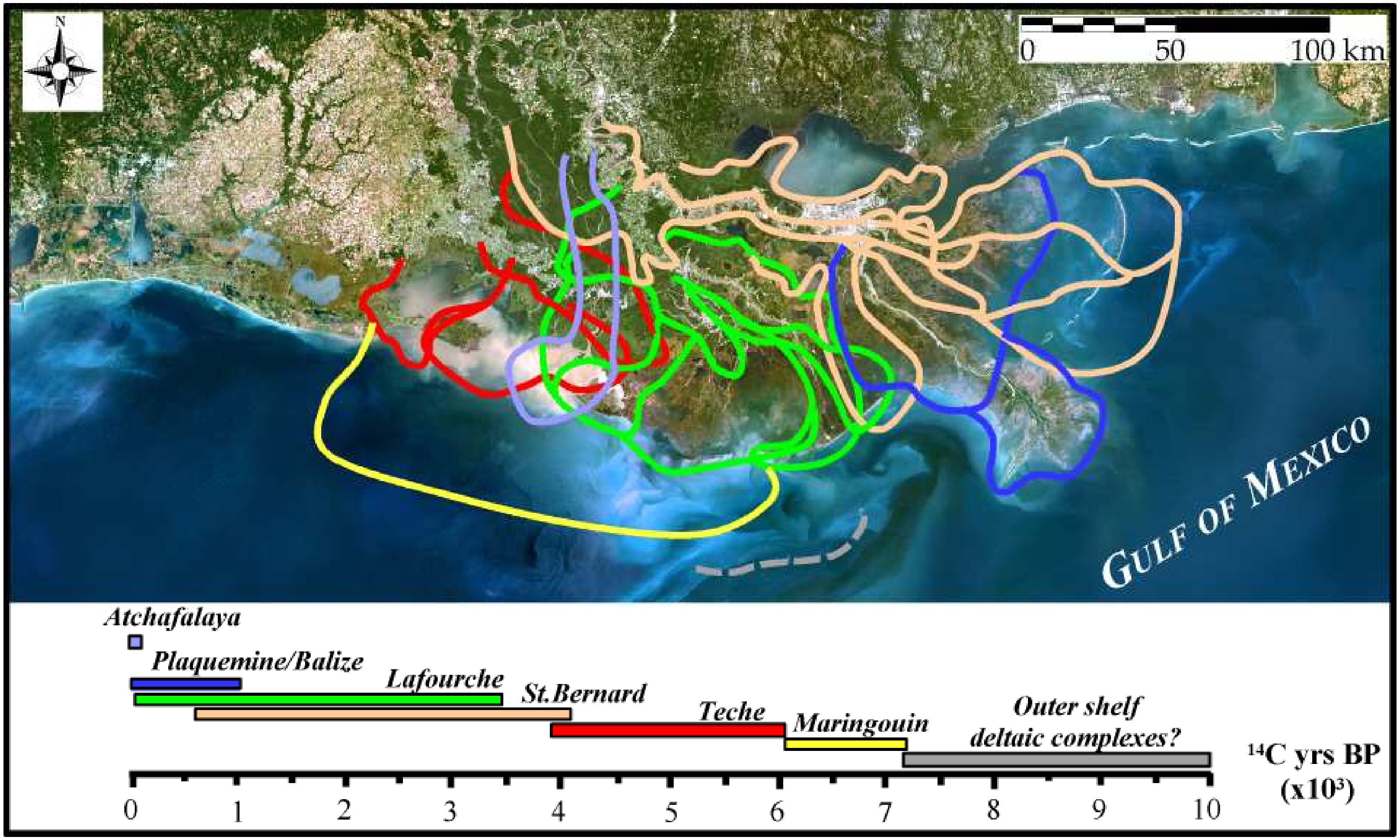


Figure 5. Distribution and chronology of Holocene Mississippi River delta complexes. Through distributary switching and abandonment processes a package of primarily deltaic deposits has prograded to create much of the Louisiana Coastal Zone. Deltaic depocenters have been reworked by marine processes to form transgressive coastlines, barrier island systems, and ultimately submerged sand shoals on the continental shelf (from Kulp et al., 2005).

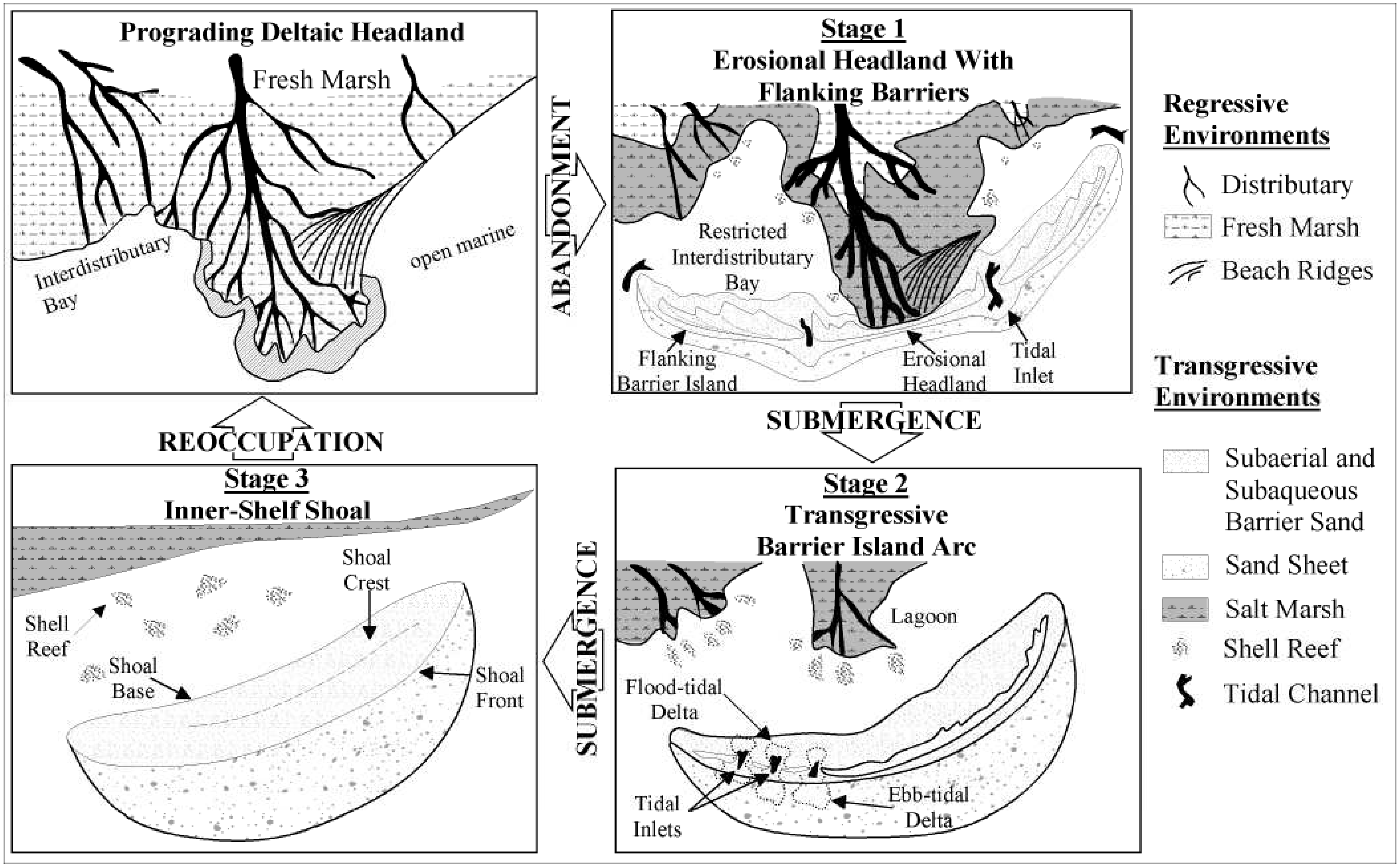


Figure 6. Conceptual regressive and transgressive model showing formation of transgressive depositional systems along the Louisiana Coastal Zone. After abandonment prograded deltaic headlands are reworked by marine processes, resulting in transgression and their ultimate transformation to an inner-shelf, sand-rich shoal (modified from Penland et al., 1989).

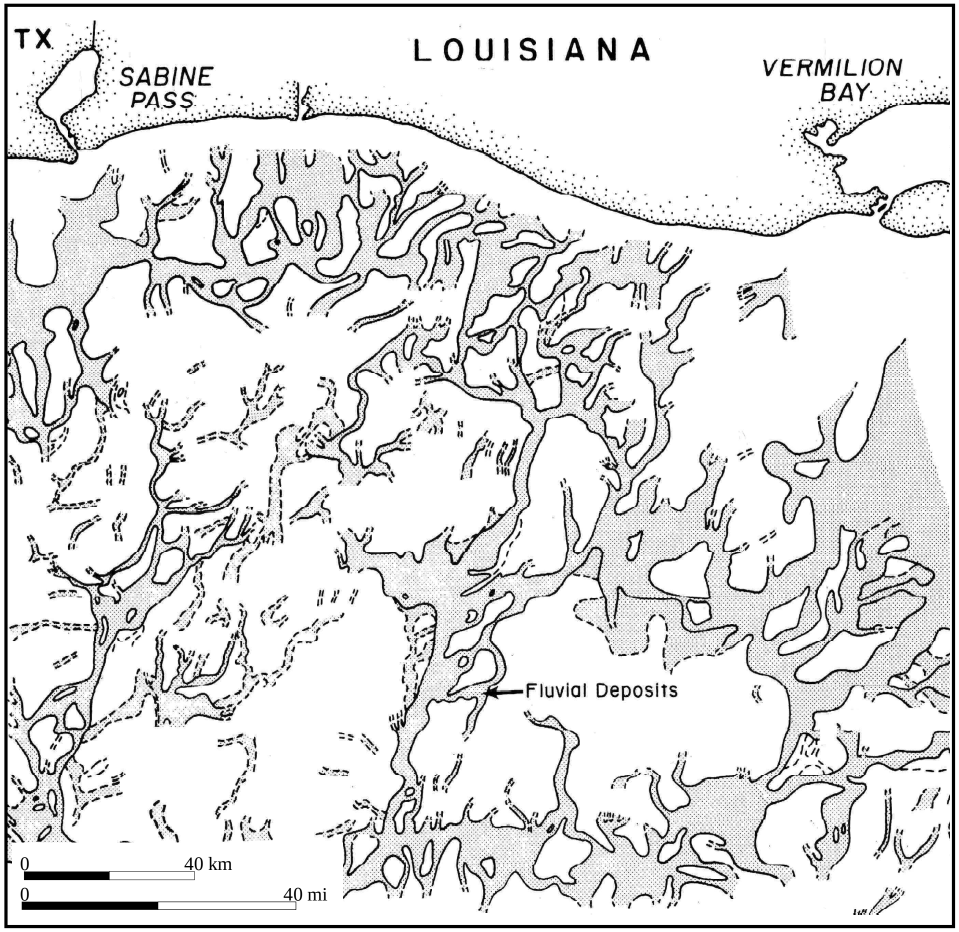


Figure 7. Map showing the distribution of late Wisconsin, incised fluvial systems offshore of the western Louisiana Chenier Plain. Location of the map is shown in figure 1 (from Suter et al., 1987).

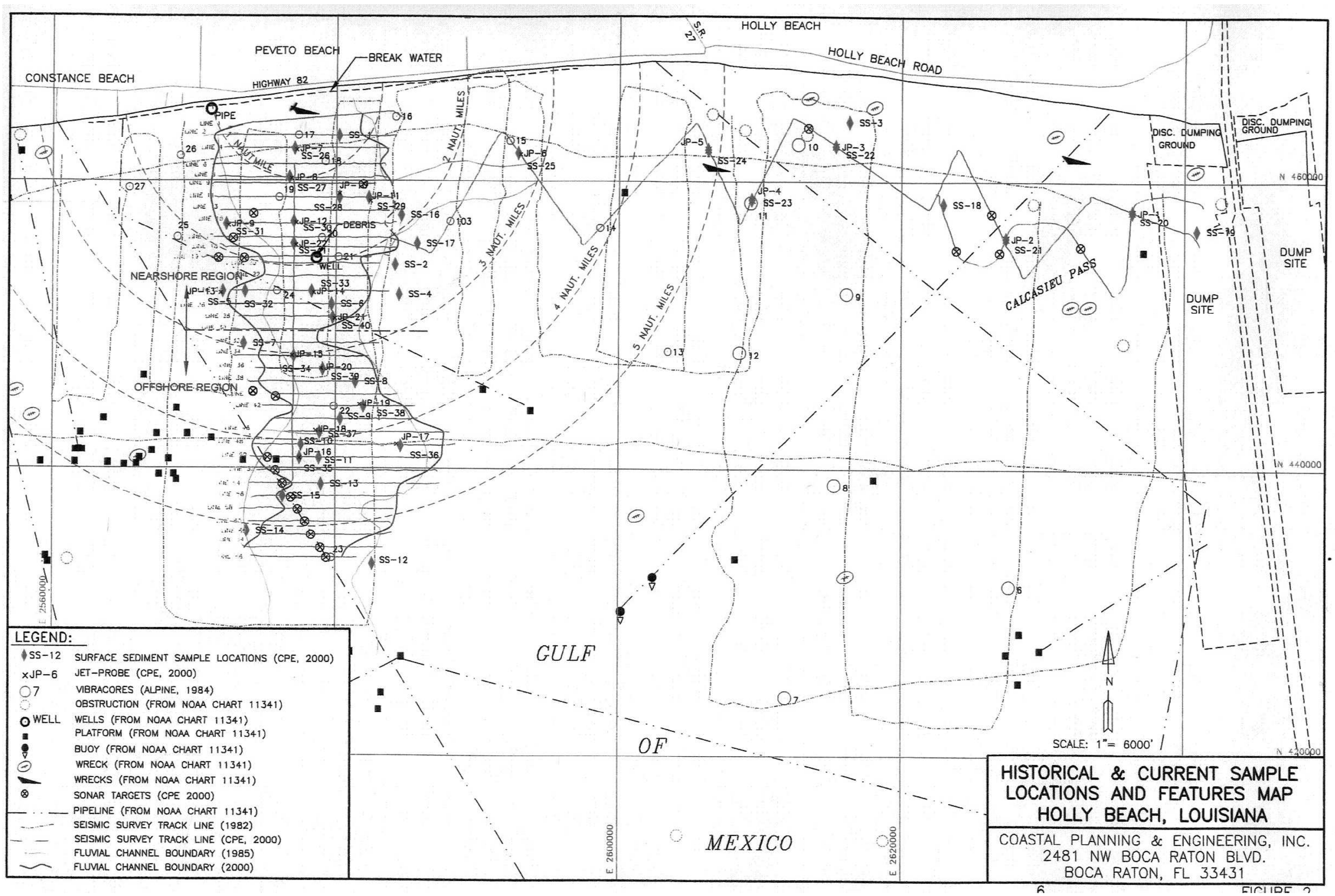


Figure 8. Base map from CPE (2002) showing the distribution of vibracores, jet probes, and high- resolution seismic profiles in the Pevoto Beach Channel deposit.

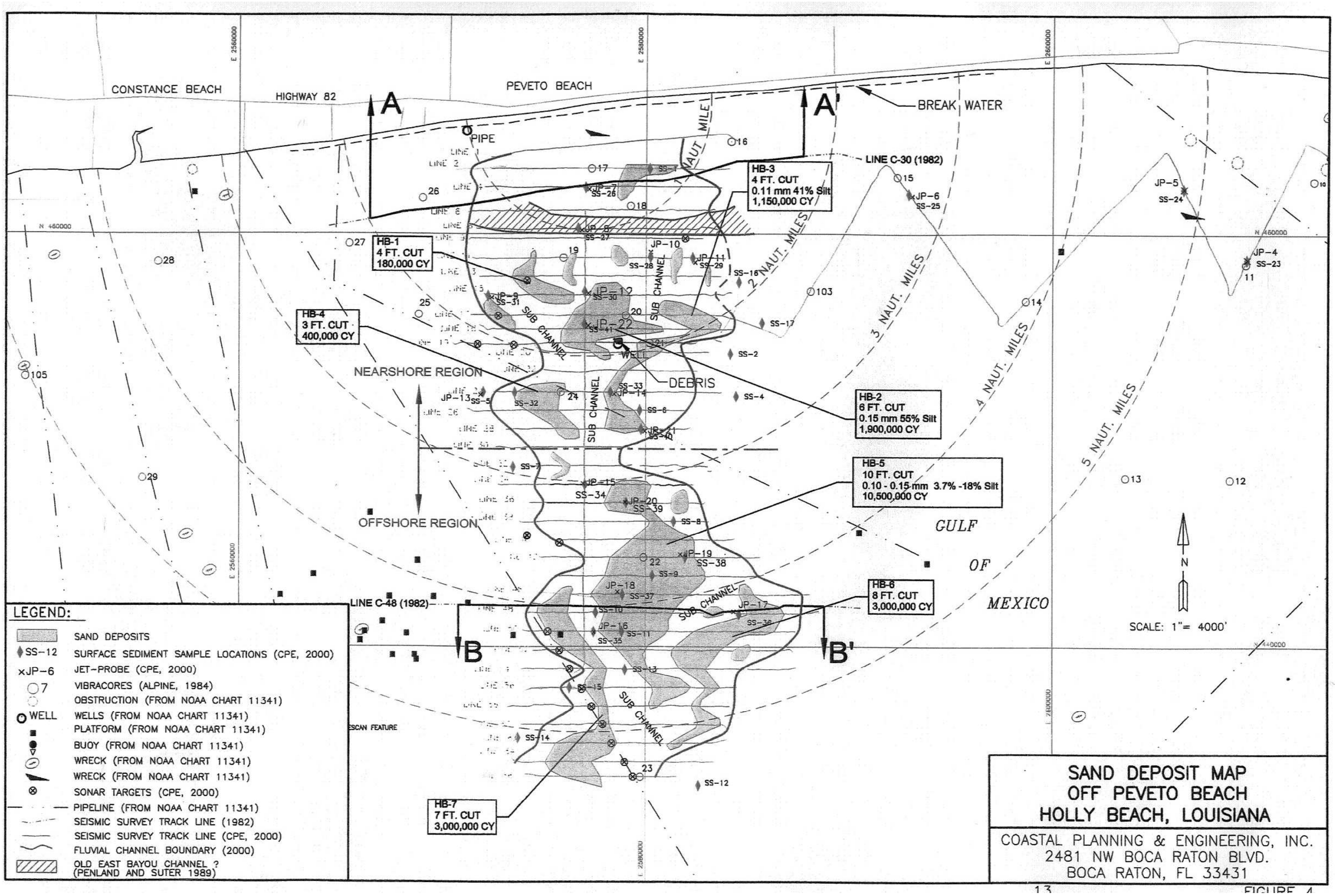


Figure 9. Base map of the sand-rich strata within the Pevoto Channel. Note the distribution of the sand bodies relative to the distribution of sub-channels as defined by CPE (2002). Lines of cross section A-A' and B-B' correspond to the location of figures 11 and 12, respectively.

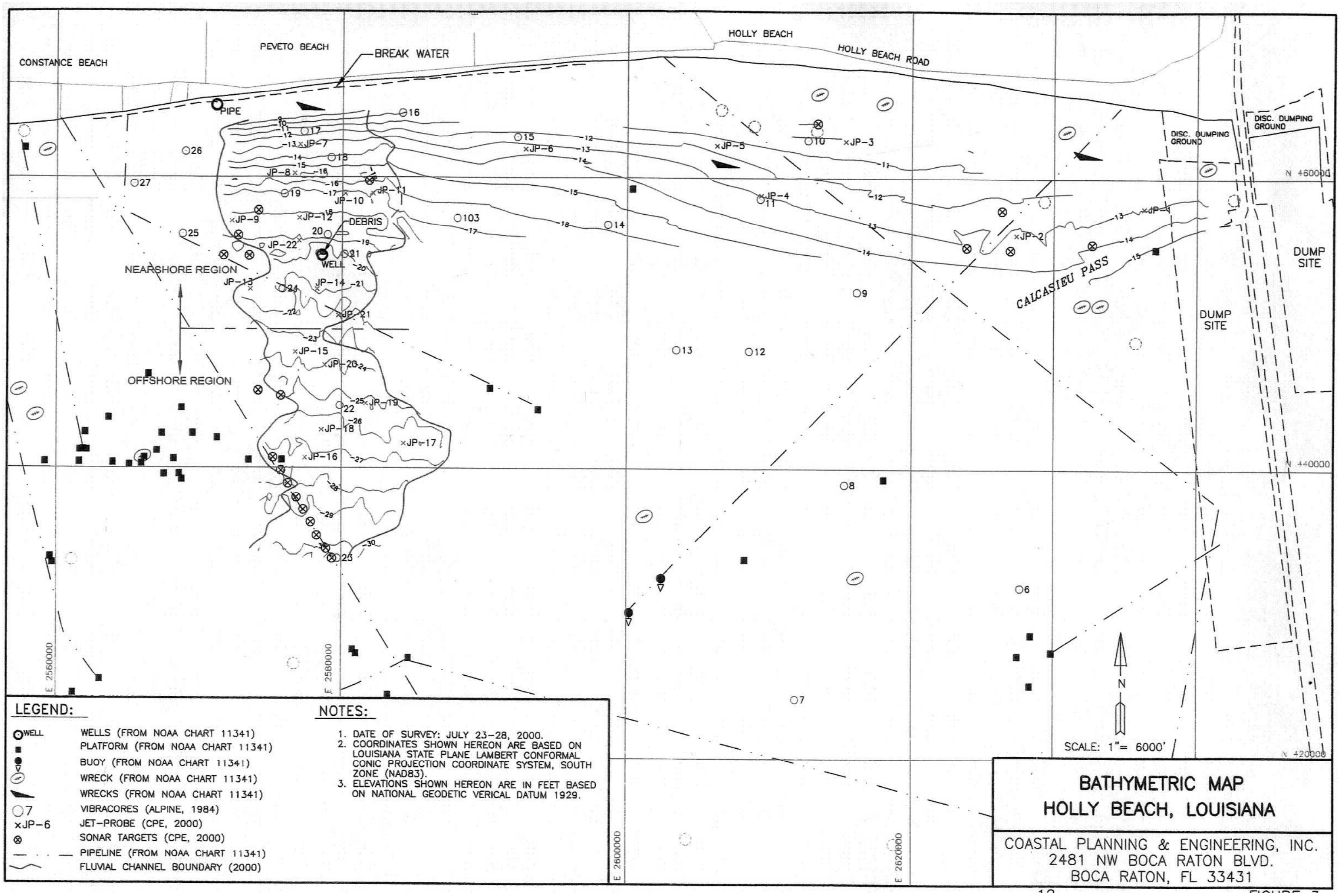


Figure 10. Base map of the Pevoto Channel showing the bathymetry of the study site. Contours are shown in feet NGVD 29.

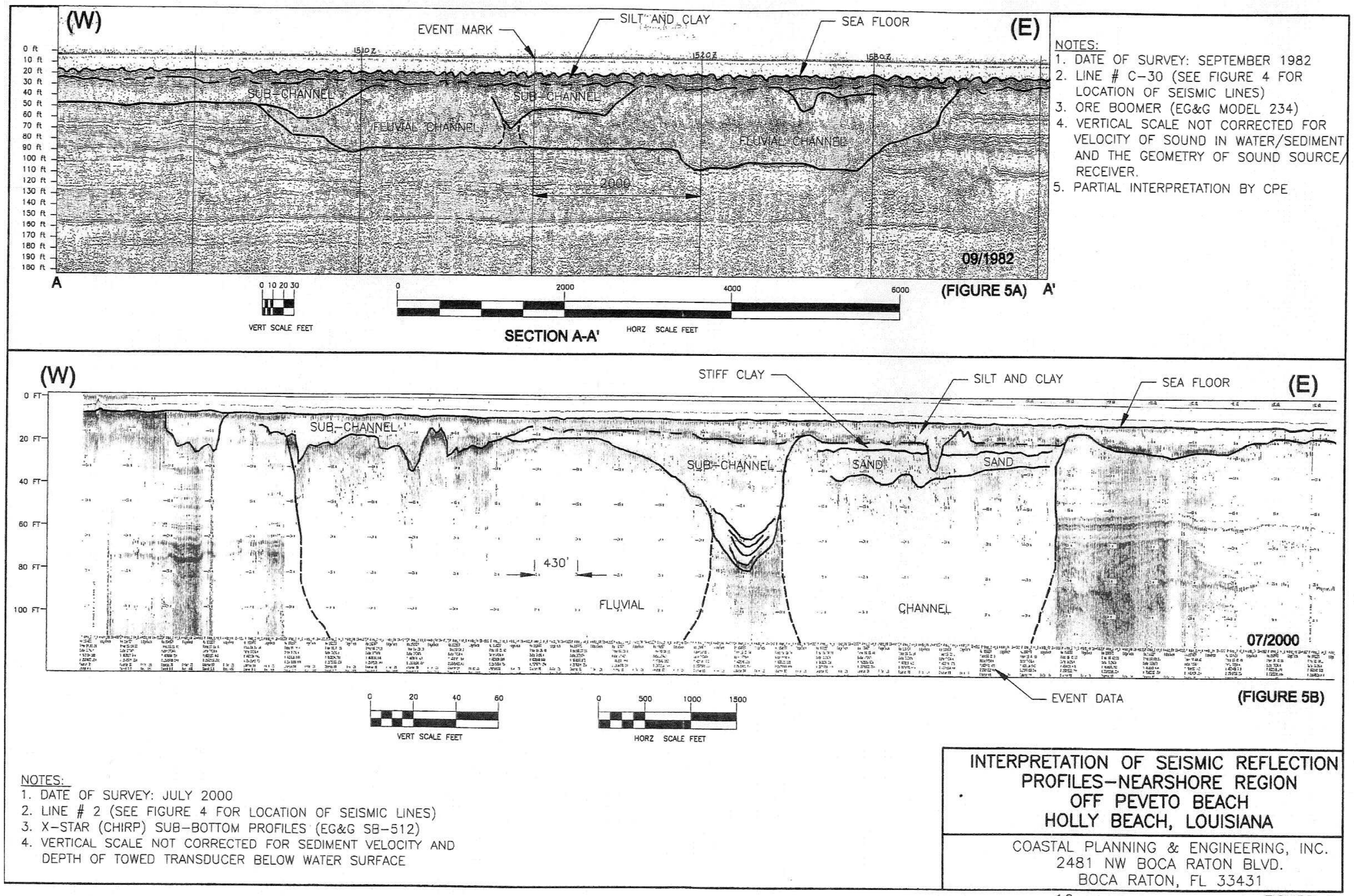


Figure 11. High-resolution seismic profiles across the northern part of the Pevoto channel showing the subsurface geologic framework of the fluvial sedimentary bodies and stratigraphic characteristics of the overburden. Upper seismic profile is from investigations conducted by the U.S. Geological Survey in the 1980's and lower profile is from CPE (2002) approximately across the same location. Location of profile is shown in figure 9.

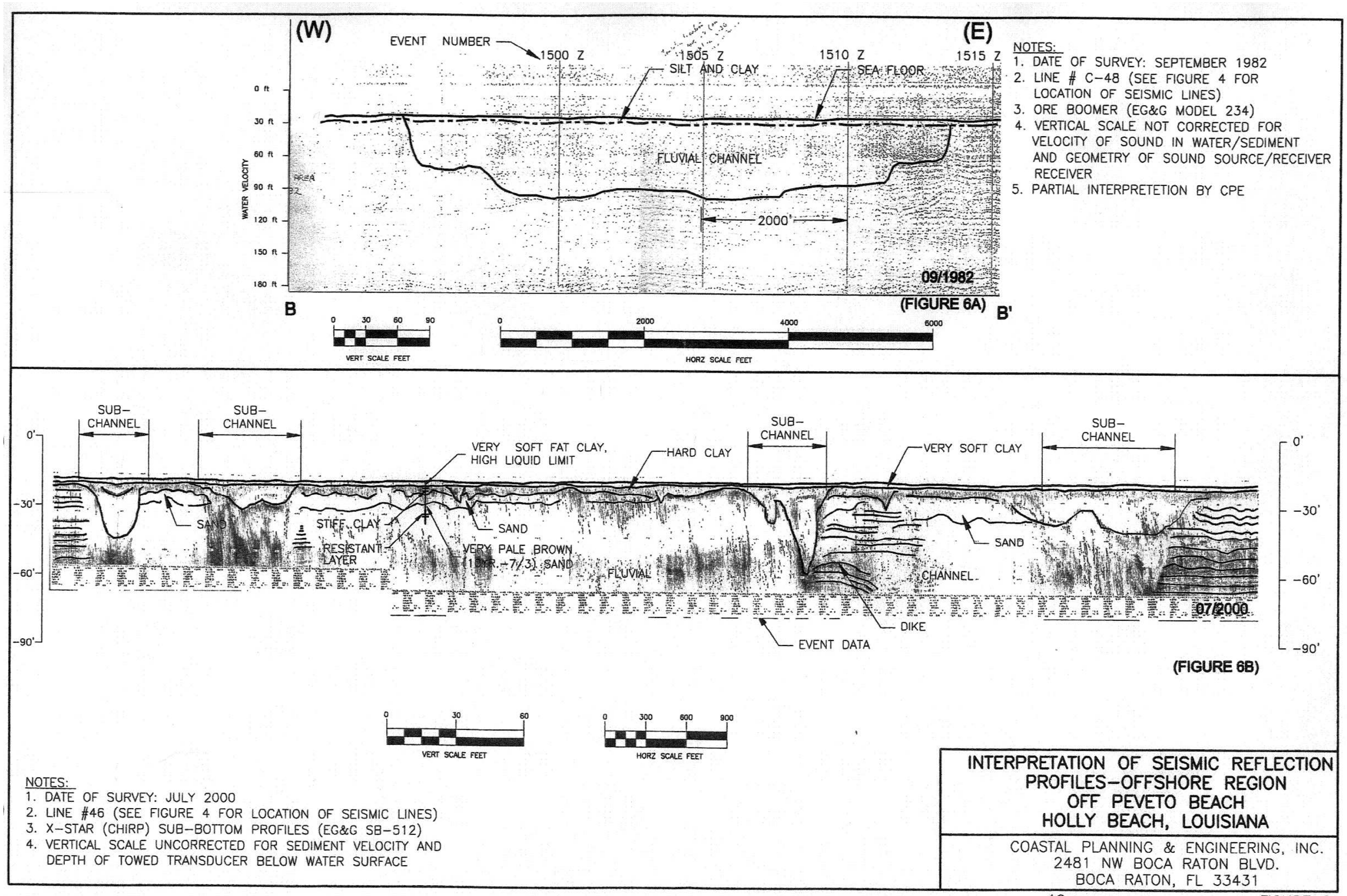


Figure 12. High-resolution seismic profiles across the southern part of the Pevoto channel showing the subsurface geologic framework of the fluvial sedimentary bodies and stratigraphic characteristics of the overburden. Upper seismic profile is from investigations conducted by the U.S. Geological Survey in the 1980's and lower profile is from CPE (2002) approximately across the same location. Location of profile is shown in figure 9.

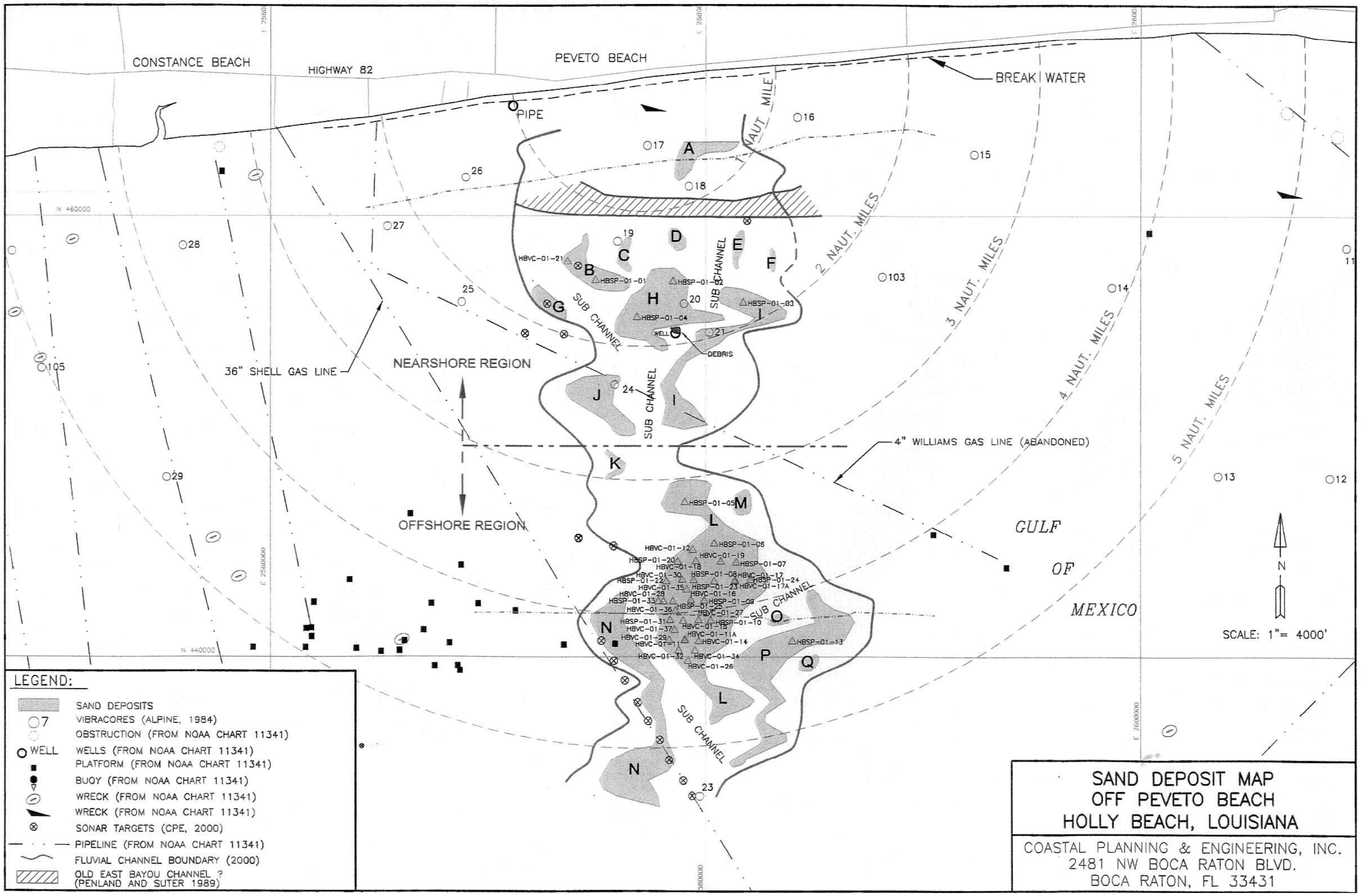


Figure 13. Base map of the primary sand bodies in the Pevoto channel system. CPE (2002) labeled these bodies as A to O and focused primarily on the unit L (south-central location) for additional detailed investigations as a borrow target.

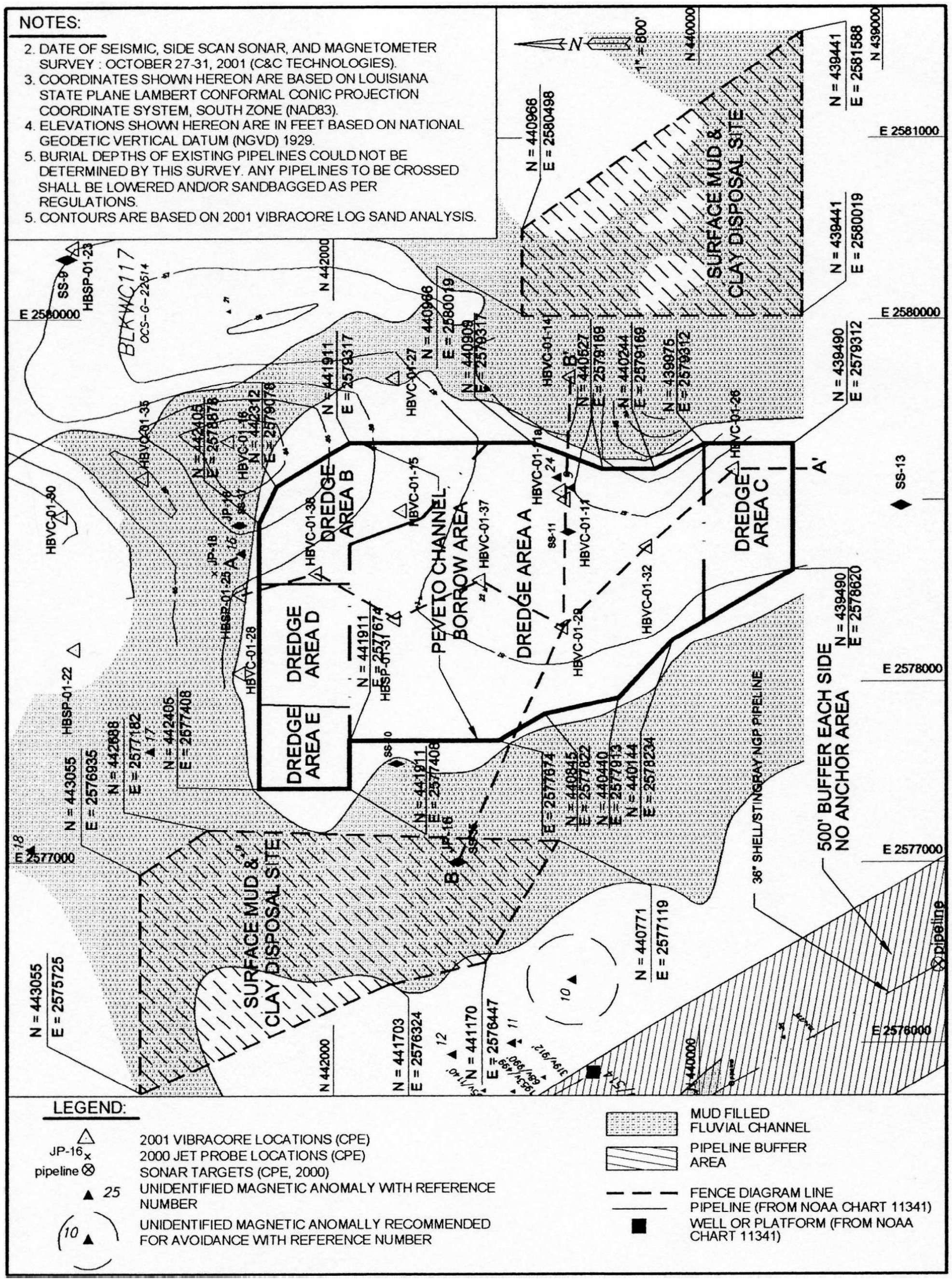


Figure 14. Close-up map of the sand body L (shown in figure 13) with the designated targets within the location. Lines of cross section (A to A'; B to B') are shown for figures 15 and 16.

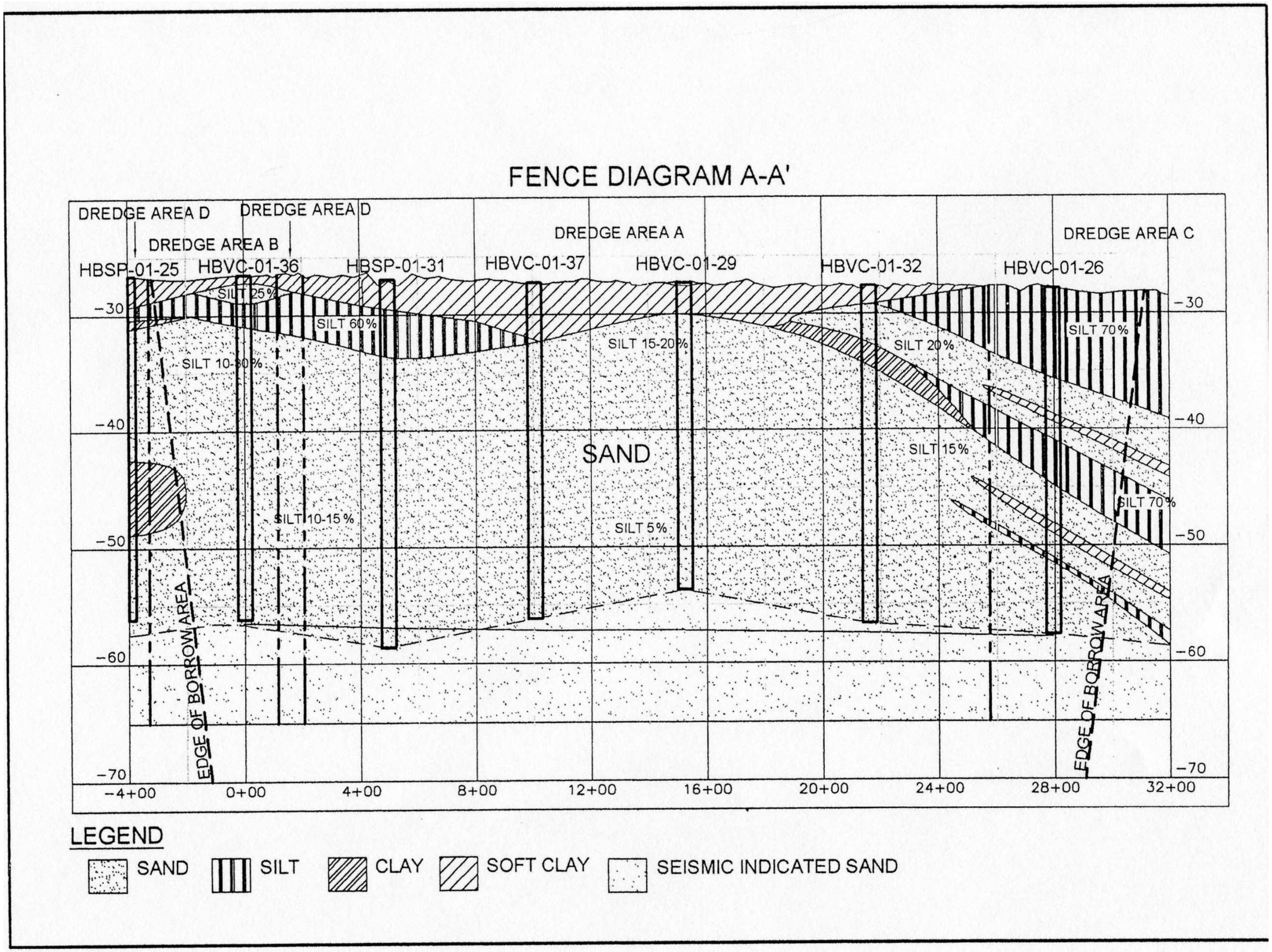


Figure 15. Lithostratigraphic cross section A-A' across sand body L. Location of cross section shown in figure 14. Variability in thickness of the silty and clayey overburden exists along this line but generally ranges between 1 and 3 m (0.3 and 9 ft).

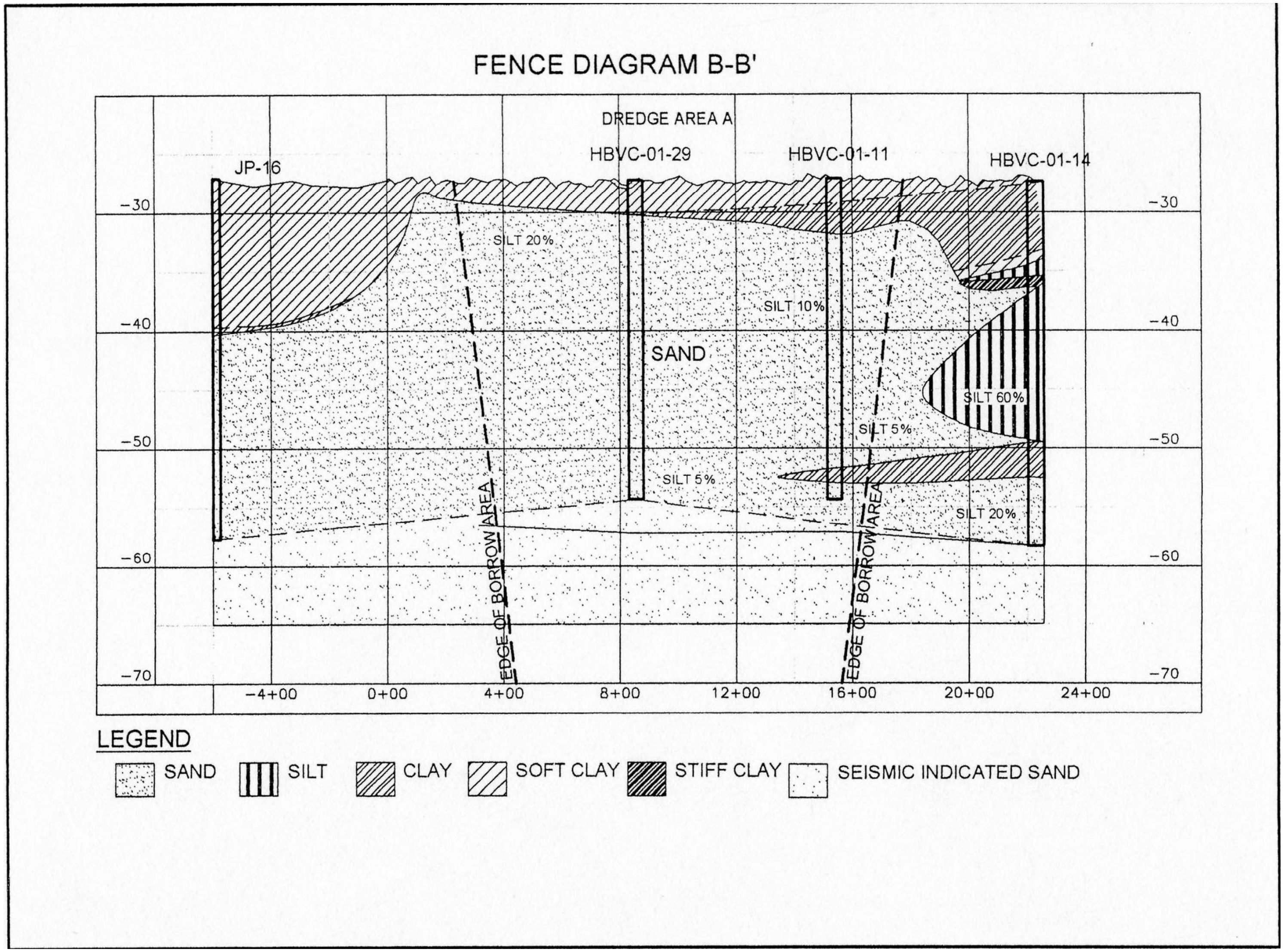
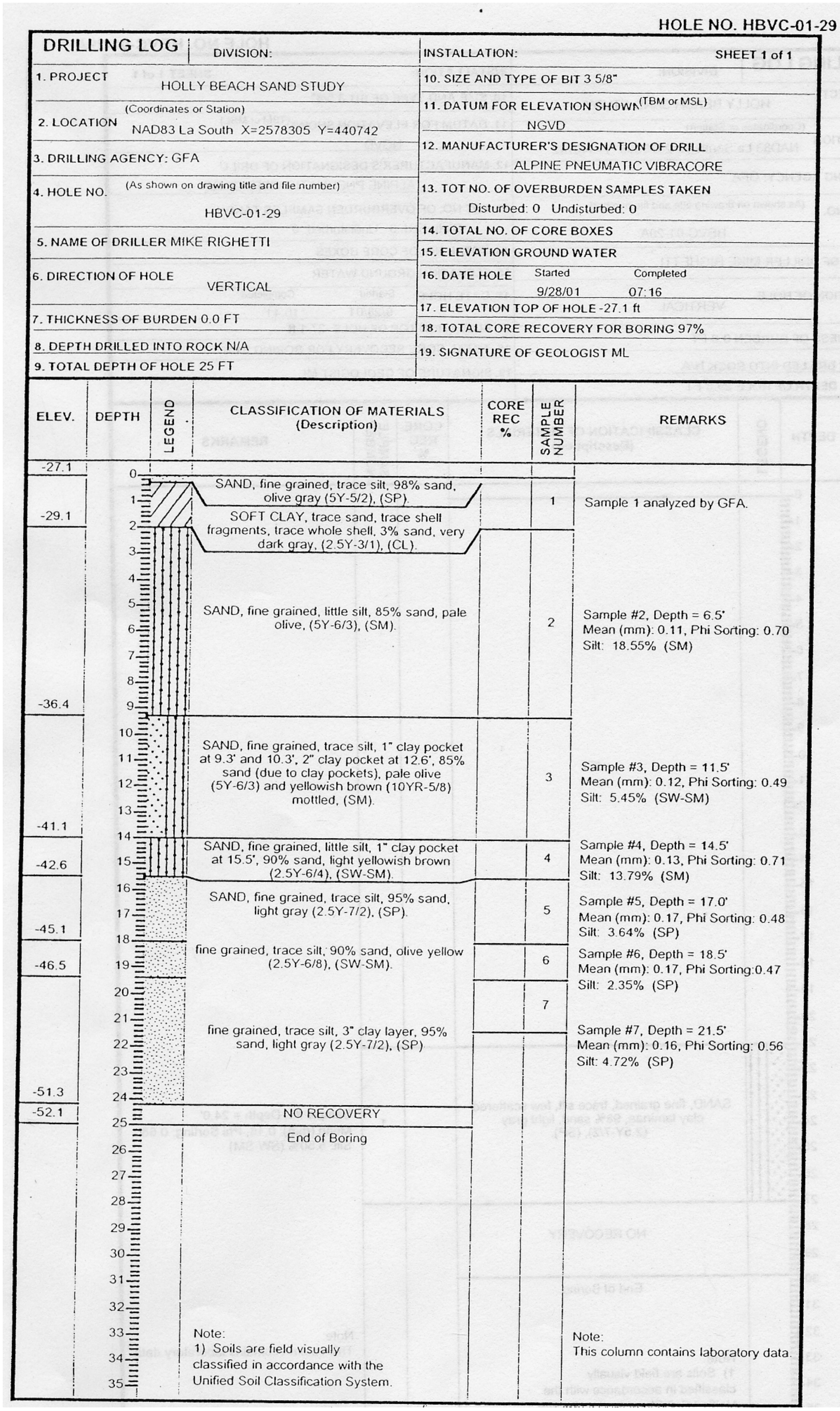


Figure 16. Lithostratigraphic cross section B-B' across sand body L. Location of cross section shown in figure 14. Note the variation in facies composition and thickness as compared to figure 15.



HOLE NO. HBVC-01-29

DRILLING LOG | DIVISION: | INSTALLATION: | SHEET 1 of 1

1. PROJECT HOLLY BEACH SAND STUDY
2. LOCATION (Coordinates or Station) NAD83 La South X=2578305 Y=440742
3. DRILLING AGENCY: GFA
4. HOLE NO. (As shown on drawing title and file number) HBVC-01-29
5. NAME OF DRILLER MIKE RIGHETTI
6. DIRECTION OF HOLE VERTICAL
7. THICKNESS OF BURDEN 0.0 FT
8. DEPTH DRILLED INTO ROCK N/A
9. TOTAL DEPTH OF HOLE 25 FT
10. SIZE AND TYPE OF BIT 3 5/8"
11. DATUM FOR ELEVATION SHOWN (TBM or MSL) NGVD
12. MANUFACTURER'S DESIGNATION OF DRILL ALPINE PNEUMATIC VIBRACORE
13. TOT NO. OF OVERBURDEN SAMPLES TAKEN Disturbed: 0 Undisturbed: 0
14. TOTAL NO. OF CORE BOXES
15. ELEVATION GROUND WATER
16. DATE HOLE Started 9/28/01 Completed 07:16
17. ELEVATION TOP OF HOLE -27.1 ft
18. TOTAL CORE RECOVERY FOR BORING 97%
19. SIGNATURE OF GEOLOGIST ML

ELEV.	DEPTH	CLASSIFICATION OF MATERIALS (Description)	CORE REC %	SAMPLE NUMBER	REMARKS
-27.1	0	SAND, fine grained, trace silt, 98% sand, olive gray (5Y-5/2), (SP).		1	Sample 1 analyzed by GFA.
-29.1	2	SOFT CLAY, trace sand, trace shell fragments, trace whole shell, 3% sand, very dark gray, (2.5Y-3/1), (CL).			
		SAND, fine grained, little silt, 85% sand, pale olive, (5Y-6/3), (SM).		2	Sample #2, Depth = 6.5' Mean (mm): 0.11, Phi Sorting: 0.70 Silt: 18.55% (SM)
-36.4	9	SAND, fine grained, trace silt, 1" clay pocket at 9.3' and 10.3', 2" clay pocket at 12.6', 85% sand (due to clay pockets), pale olive (5Y-6/3) and yellowish brown (10YR-5/8) mottled, (SM).		3	Sample #3, Depth = 11.5' Mean (mm): 0.12, Phi Sorting: 0.49 Silt: 5.45% (SW-SM)
-41.1	14	SAND, fine grained, little silt, 1" clay pocket at 15.5', 90% sand, light yellowish brown (2.5Y-6/4), (SW-SM).		4	Sample #4, Depth = 14.5' Mean (mm): 0.13, Phi Sorting: 0.71 Silt: 13.79% (SM)
-42.6	15	SAND, fine grained, trace silt, 95% sand, light gray (2.5Y-7/2), (SP).		5	Sample #5, Depth = 17.0' Mean (mm): 0.17, Phi Sorting: 0.48 Silt: 3.64% (SP)
-45.1	18	fine grained, trace silt, 90% sand, olive yellow (2.5Y-6/8), (SW-SM).		6	Sample #6, Depth = 18.5' Mean (mm): 0.17, Phi Sorting:0.47 Silt: 2.35% (SP)
-46.5	19	fine grained, trace silt, 3" clay layer, 95% sand, light gray (2.5Y-7/2), (SP)		7	Sample #7, Depth = 21.5' Mean (mm): 0.16, Phi Sorting: 0.56 Silt: 4.72% (SP)
-51.3	24	NO RECOVERY			
-52.1	25	End of Boring			

Note:
1) Soils are field visually classified in accordance with the Unified Soil Classification System.

Note:
This column contains laboratory data.

Figure 17. Stratigraphic log for core HBVC01-29, providing details of the lithostratigraphic characteristics at a central location within the target area. This core is crossed by both stratigraphic cross sections shown in figure 15 and 16.

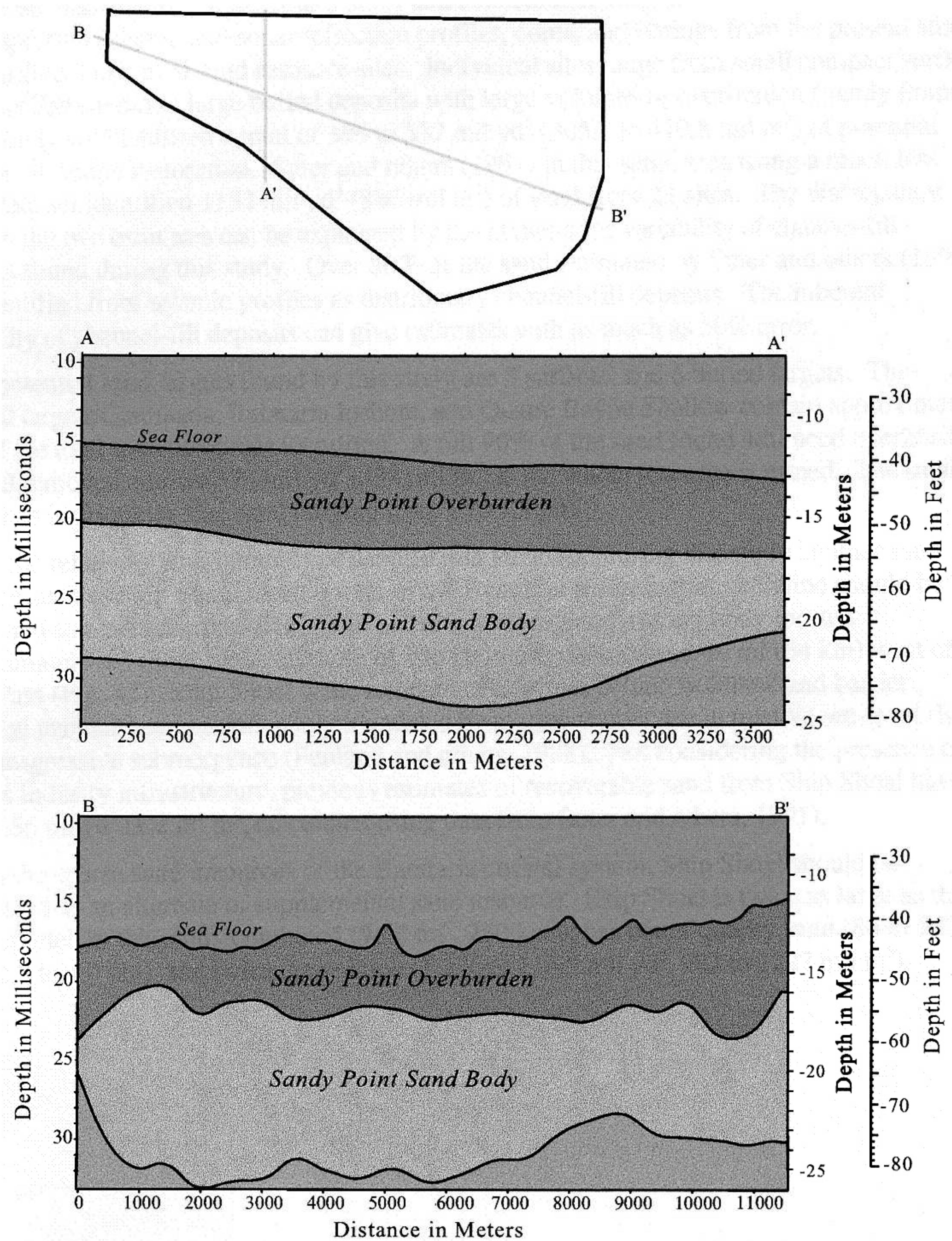


Figure 18. Schematic area map and lithostratigraphic framework model for the Sandy Point Borrow site. The upper polygon (top of figure) defines the area originally recognized by Kindinger et al. (2002) as a potential borrow site in the Barataria Bight. The approximate location of the polygon is shown in figure 1. The lower two diagrams provide schematic cross sections through the site, indicating the geometry, bounding surfaces and overburden (from Kindinger et al., 2002).

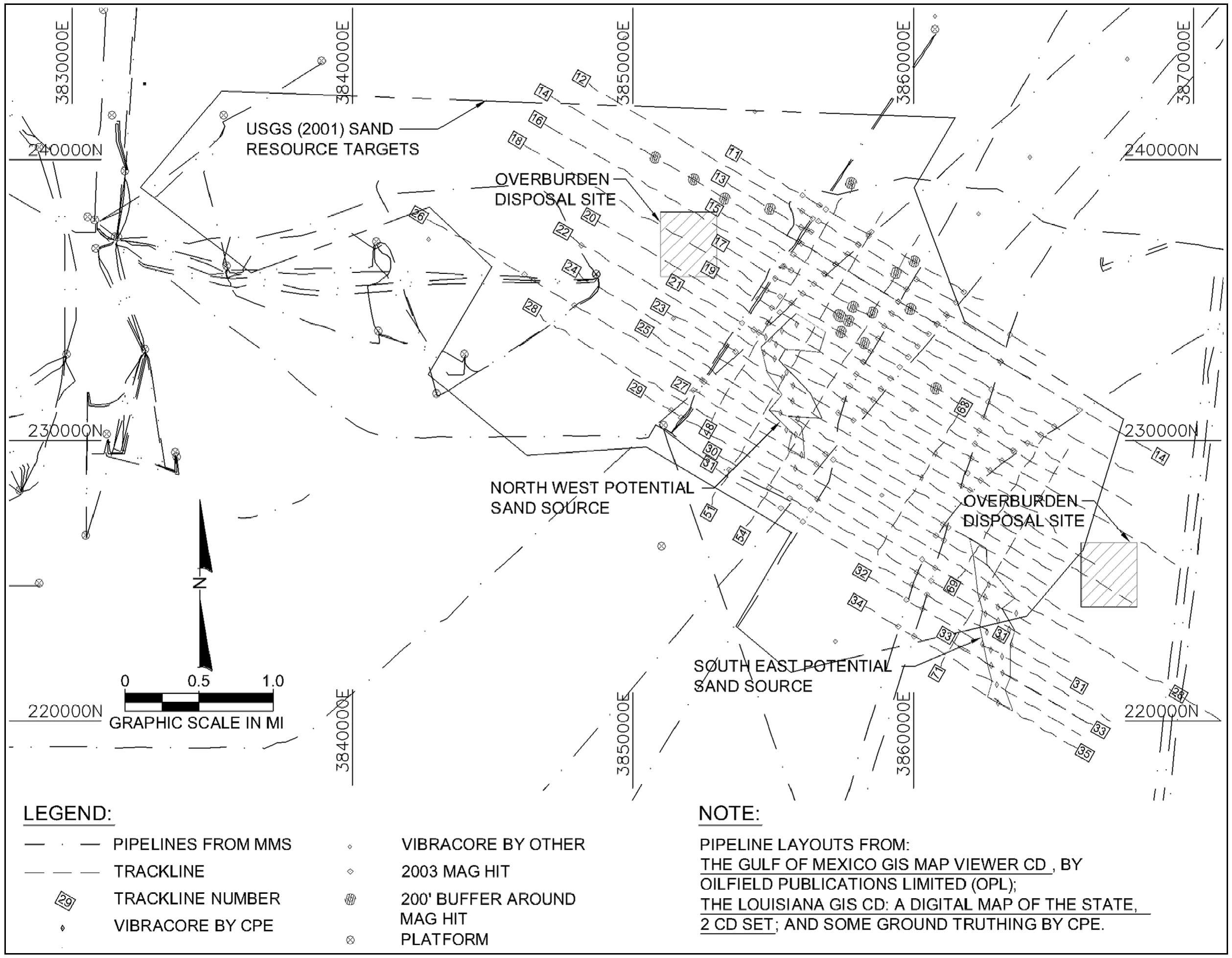


Figure 19. Base map of the Sandy Point borrow site defined by Kindinger et al. (2002) (light gray outer polygon). Within this polygon CPE (2002) defined a northwest and southeast borrow site using vibracores and high-resolution seismic profiles.

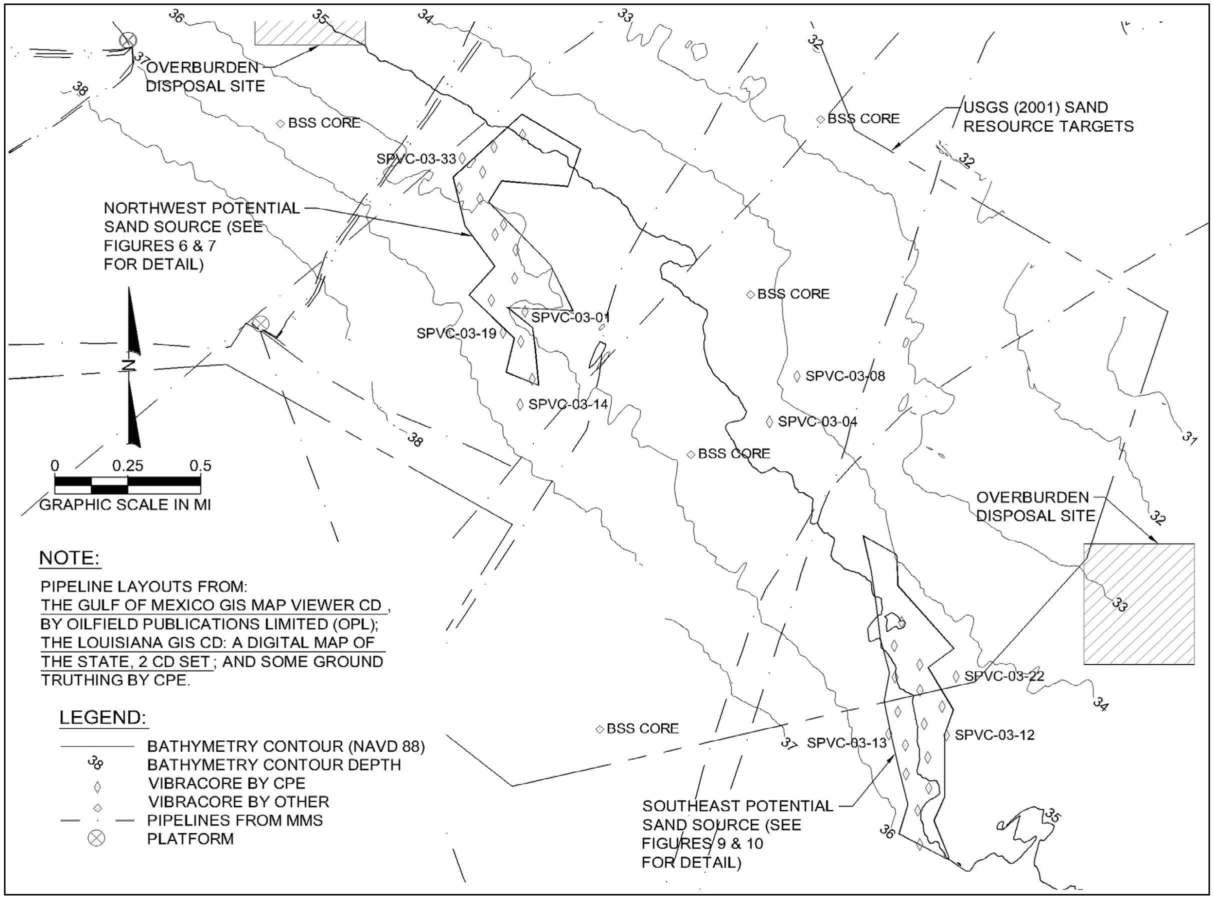


Figure 20. Base map of the Sandy Point area showing the bathymetry determined by CPE (2002) as well as the distribution of cores obtained during their investigation. (SPVC-03; BSS cores from Kindinger et al., 2002).

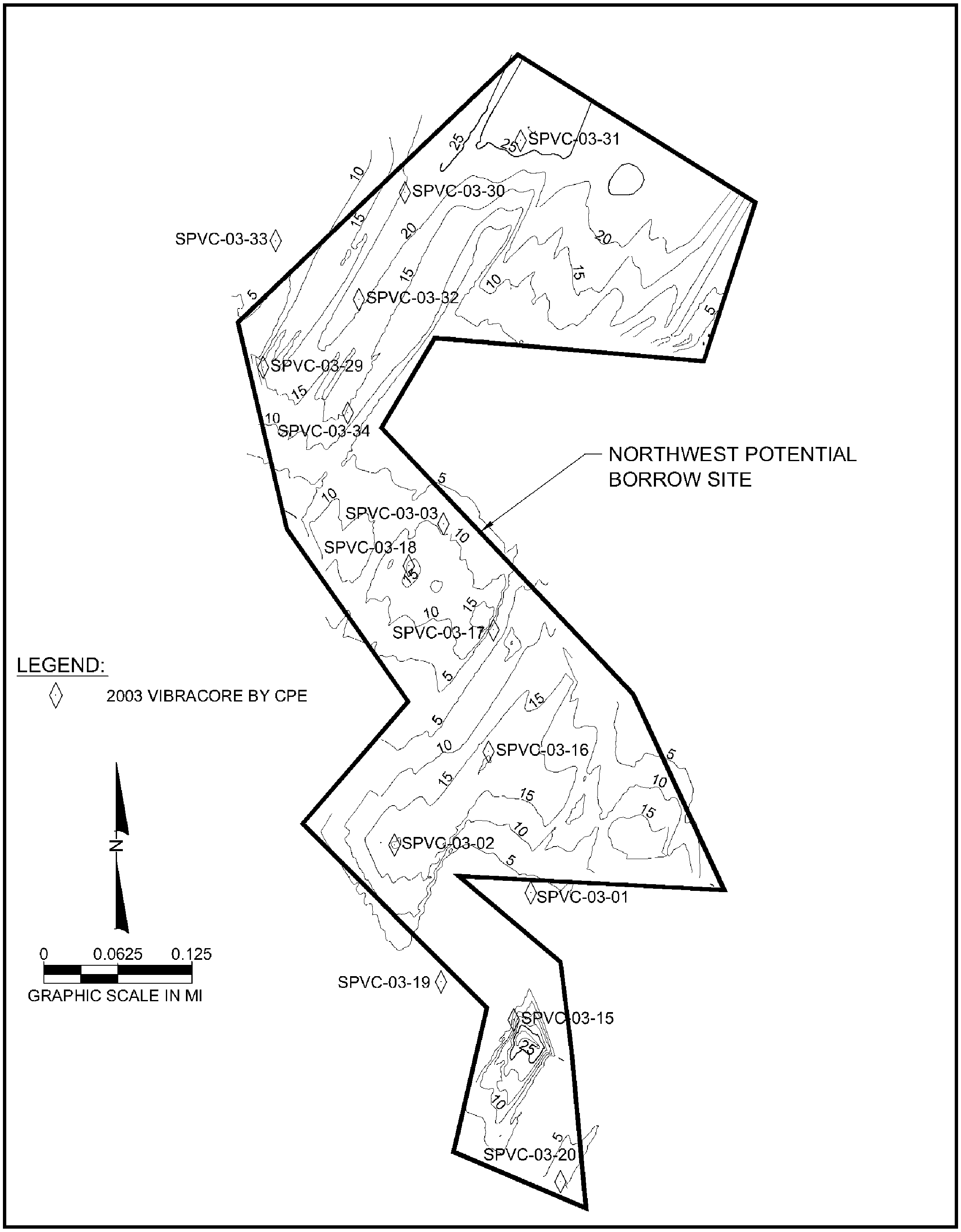


Figure 21. Isopach map of the sand body within the northwest borrow area of the Sandy Point site. Contours are in feet.

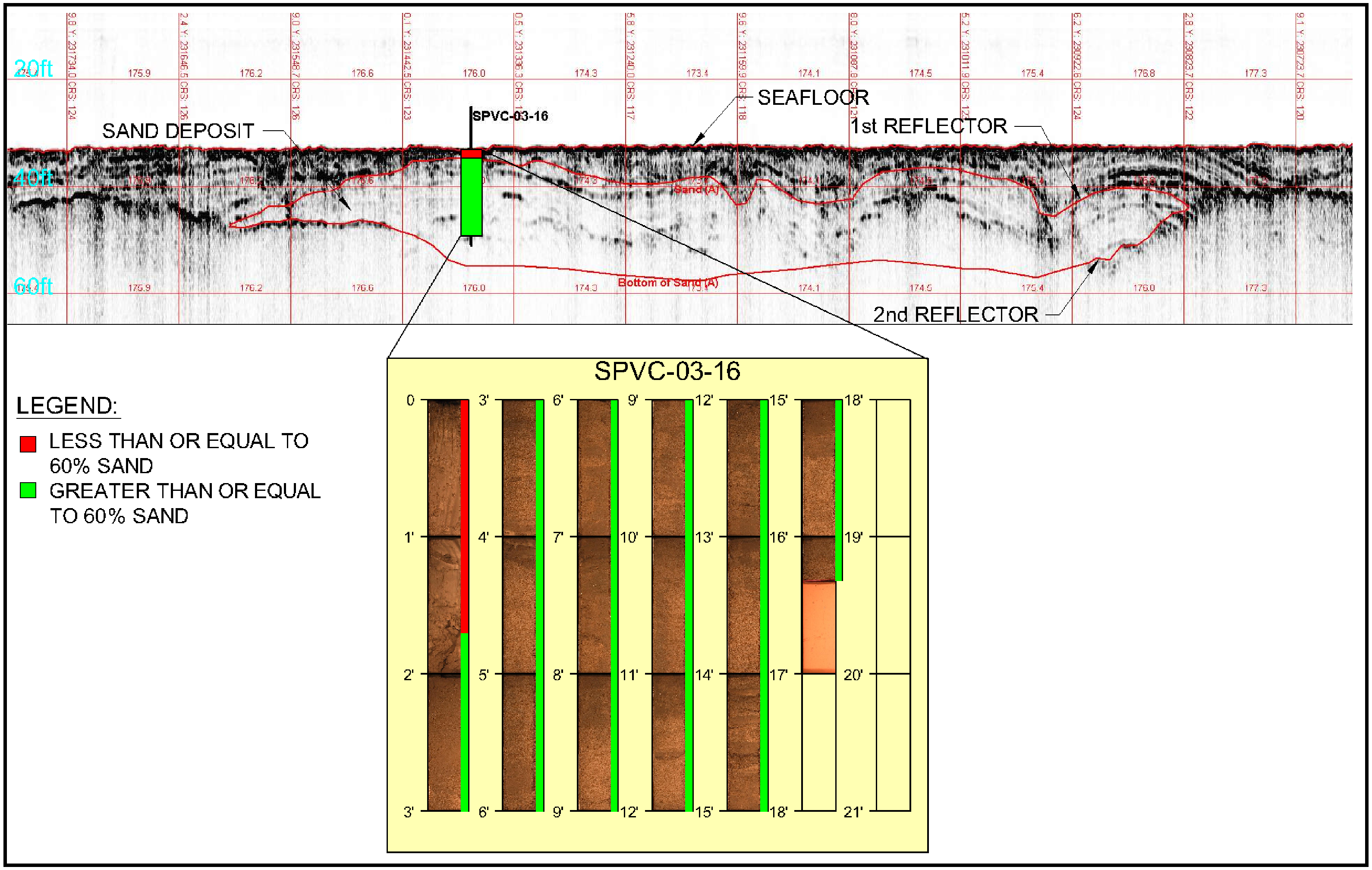


Figure 22. High-resolution seismic profile showing the subsurface geometry of the northwestern borrow site sand body and overburden. Location of cross section is shown in figure 19.

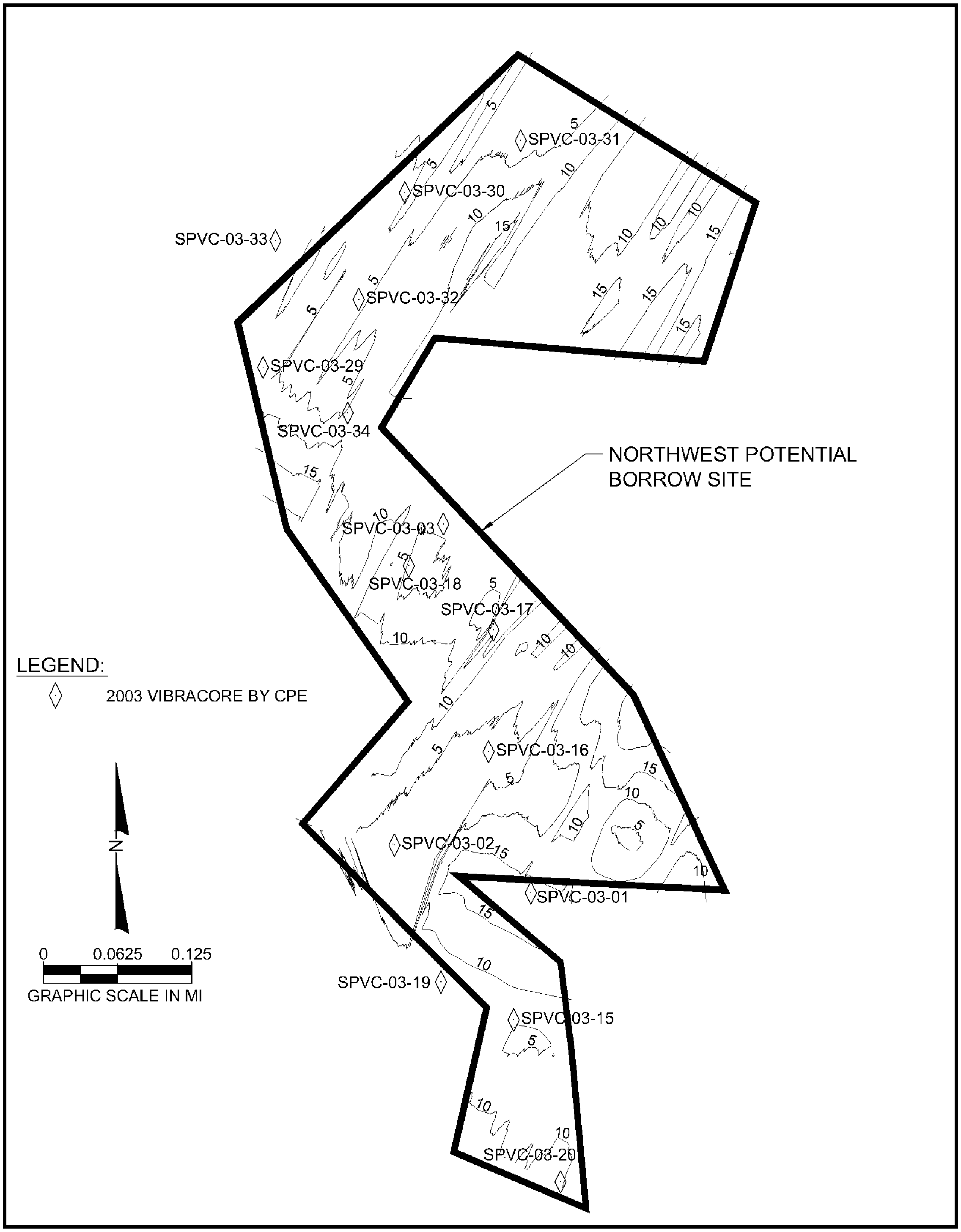


Figure 23. Map of the northwestern borrow site that shows the thickness of the overburden as determined by CPE (2002) from vibracores and seismic profiles. Contours are in feet.

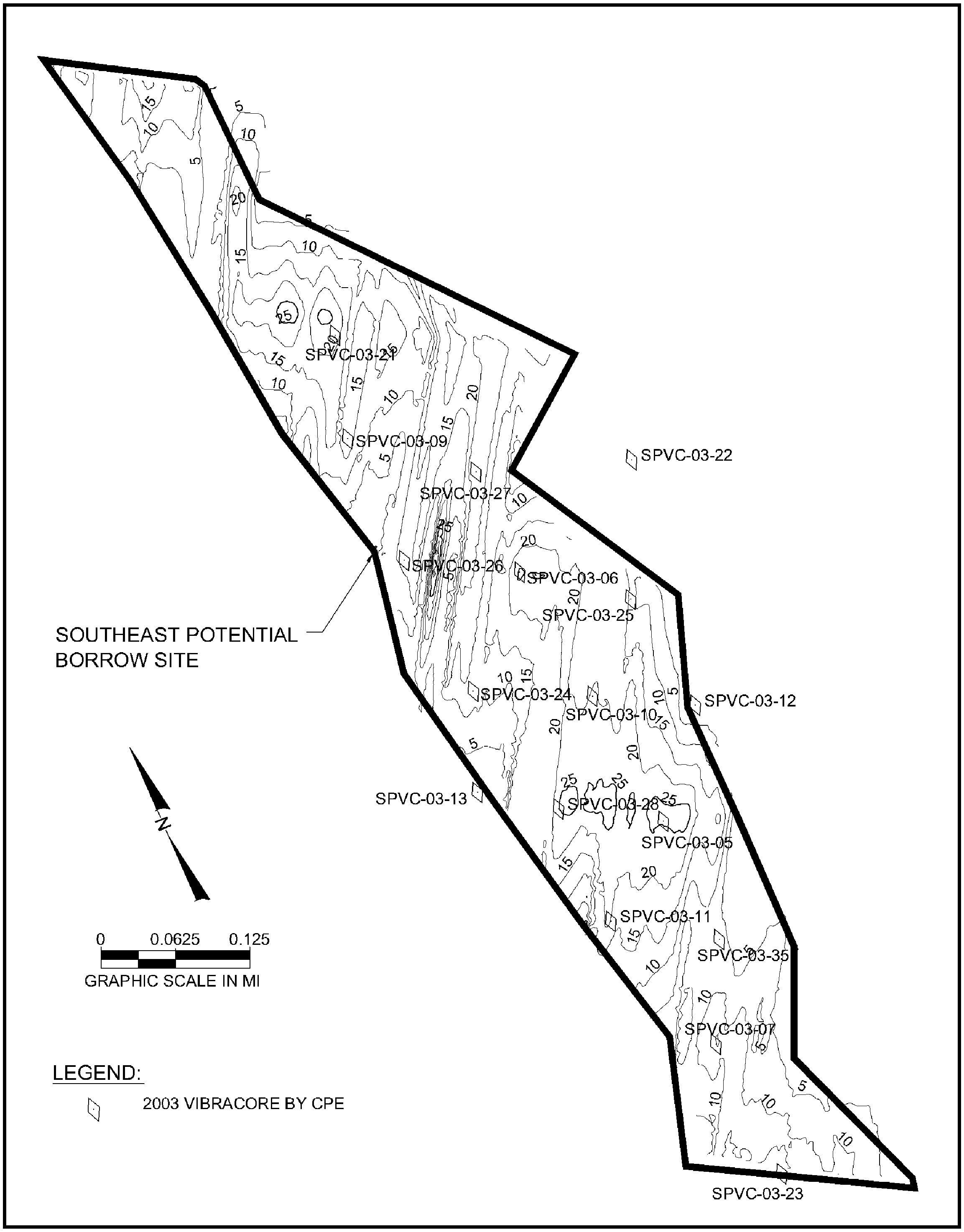


Figure 24. Isopach map of the sand body within the southeast borrow area. Contours are in feet.

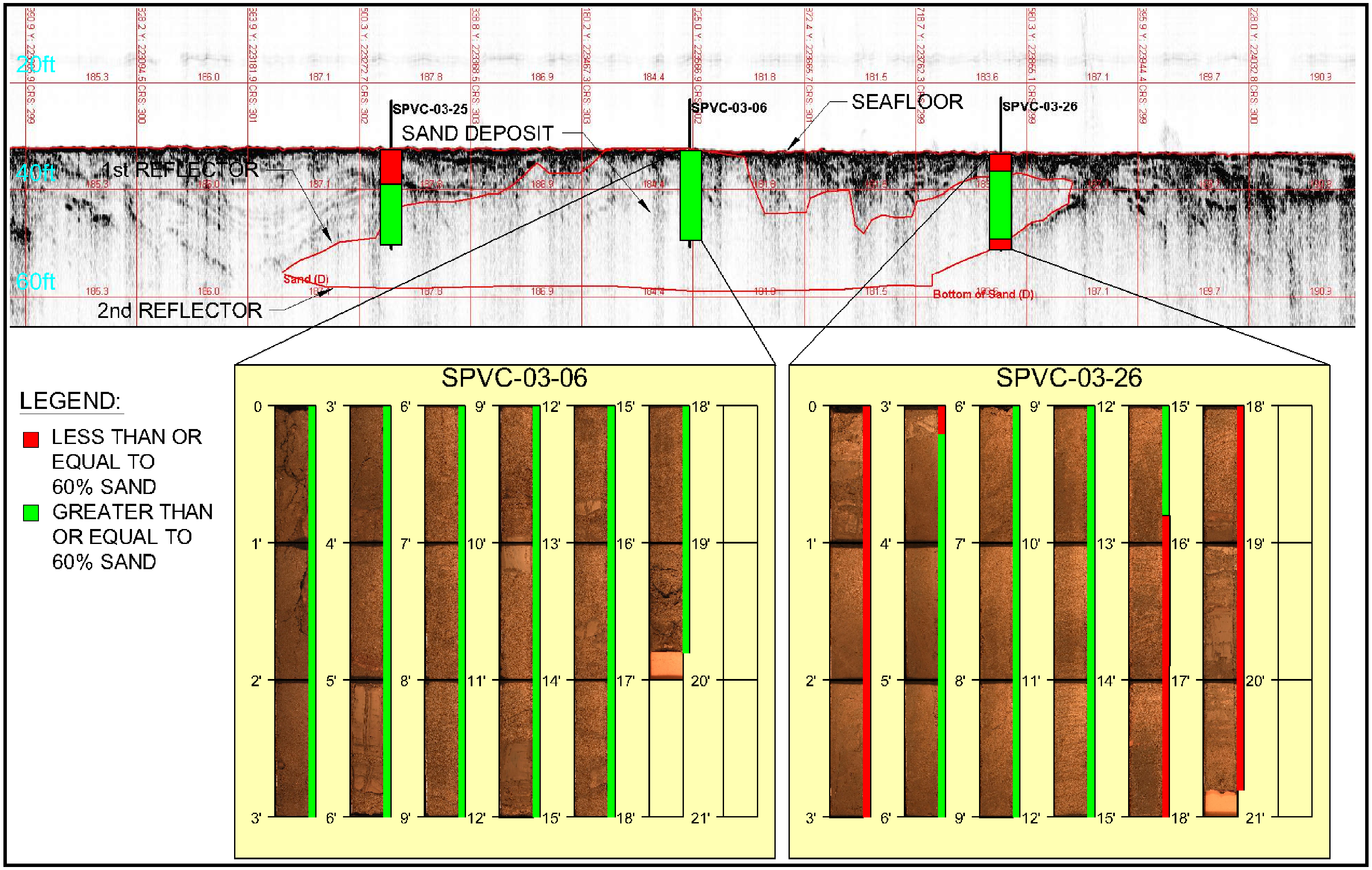


Figure 25. High-resolution seismic profile showing the subsurface geometry of the southeastern borrow-site sand body and overburden. Location of cross section is shown in figure 19.

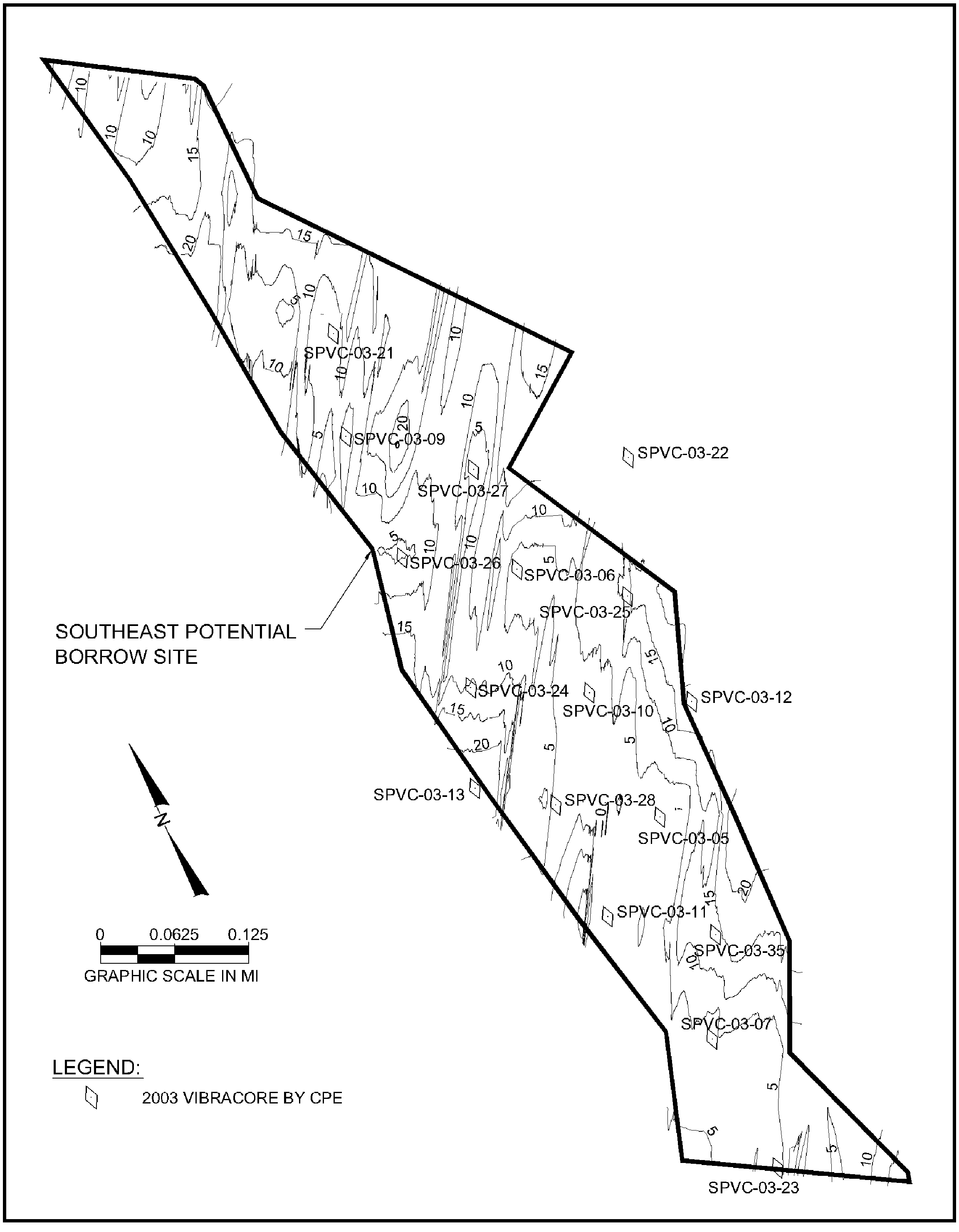


Figure 26. Map of the southeastern borrow site that shows the thickness of the overburden as determined by CPE (2002) from vibracores and seismic profiles. Contours are in feet.

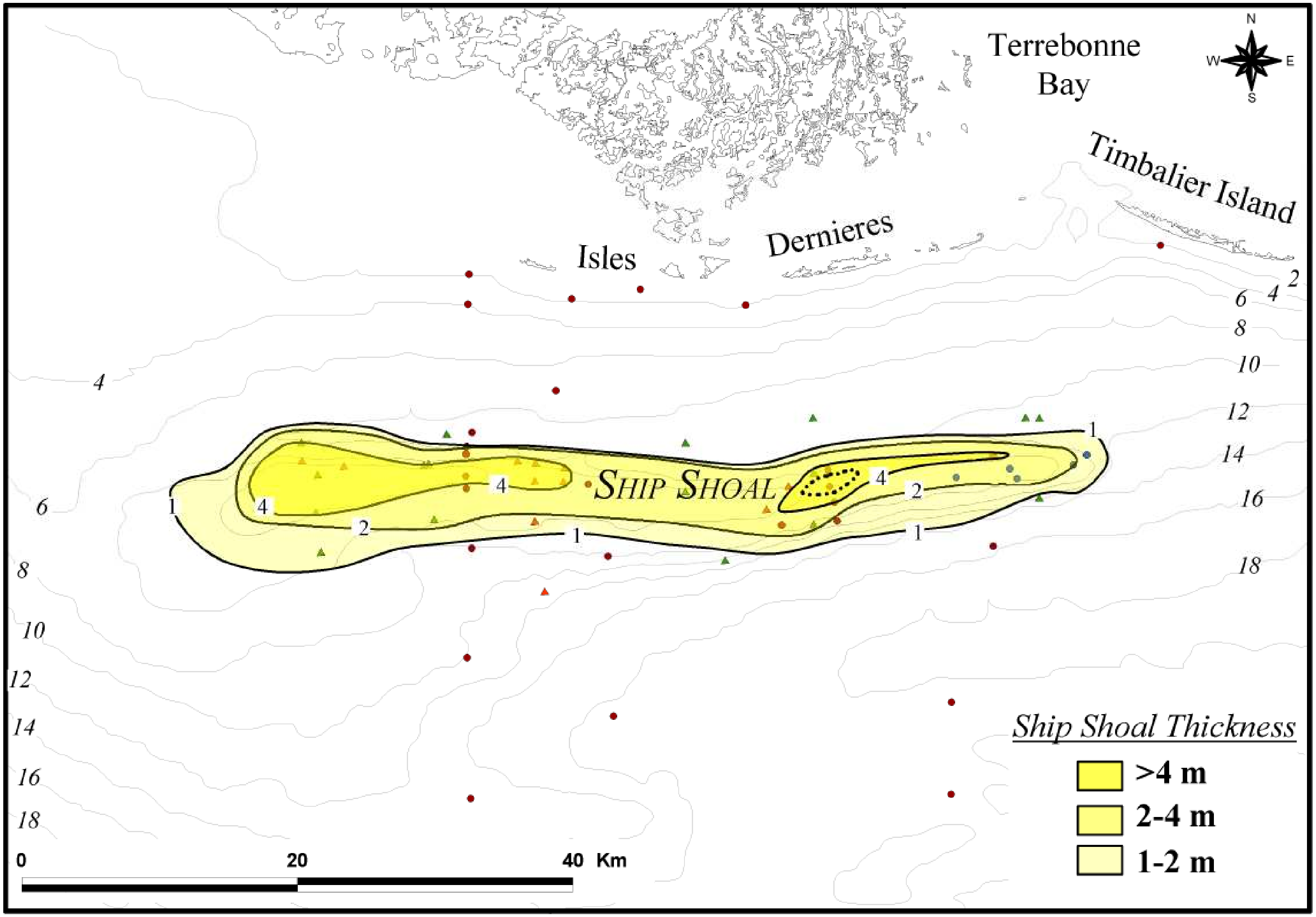


Figure 27. Isopach map of the Ship Shoal offshore sandy deposit with bathymetry (from Kulp et al., 2005).

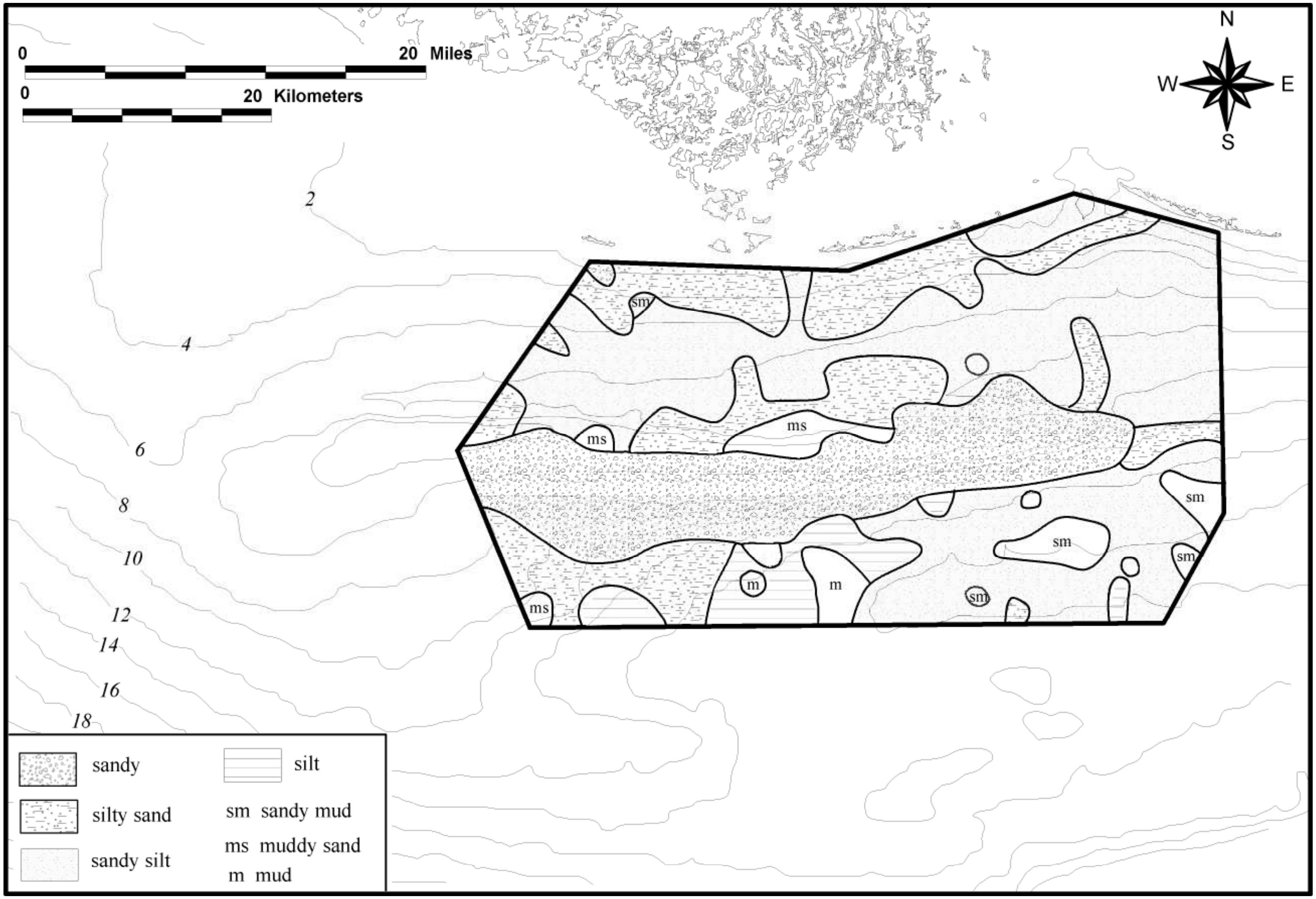


Figure 28. Lithofacies map of the Ship Shoal area showing the distribution of facies mapped by Williams et al. (1989).

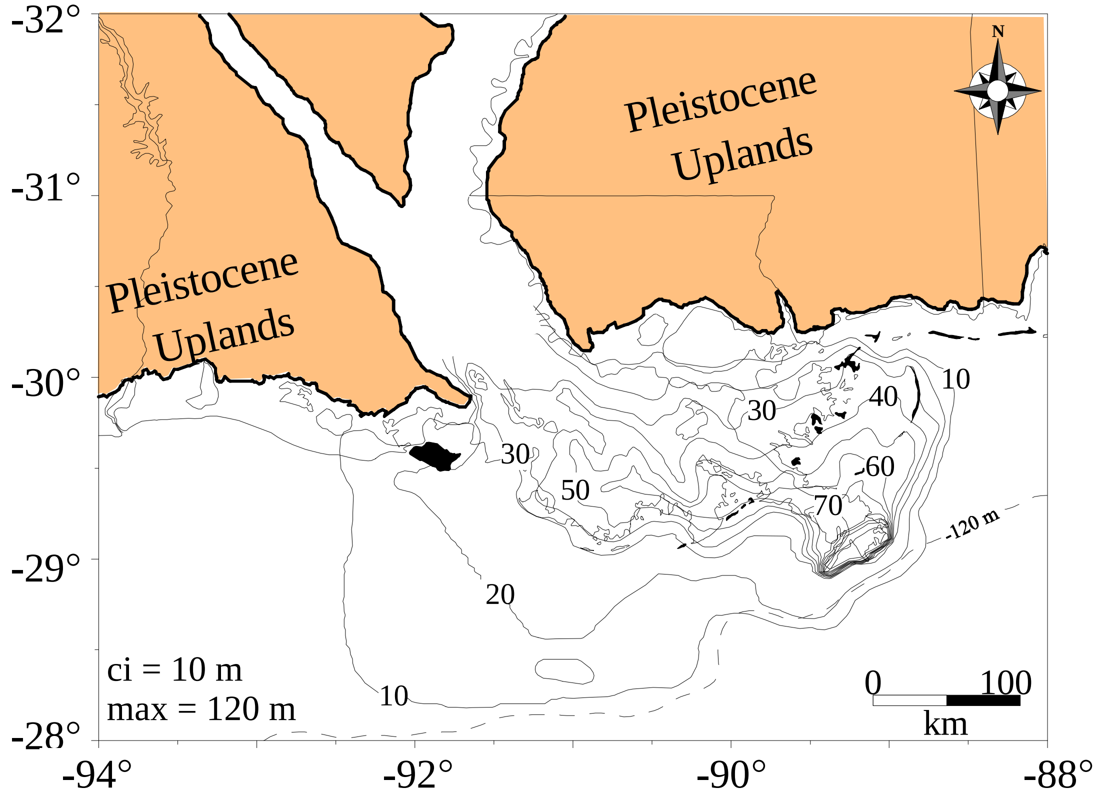


Figure 29. Isopach map of the Holocene deposits across southern Louisiana and the adjacent continental shelf, maximum thickness is approximately 120 m in the vicinity of the modern Plaquemine depocenter (from Kulp et al., 2002).

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APPENDIX B:
FIELD SURVEYS

APPENDIX B.1:
REPORT ON FIELD SURVEYS FROM ERIS (INCLUDING FIELDWORK PHOTOS)

Environmental Resource Information Services

Appendix

Environmental Resource Information Services
Environmental and GIS
Consultants

May 3, 2007

Baird & Associates
Dr. Rob Nairn, P.Eng., Principal
627 Lyons Lane, Suite 200
Oakville, Ontario, Canada L6J 5Z7

Final Report for Holly Beach Project 2006 and 2007

Rob
The following is the final report of the various operations we conducted June 8th to June 16th of 2006 and March 4th to 6th 2007 in the barrow pit 4.75 miles offshore from the shoreline near Holly Beach, Louisiana.

1) Diving operations June 9, 10 & 11th
Diving on sites 1 and 2, inside the barrow pit, we discovered that the pit had been filled approximately 20 ft.. with fill material estimated to come from Hurricane Rita. The material we discovered there was very fine with a thin crust on top that allowed the divers to rest on without falling through. Our core samples were dense enough that it allowed us to take our benthic samples. Visibility on the surface was two to three ft., visibility on the bottom at sample sites were zero to six inches. Once samples were obtained, we tried sticking our arms into the fill material and could not reach solid density. We did notice upon deploying our fifty. pound diving weight with the buoy that once we felt the weight reach the top layer, it sunk approximately ten to twelve ft. before stopping. Diving on site 4 was outside the pit. Bottom density was still soft. with zero to six inches of visibility, and material was very fine. Diving at sites 3, 5, and 6 we discovered that the bottom material was coarse with broken shell material and grainy sand, and we were barely able to take our core samples because of the density. Visibility on the bottom was one to two ft. and three ft. on the surface. Diving on site 7, visibility on the surface was three ft., visibility on the bottom was one foot with surface material being a fine, silty material with medium density. Diving on site 8, visibility on the surface was three ft., visibility on the bottom was one foot with a fine and slightly more dense material than that of site 7. Currents observed during

all diving operations were approximately one knots currents on the surface and approximately half not currents on the bottom.

2) ADCP Deployment June 12-14th
ADCO was deployed at site 7 on June 12th and remained there until the 14th. Currents were observed during the deployment of the bottom mount bracket to be approximately one knot on the surface and a half knot at the bottom. ADCP was recovered on June 14th and we will be post processing data for publication as soon as possible.

3) Water Quality Monitoring June 13th
The water quality monitoring was performed with an YSI Model No. 6920 over a twelve hour period starting at approximately 8:30 a.m. and run every hour at site 2 and site 7 at surface, .2H, .4H, .6H, .8H, and bottom. Weather conditions during monitoring were good with southeast winds at five mph and zero to one foot seas. Attached you will find an Excel spreadsheet with the results of this monitoring. Parameters that were observed were depth, temperature, Ph, conductivity, turbidity, and dissolved oxygen's.

4) Bathometric Survey June 14th and 15th
Bathometric survey on June 14th was conducted at various transect lines designated by Baird and Associates for comparison with last years data. Sea conditions were one to two foot seas with southeast winds five to ten mph. Bathometric survey on June 15th was conducted on a 100 ft. by 100 ft. grid that was provided to us by Baird and Associates. All lines were run and our sea conditions were two to three foot seas. June 16th we were unable to return to the site as weather deteriorated with thunderstorms and four to five foot seas. Long range weather revealed no break in weather for four to five days. ERIS consulted with Rob Nairin of Baird and Associates and the decision was made to pull off the site, evaluate what data we have collected, and make the decision to return or not to collect more data. We have delivered the critical transect data to Baird and Associates for their analysis. The rest of the data will be post processed and delivered as soon as possible. General depth conditions that we observed were from 27 ft.. to 30 ft.. outside the pit and from 38 ft.. to 41 ft.. inside the pit. Keeping in mind that last years survey revealed an average depth outside the pit of 30 ft.. and 57 to 58 ft.. Inside the pit.

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Email: philh@eris3.com

March 4, 5 & 6 2007 Survey

1) Diving Operations March 4
Water was colder this time of year at 16°c as compared to June 06 at 22.5°c and there was a strong current running along shore. Visibility was down from last June with 1 foot range on the surface and zero visibility on the bottom with almost no light and a strong current. Site 9 over the old spoil mound was a course material and very hard as we had to work to get our sample tubes down far enough for a sample core. Site 10 was inside the pit and had a very loose fine material and no crust on the top layer. We had a hard time not sinking down into the muck. Site 11 and 12 were just east of the pit and both sites were still zero visibility with a strong current along the bottom. We collected data from the ADCP during our diving ops and this data has been submitted to you for your analysis and review.

2) ADCP Data collection March 5 & 6
ADCP was a RDI 1200 Navigator mounted on the aft platform of a 41 foot research boat and was run in the bottom tracking mode during the diving operations on the 4th and on the 5th & 6th along preset transect lines (a north-south line, an east-west line and a diagonal line) provided by Baird as well as during bathometric data collection along the extended survey lines. This data collection was monitored and collected in a live time mode onboard and started on the morning of March 5th and was run 4 times along the transect lines until 0300 on the 6th of March. During this time we ran our extended bathometric survey lines that we were unable to collect last year and collected data from the ADCP to add to the data collected along the transect lines. We have provided a copy of the raw files along with a excel spread sheet that will help sort out what raw file goes with the corresponding lines.

3) Bathometric Survey March 5 & 6
Bathometric survey was conducted on March 5 & 6 along the extended survey lines provided by Baird in May of 2006. We were not able to run at that time due to bad weather. We also ran a north-south line from last year's survey to compare it with the same line ran in June of 2006. Survey started in the morning of March 5th and continued until 0300 March 6th and ran with the ACDP. The equipment used for bathy data collection was an Odem Hydrotrac with a 3 degree beam transducer; the ADCP was a RDI 1200 Navigator. Both these units were mounted on the stern platform of a 41 foot offshore

research boat and were placed so as to insure they were clear of any bubble trails.

We had 2-3 foot seas with a light north wind and a strong along shore current running east to west. Data was collected, post processed and delivered to Baird. The datum used for this project on the horizontal control was Louisiana State Plane South coordinates and the vertical control was MLLW obtained from the Calcasieu Pass tide gauge.

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Figure B.1.1 ADCP & Bathy Setup 2007-1

Figure B.1.2 ADCP & Bathy Setup 2007-2

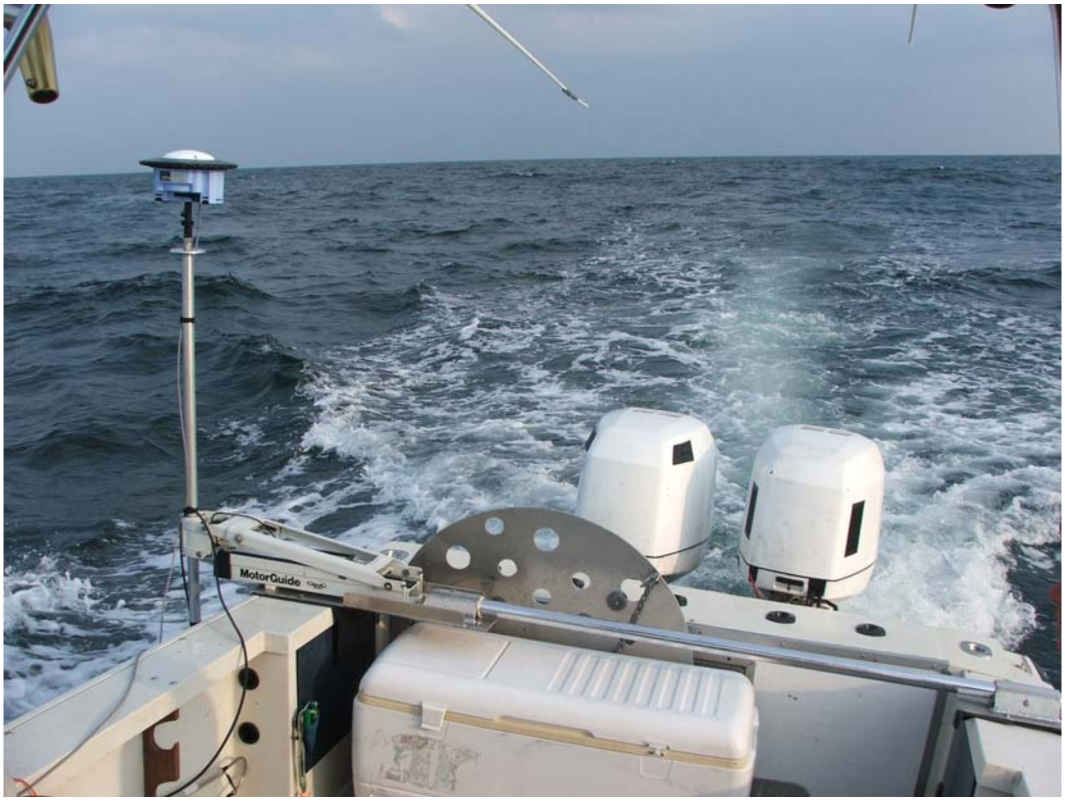

Figure B.1.3 Bathy Survey 2006-1

Figure B.1.4 Bathy Survey 2006-2

Figure B.1.5 Bathy Survey 2006-3

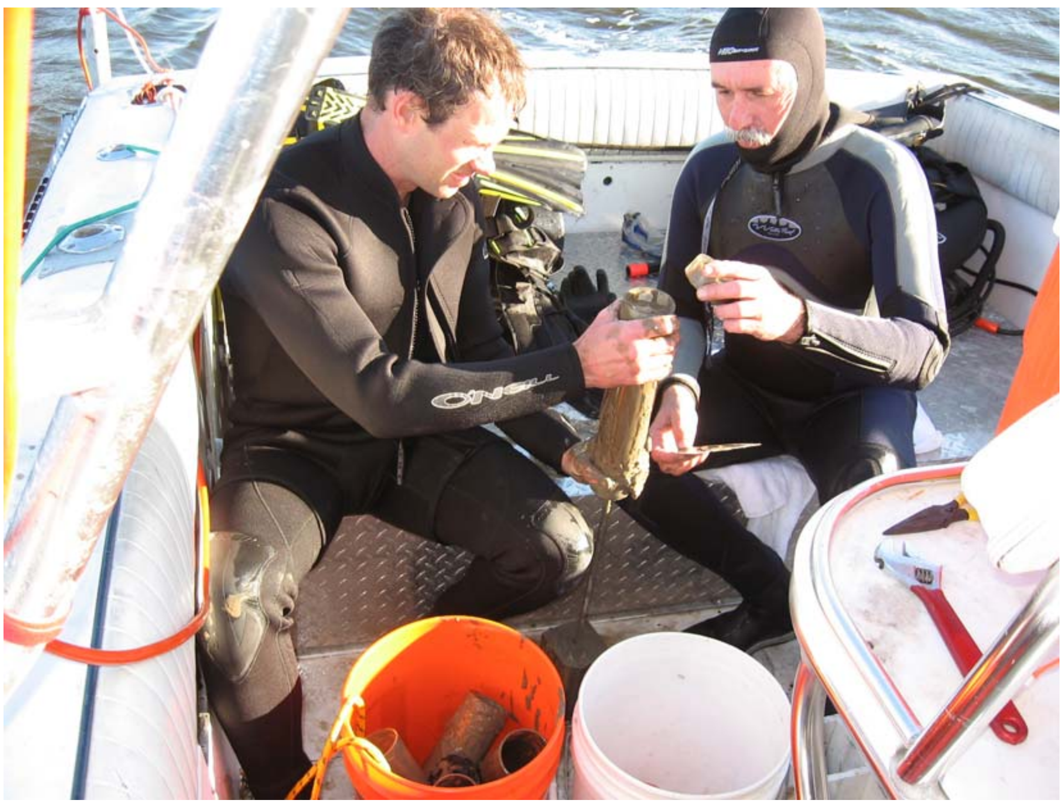

Figure B.1.6 Benthic Sampling 2007-1

Figure B.1.7 Benthic Sampling 2007-2

Figure B.1.8 Benthic Sampling 2007-3

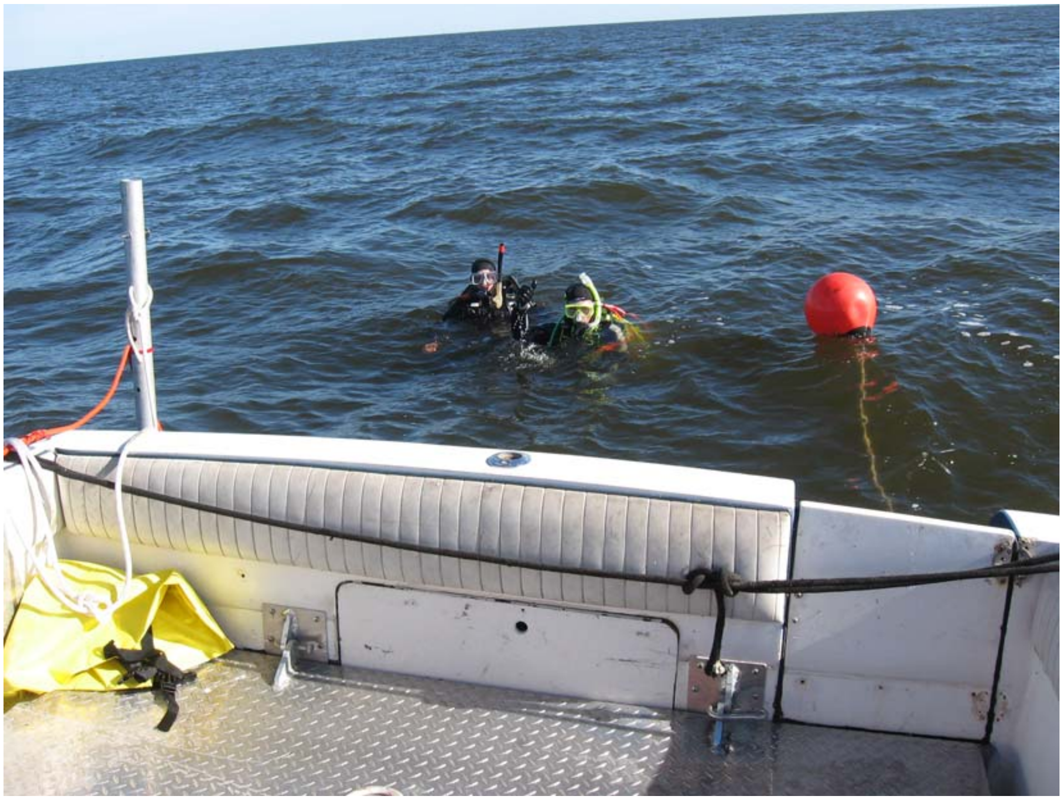

Figure B.1.9 Dive OPS 2007-1

Figure B.1.10 Dive OPS 2007-2

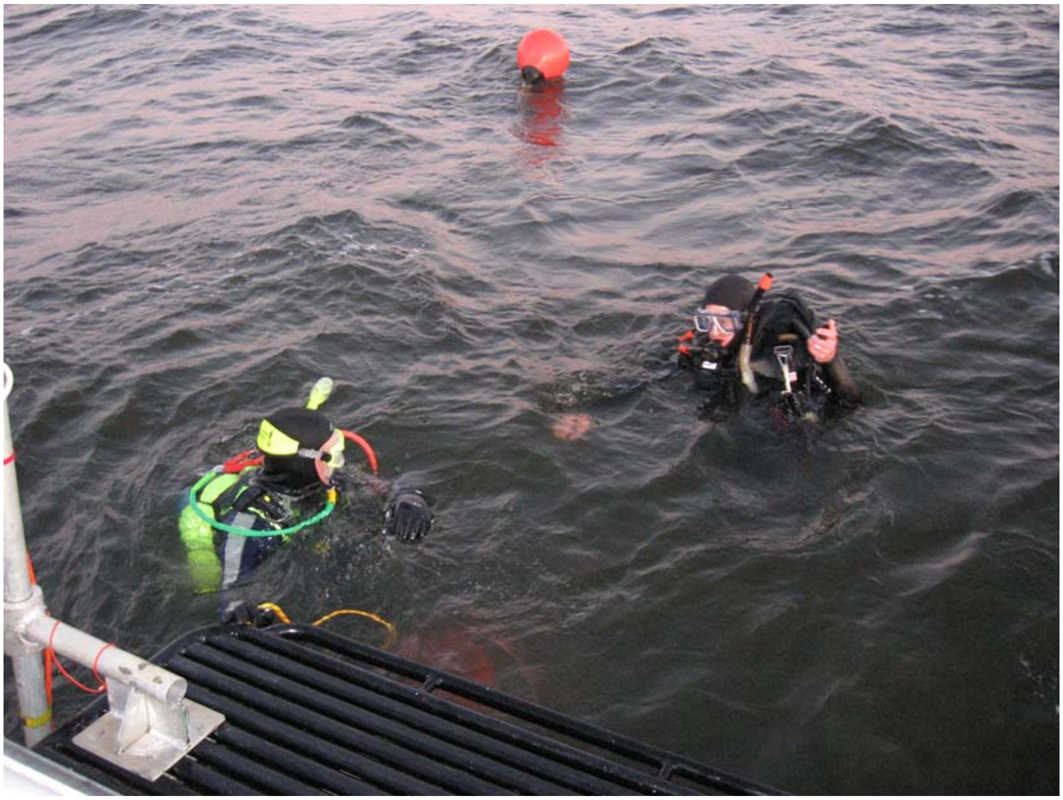

Figure B.1.11 Dive OPS 2007-3

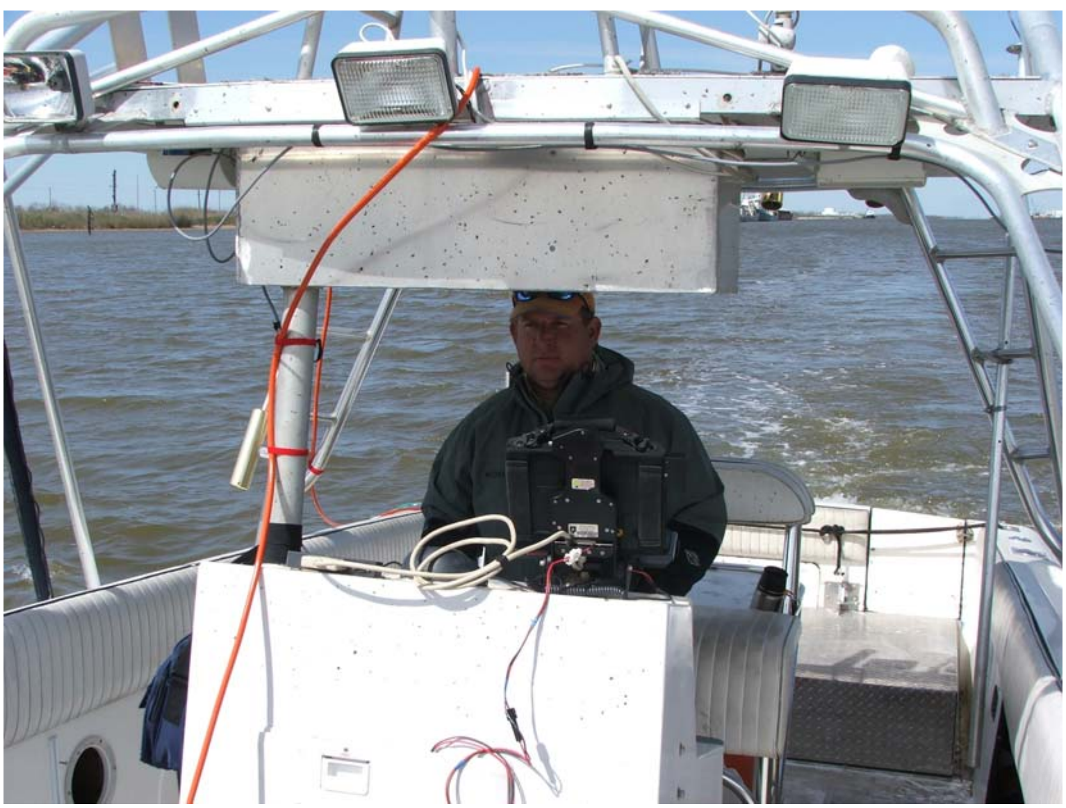

Figure B.1.12 Running ADCP & Bathy 1

Figure B.1.13 Running ADCP & Bathy 2

Figure B.1.14 Running ADCP & Bathy 3

Figure B.1.15 Sunset After a Long Day on the Pond

Figure B.1.16 Water Quality Sampling 1

Figure B.1.17 Water Quality Sampling 2

Figure B.1.18 Water Quality Sampling 3

Figure B.1.19 Water Quality Sampling 4

Figure B.1.20 Water Quality Sampling 5

Figure B.1.21 Water Quality Sampling 6

Appendix

APPENDIX B.2:
RESULTS OF BAIRD ANALYSIS OF ADCP DATA COLLECTED BY ERIS

W.F. Baird & Associates Coastal Engineers Ltd.

Table B.1 Summary Table of Reverse Flow Directions for all Transect Line Cross-Sections

Transect Line	File No.	Initial Direction	Reverse Flow Start Direction	Reverse Flow End Direction
North-South	143243	68	158	338
	183610	71	161	341
	162819	60	150	330
	10401	95	185	-5
East-West	141039	59	149	329
	165500	75	165	345
	190058	93	183	-3
	3629	96	186	-6
Diagonal	142104	66	156	336
	164148	67	157	337
	184830	82	172	352
	233424	86	176	356

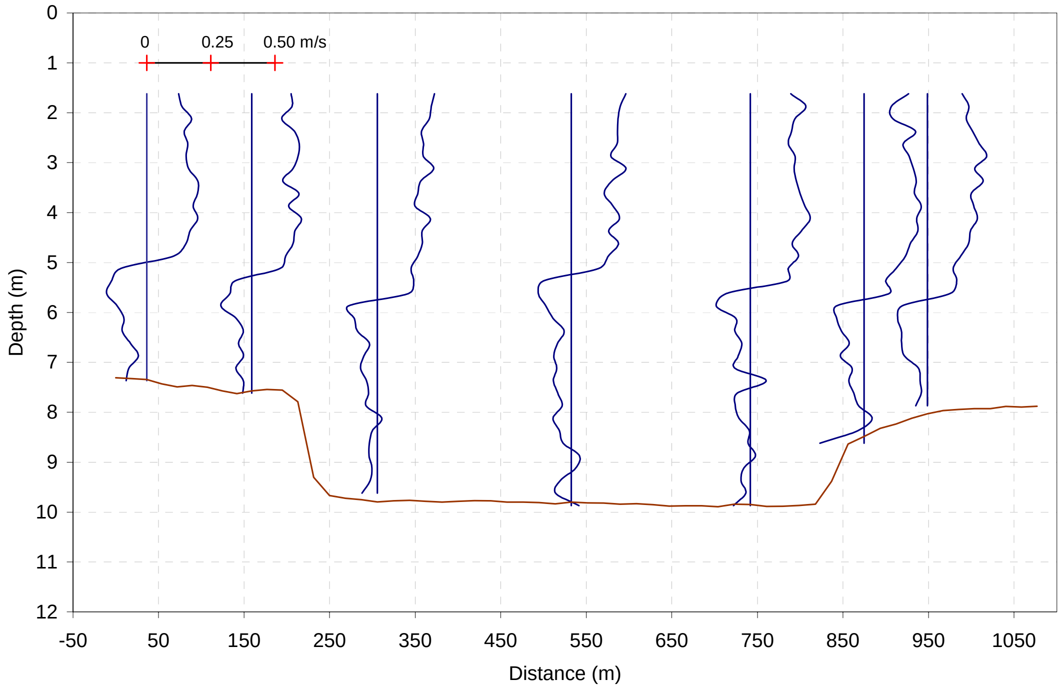

Figure B.2.1 Velocity Profiles for North-South Transect Line (File no. 143243)

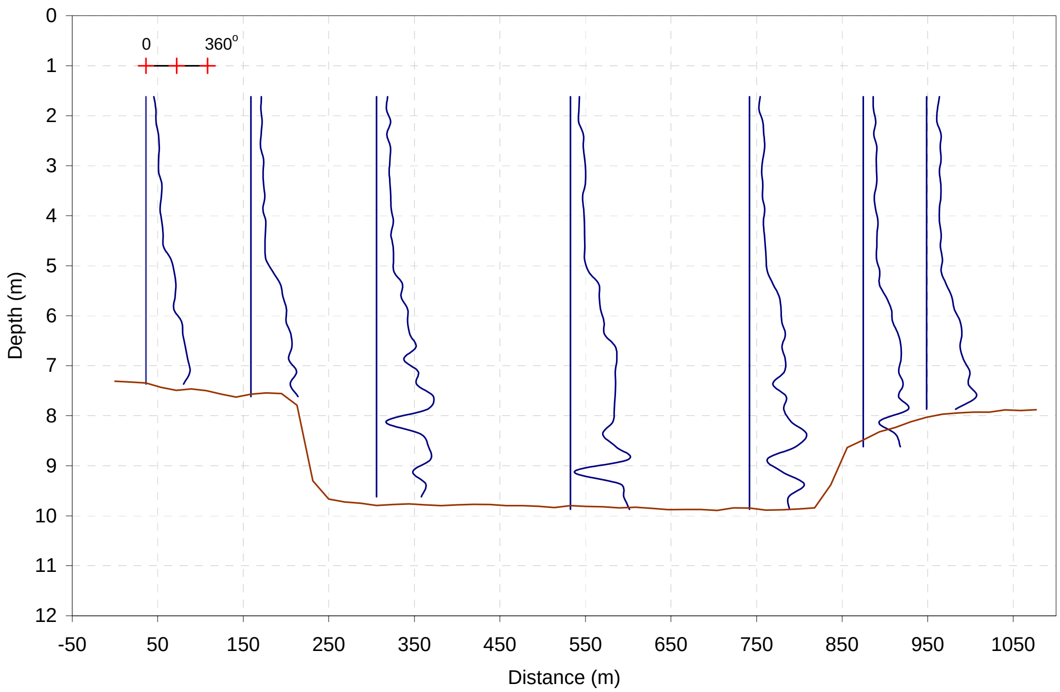

Figure B.2.2 Direction Profiles for North-South Transect Line (File no. 143243)

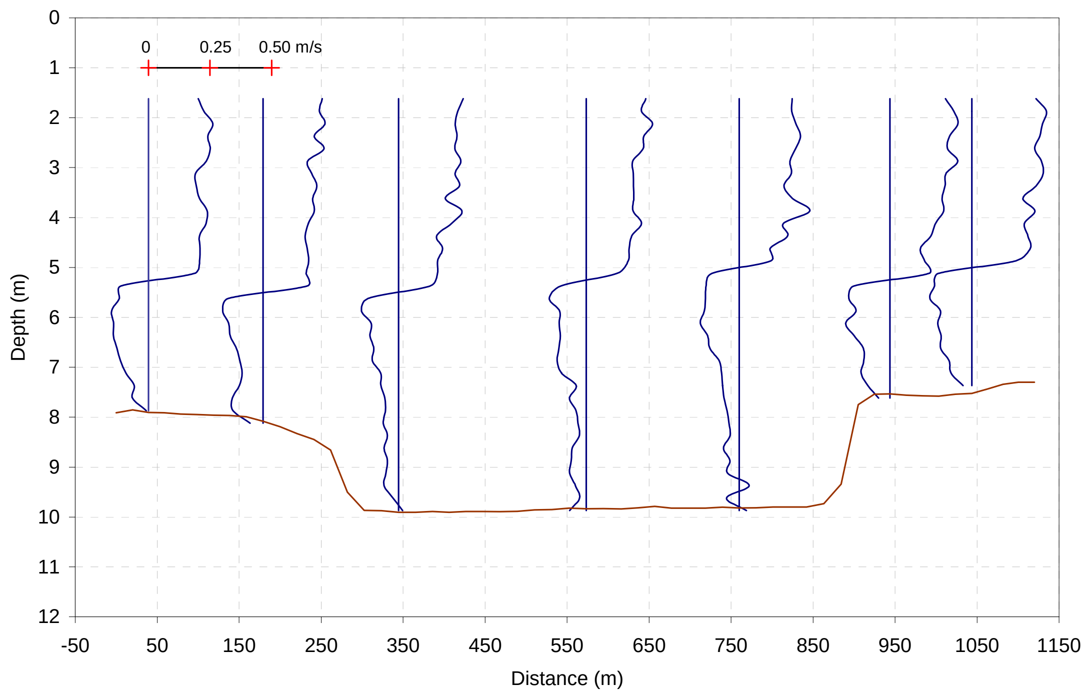

Figure B.2.3 Velocity Profiles for North-South Transect Line (File no. 162819)

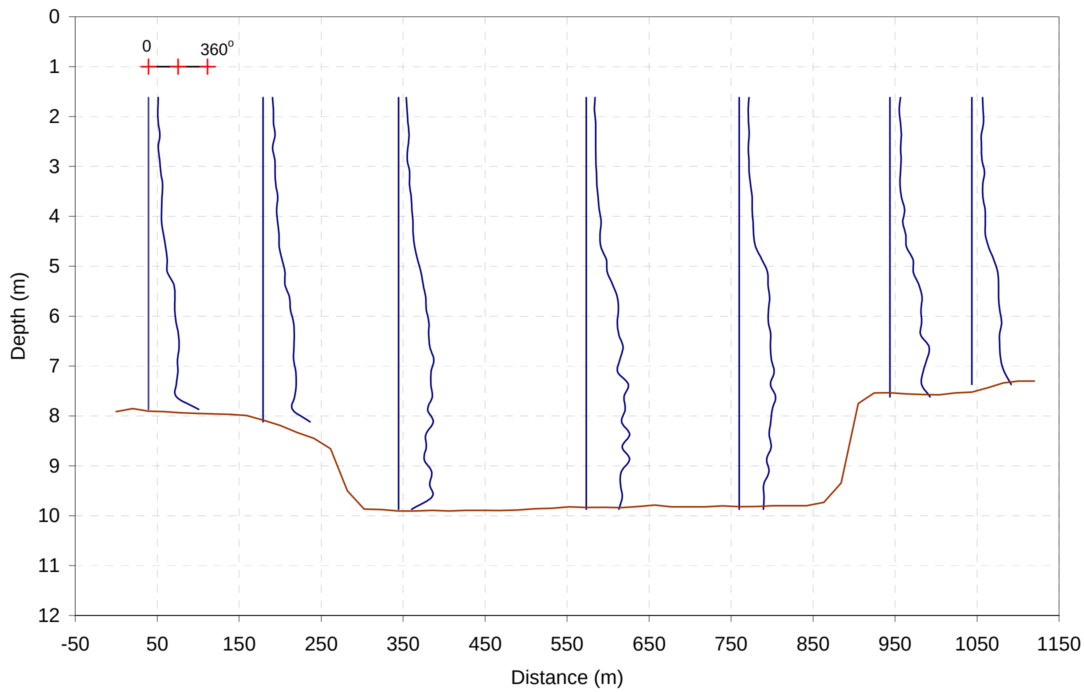

Figure B.2.4 Direction Profiles for North-South Transect Line (File no. 162819)

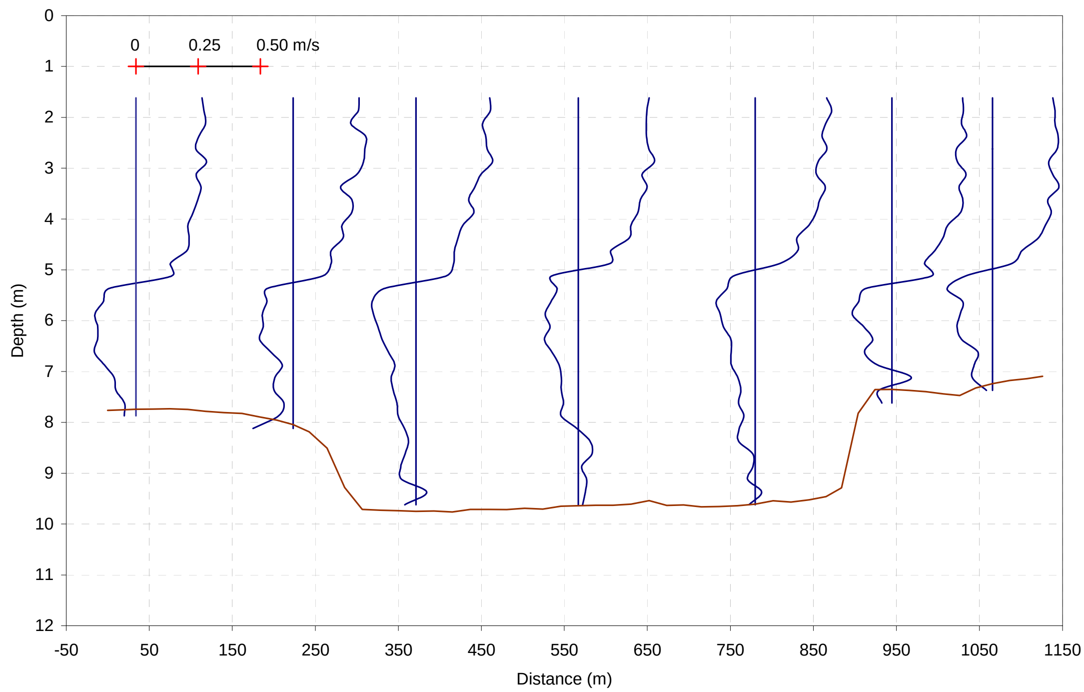

Figure B.2.5 Velocity Profiles for North-South Transect Line (File no. 183610)

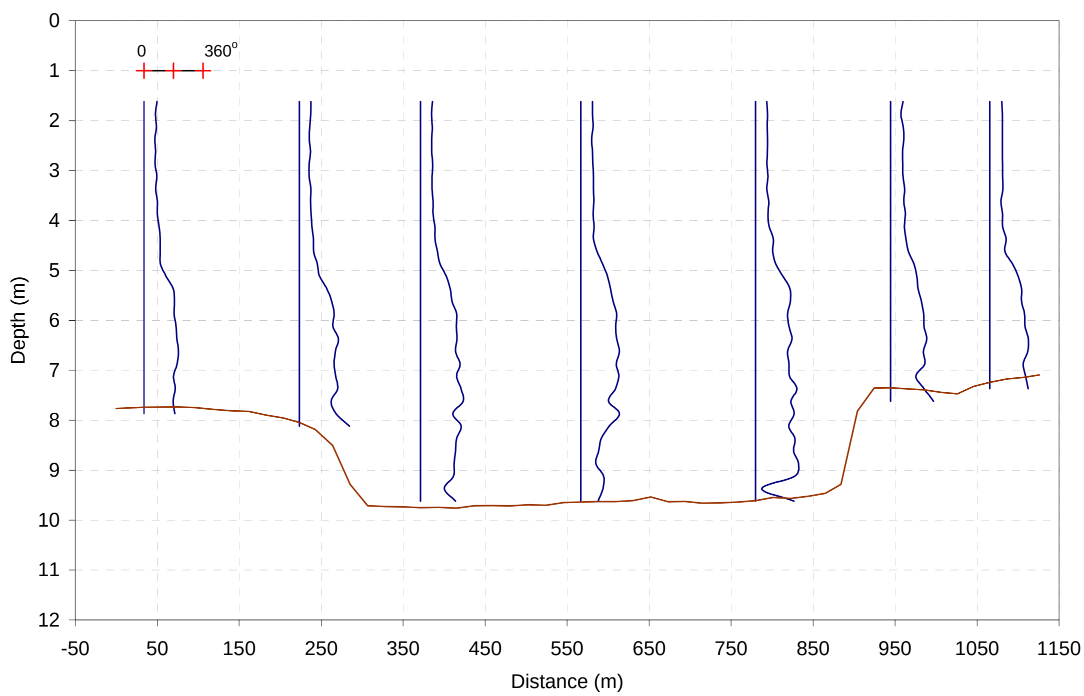

Figure B.2.6 Direction Profiles for North-South Transect Line (File no. 183610)

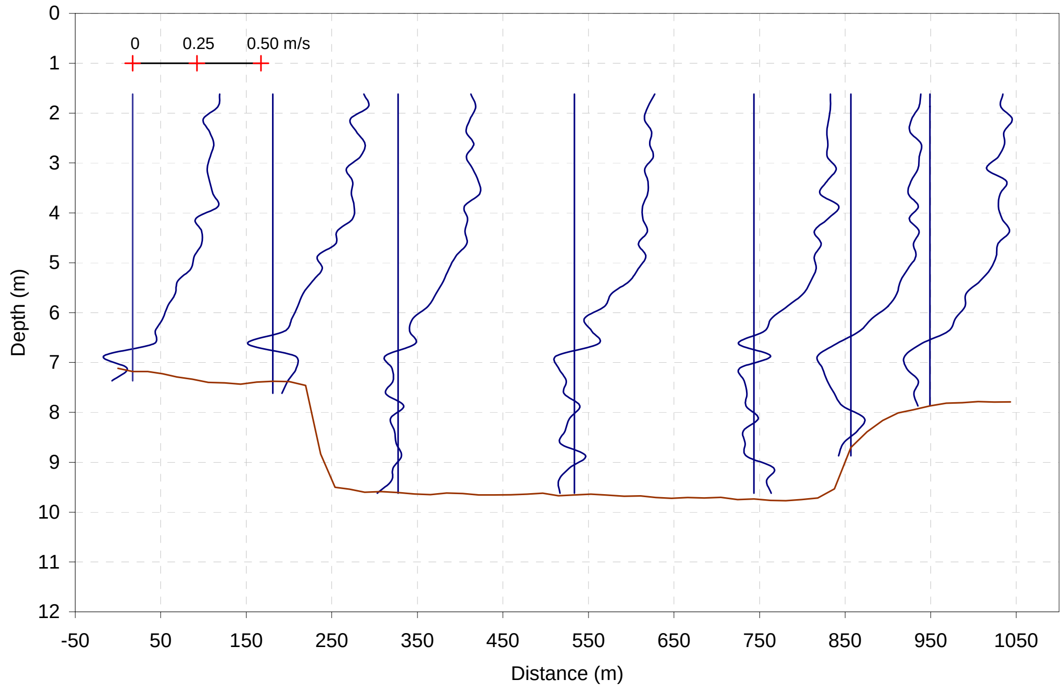

Figure B.2.7 Velocity Profiles for North-South Transect Line (File no. 10401)

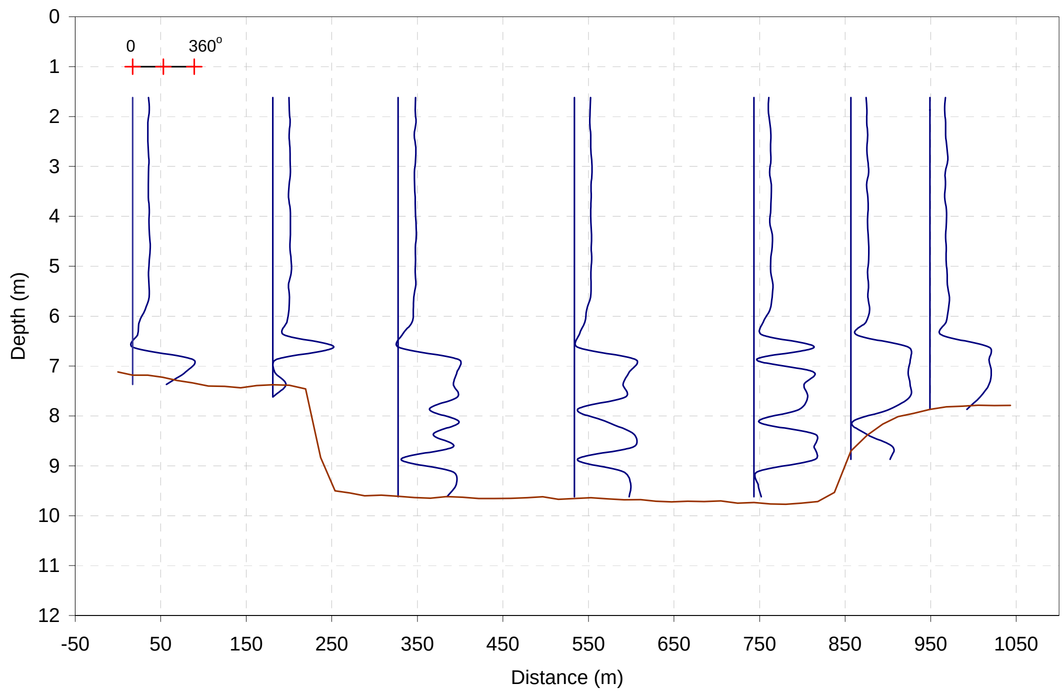

Figure B.2.8 Direction Profiles for North-South Transect Line (File no. 10401)

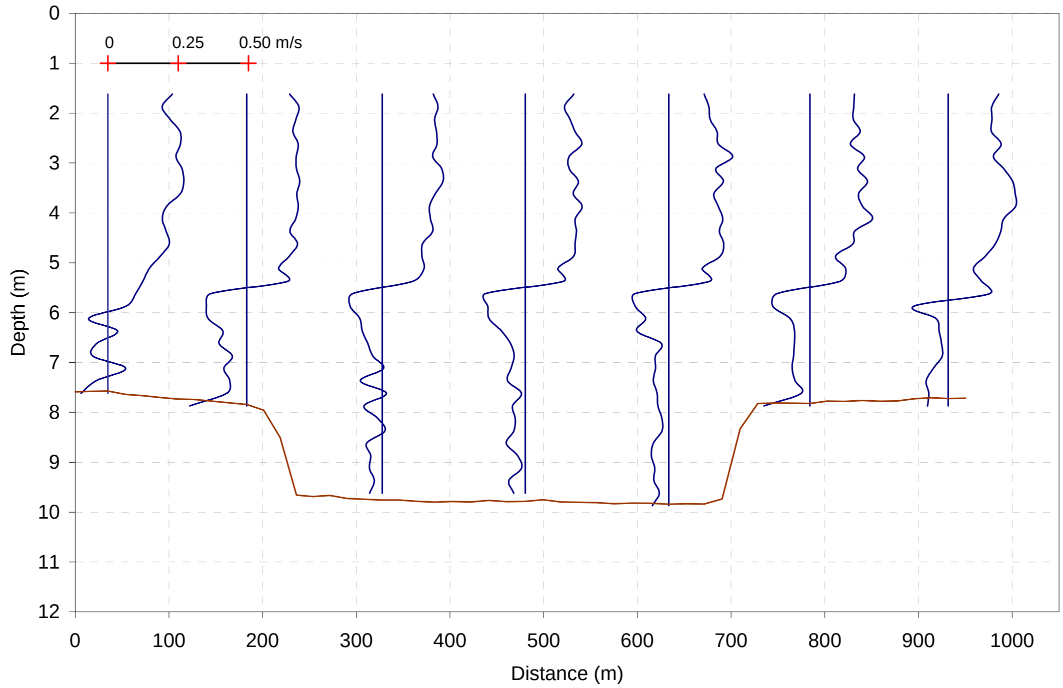

Figure B.2.9 Velocity Profiles for East-West Transect Line (File no. 141039)

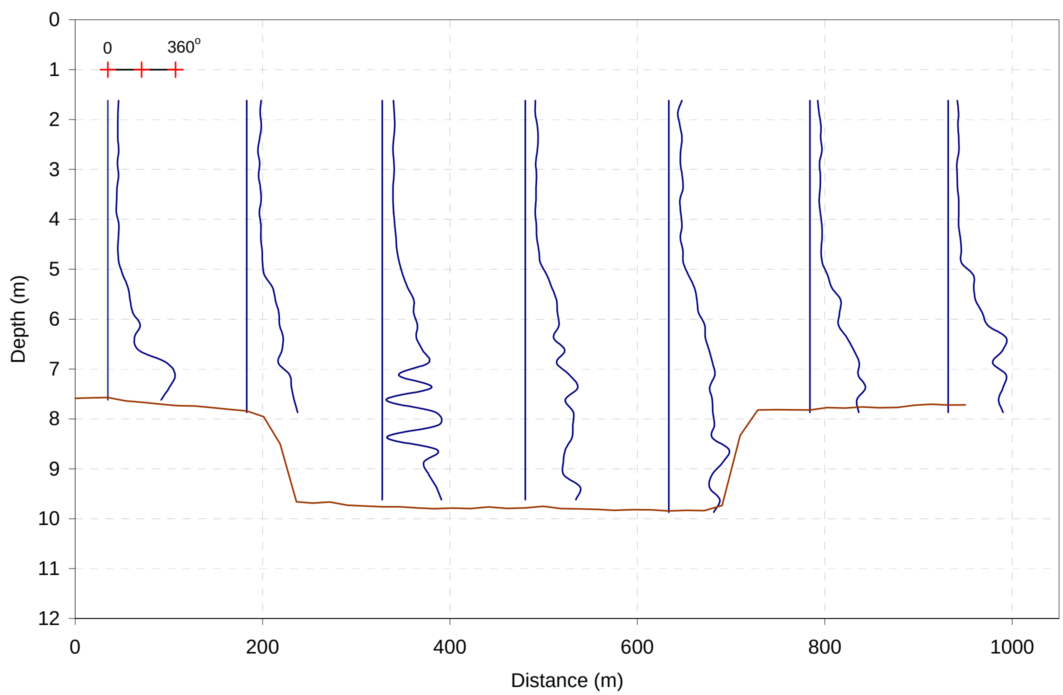

Figure B.2.10 Direction Profiles for East-West Transect Line (File no. 141039)

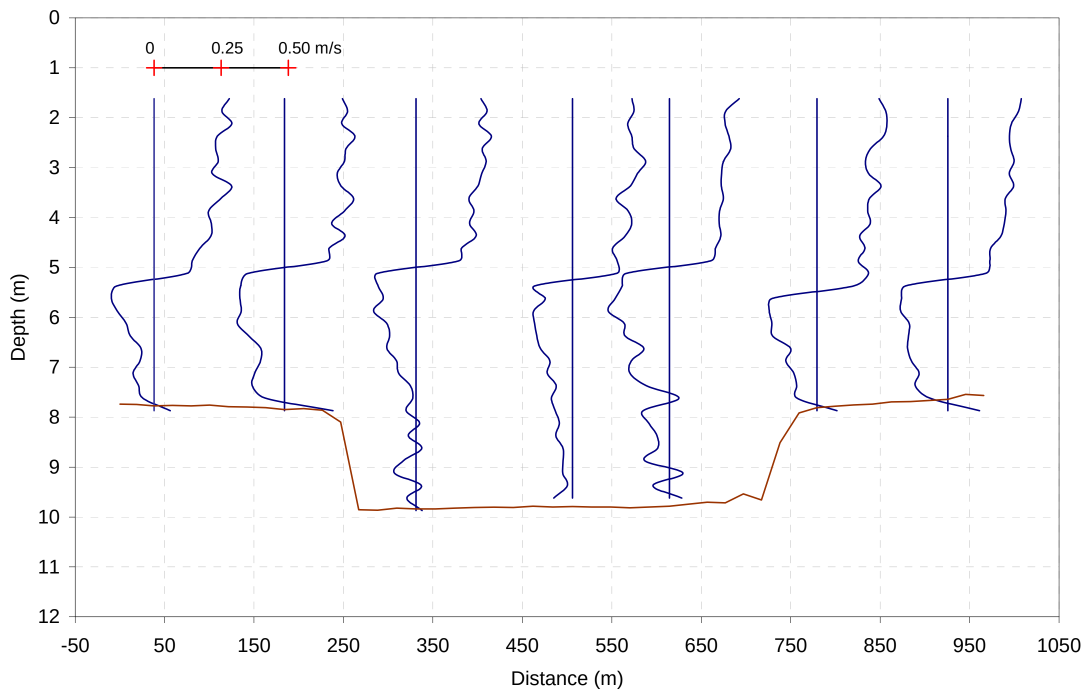

Figure B.2.11 Velocity Profiles for East-West Transect Line (File no. 165500)

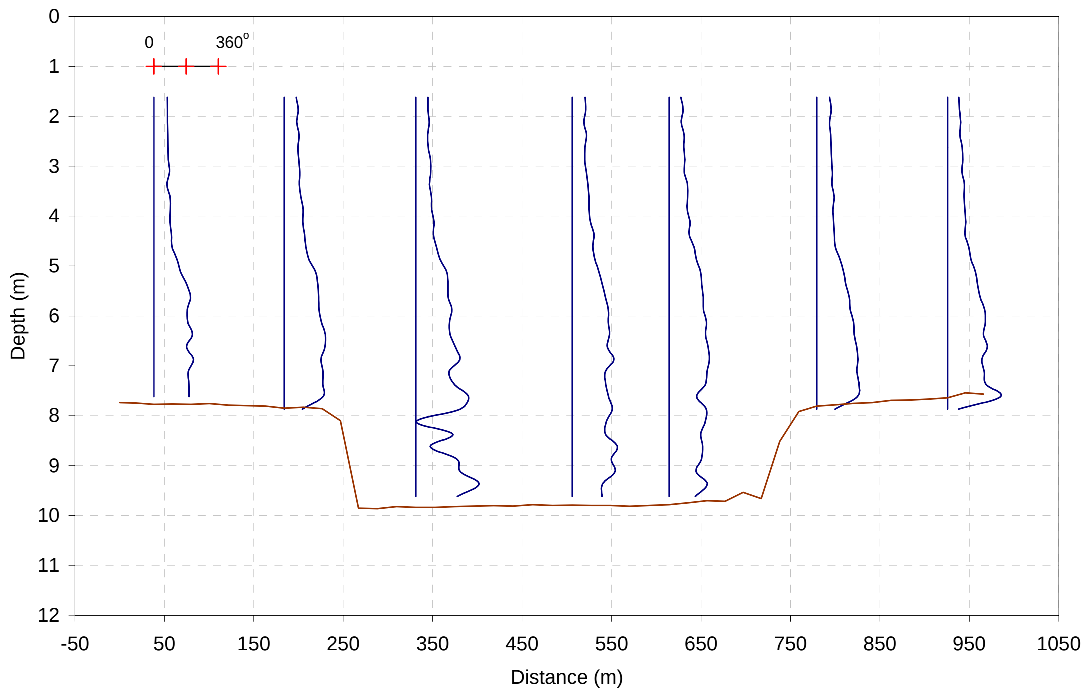

Figure B.2.12 Direction Profiles for East-West Transect Line (File no. 165500)

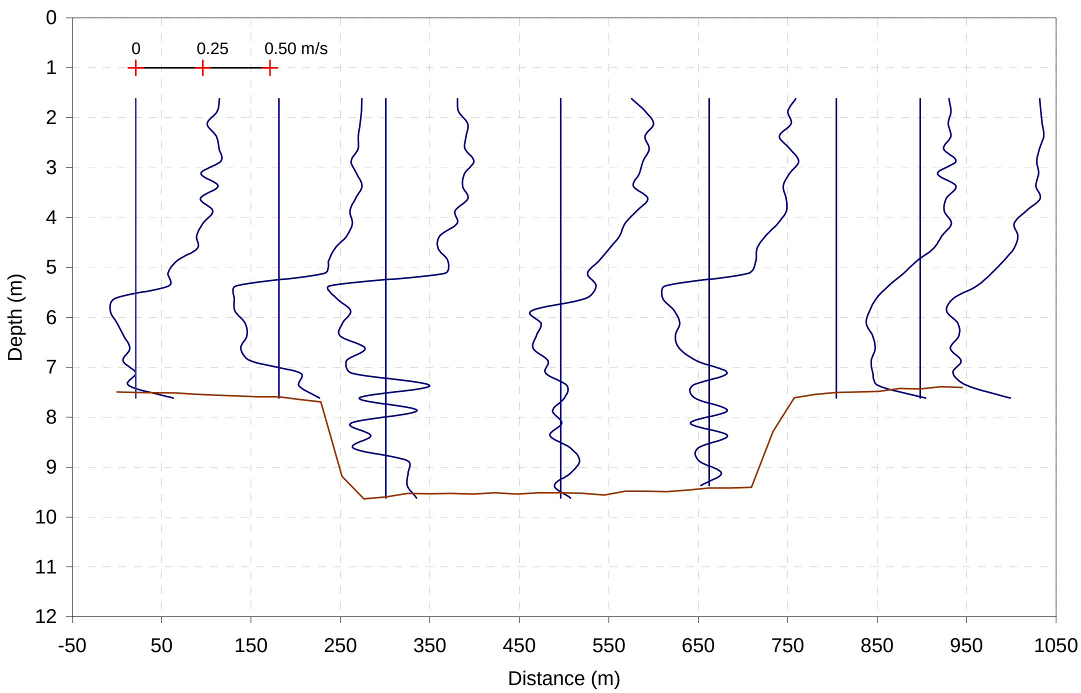

Figure B.2.13 Velocity Profiles for East-West Transect Line (File no. 190058)

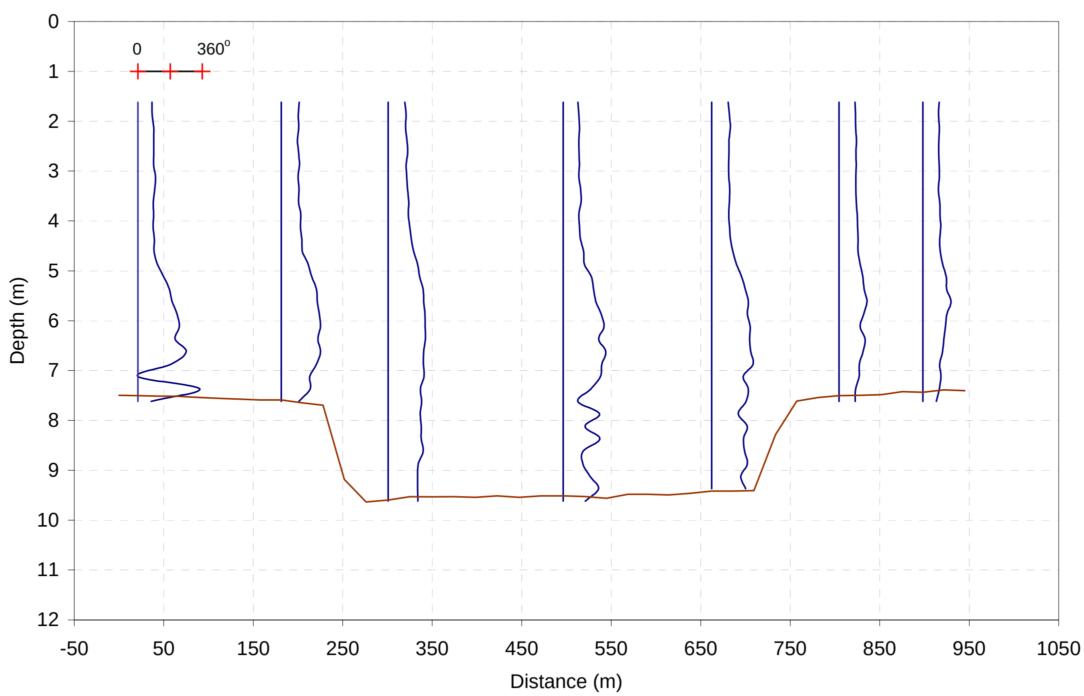

Figure B.2.14 Direction Profiles for East-West Transect Line (File no. 190058)

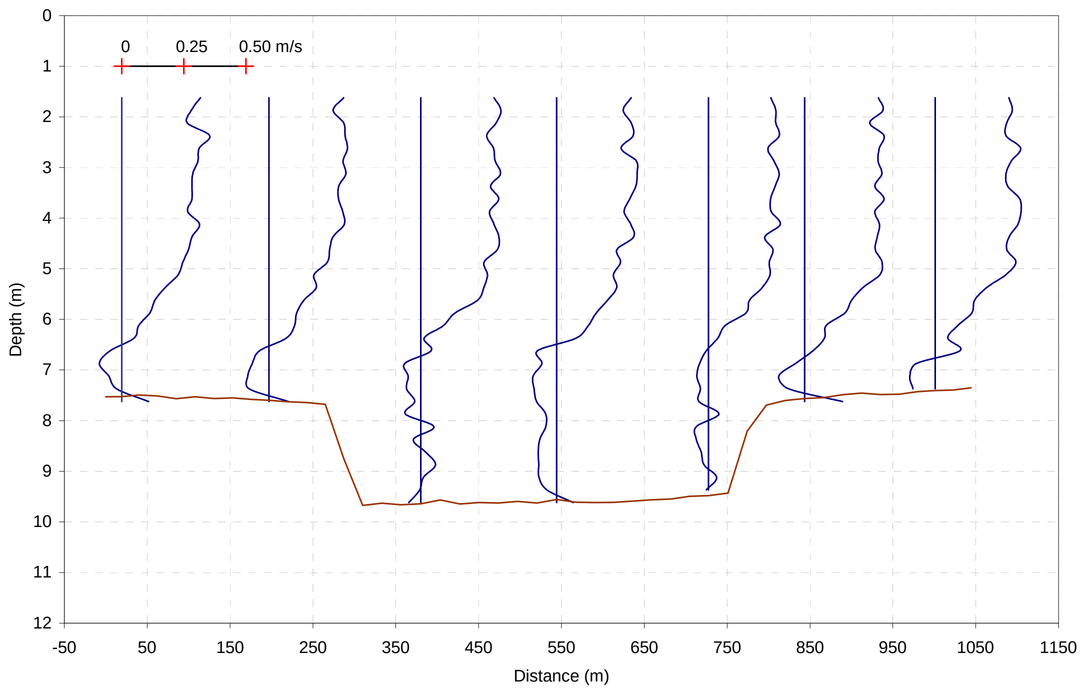

Figure B.2.15 Velocity Profiles for East-West Transect Line (File no. 3629)

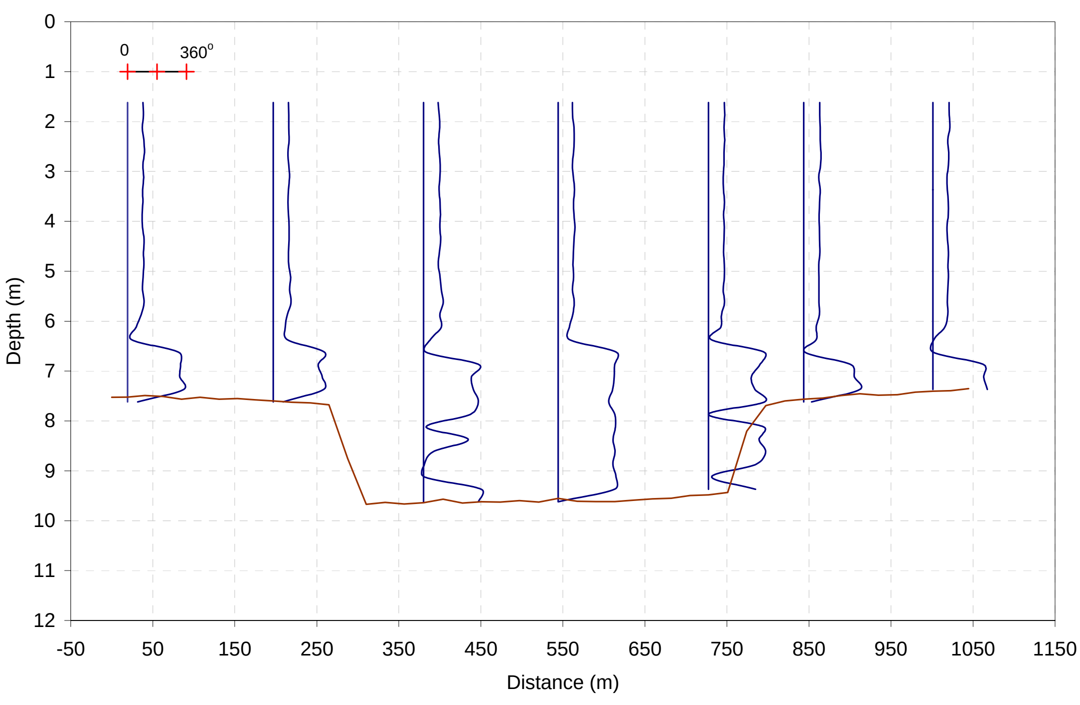

Figure B.2.16 Direction Profiles for East-West Transect Line (File no. 3629)

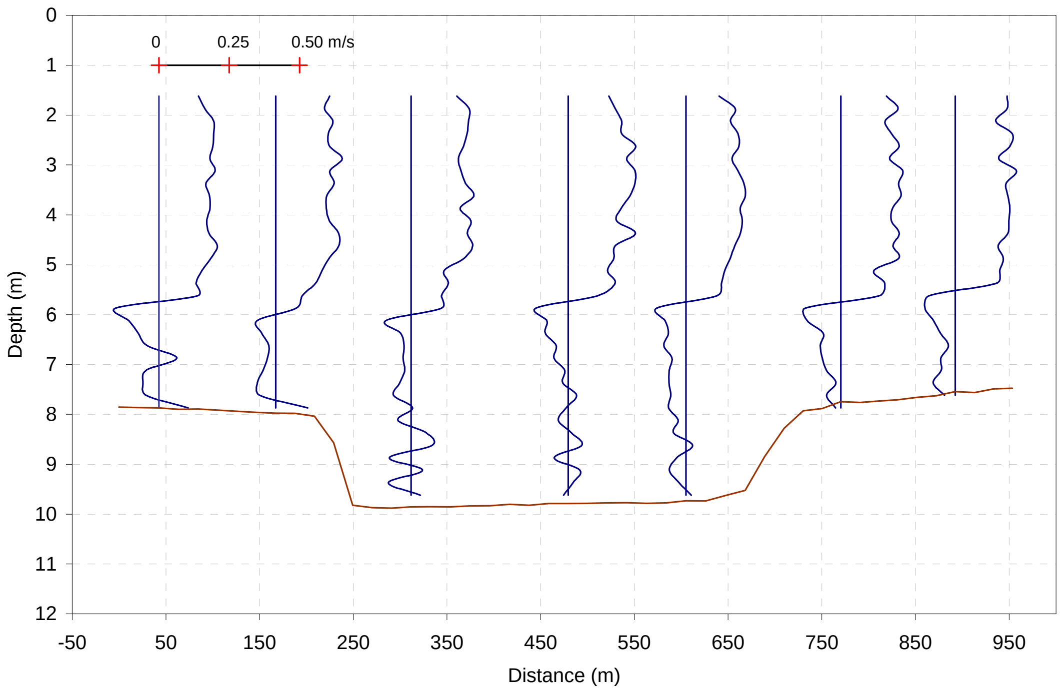

Figure B.2.17 Velocity Profiles for Diagonal Transect Line (File no. 142104)

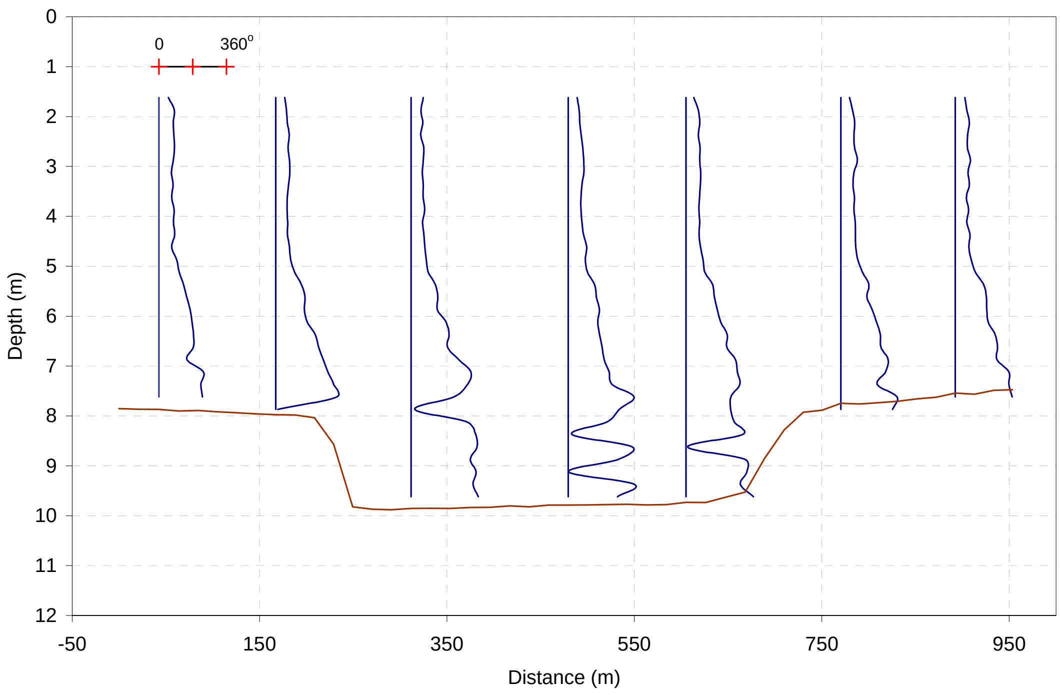

Figure B.2.18 Direction Profiles for Diagonal Transect Line (File no. 142104)

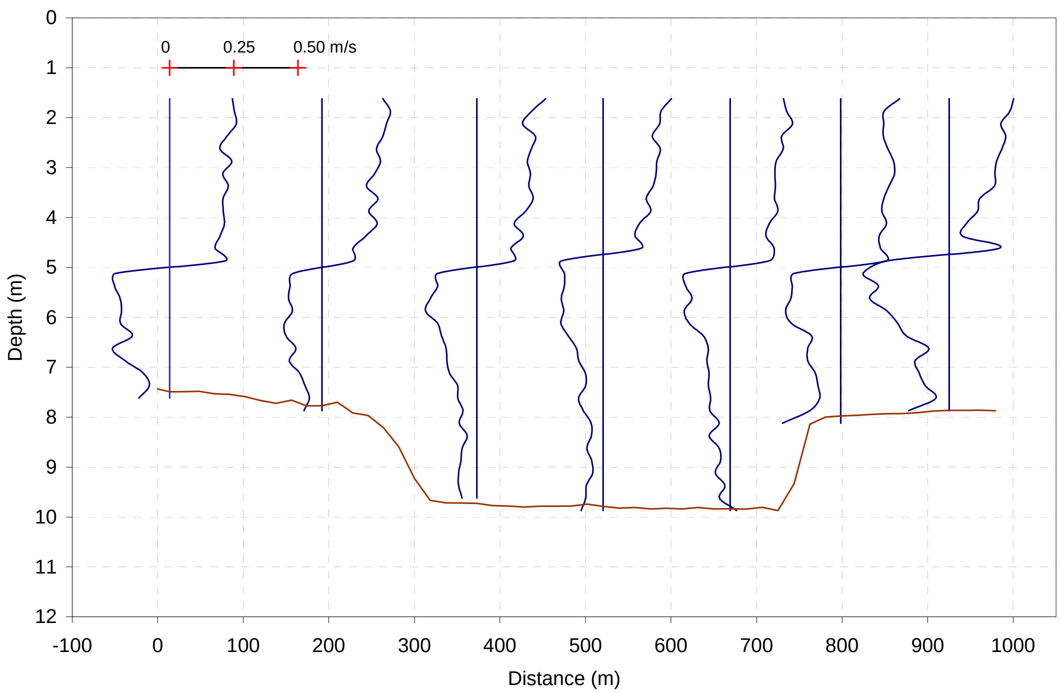

Figure B.2.19 Velocity Profiles for Diagonal Transect Line (File no. 164148)

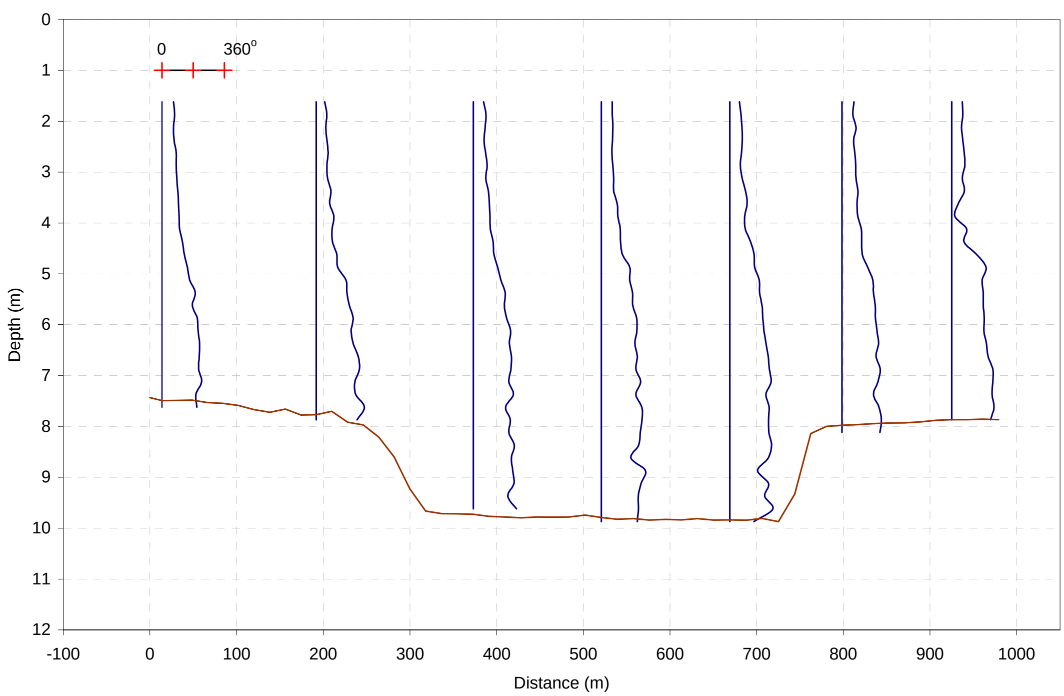

Figure B.2.20 Direction Profiles for Diagonal Transect Line (File no. 164148)

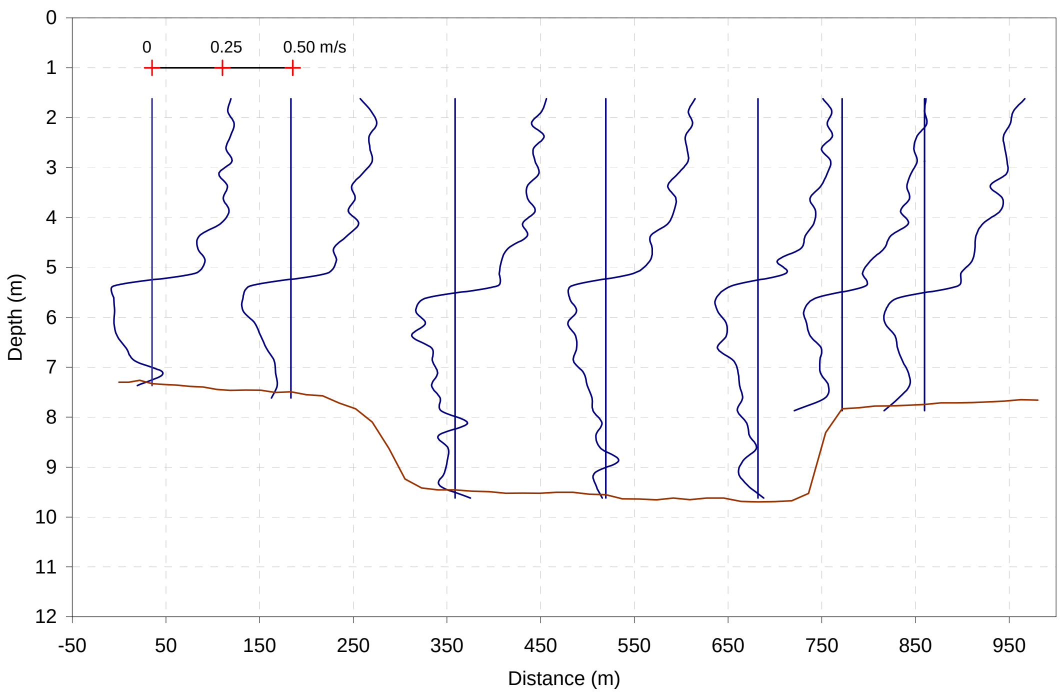

Figure B.2.21 Velocity Profiles for Diagonal Transect Line (File no. 184830)

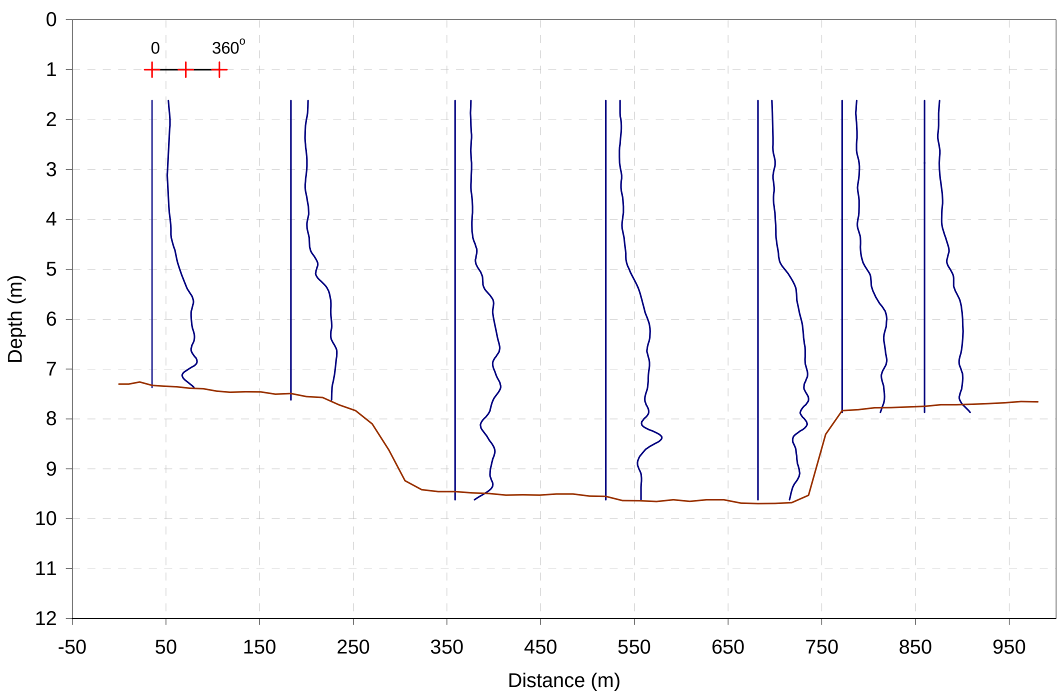

Figure B.2.22 Direction Profiles for Diagonal Transect Line (File no. 184830)

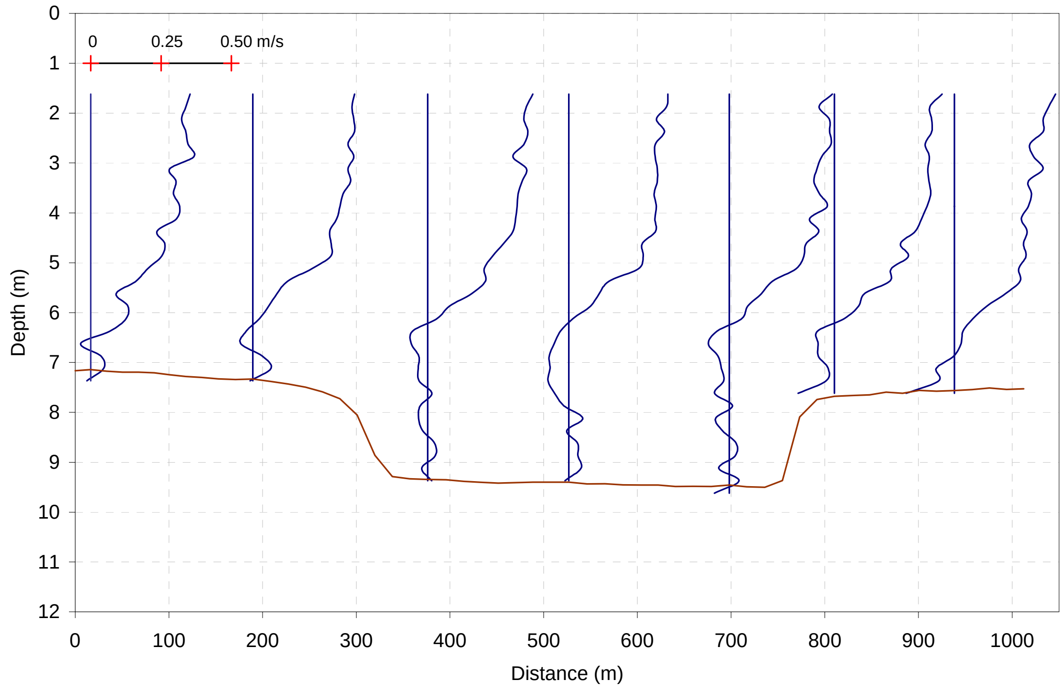

Figure B.2.23 Velocity Profiles for Diagonal Transect Line (File no. 233424)

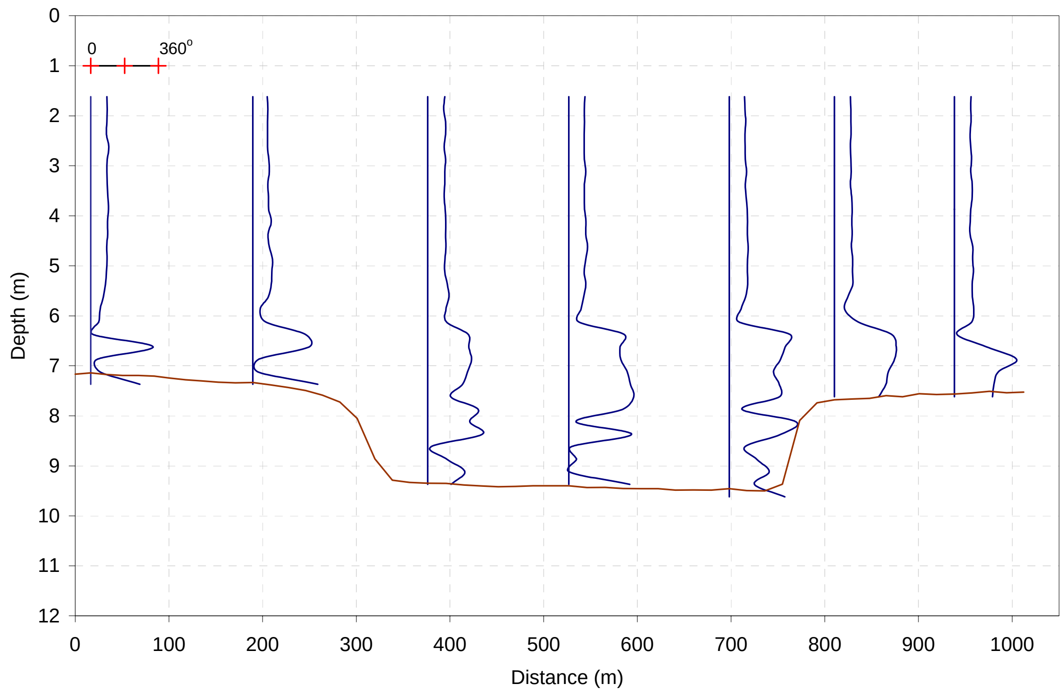

Figure B.2.24 Direction Profiles for Diagonal Transect Line (File no. 233424)

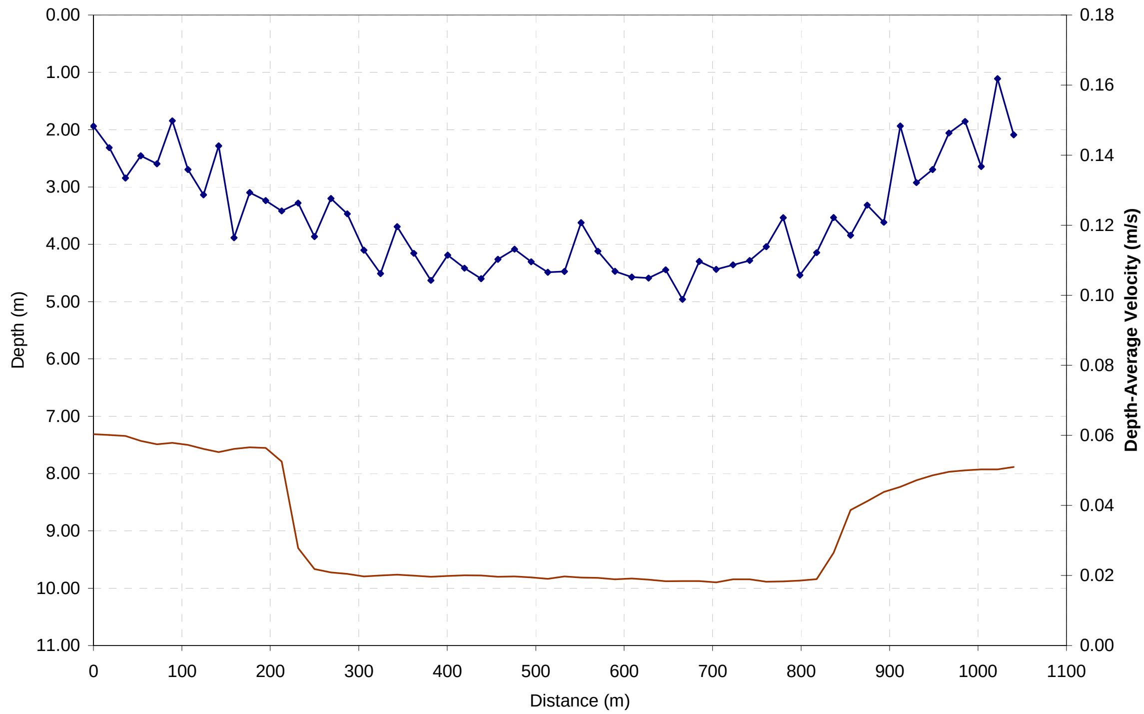

Figure B.2.25 Depth-Average Flow Velocity Change Across North-South Cross-Section (File no. 143243)

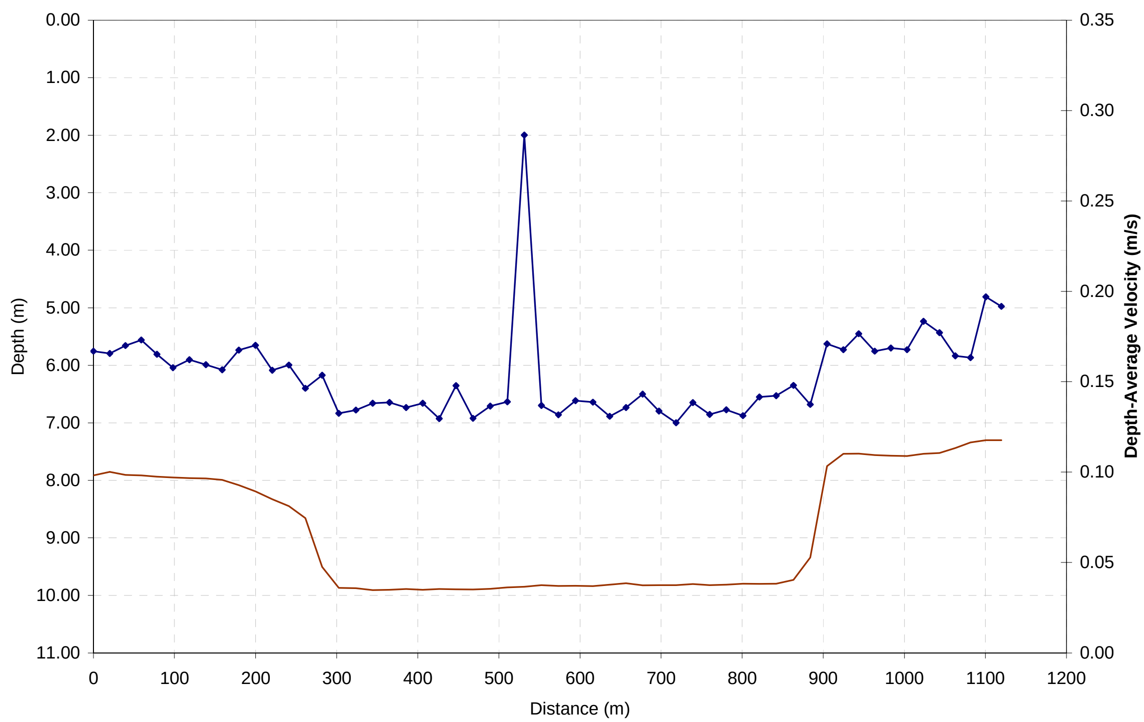

Figure B.2.26 Depth-Average Flow Velocity Change Across North-South Cross-Section (File no. 162819)

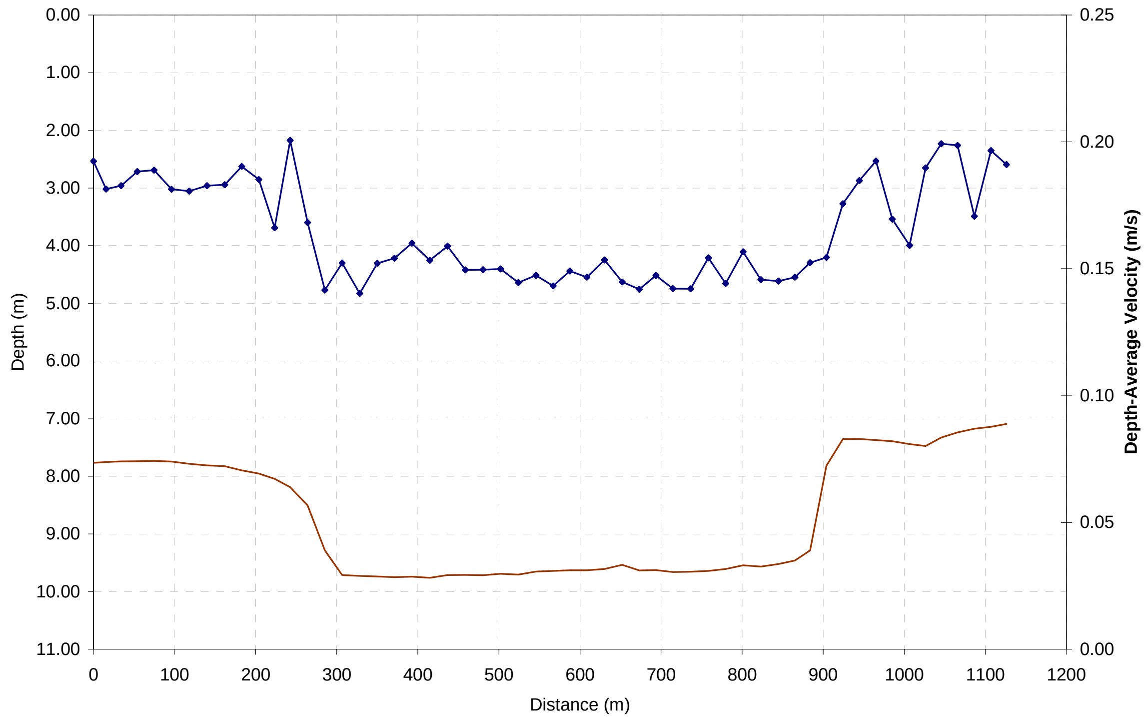

Figure B.2.27 Depth-Average Flow Velocity Change Across North-South Cross-Section (File no. 183610)

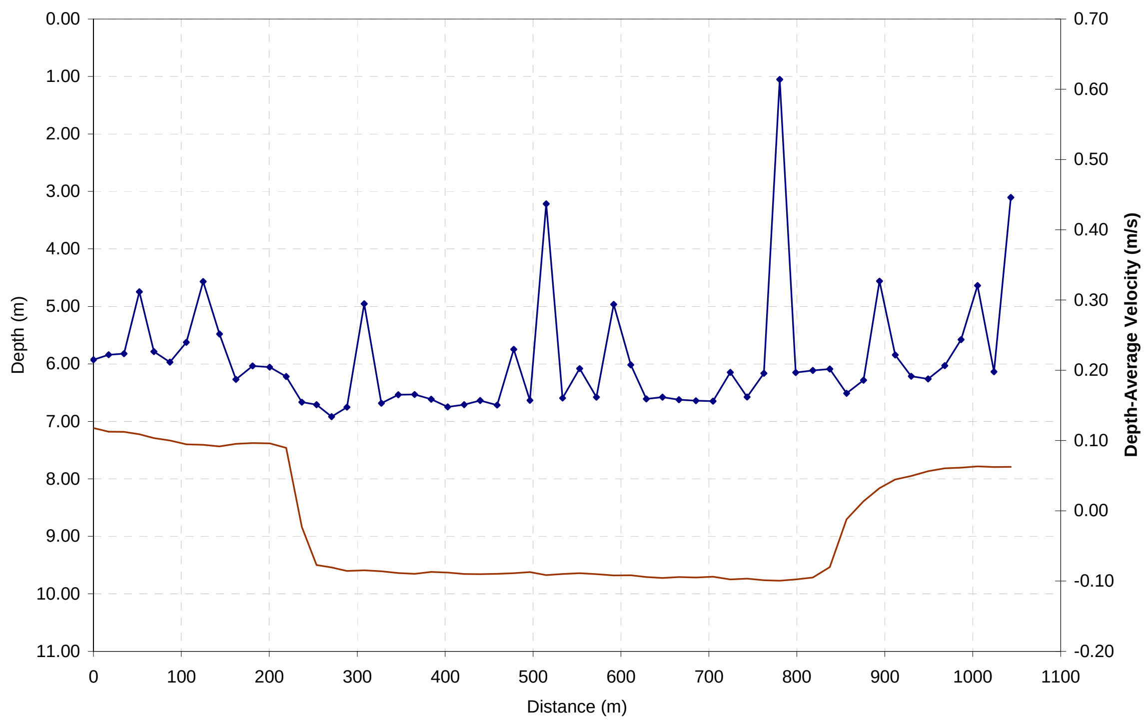

Figure B.2.28 Depth-Average Flow Velocity Change Across North-South Cross-Section (File no. 10401)

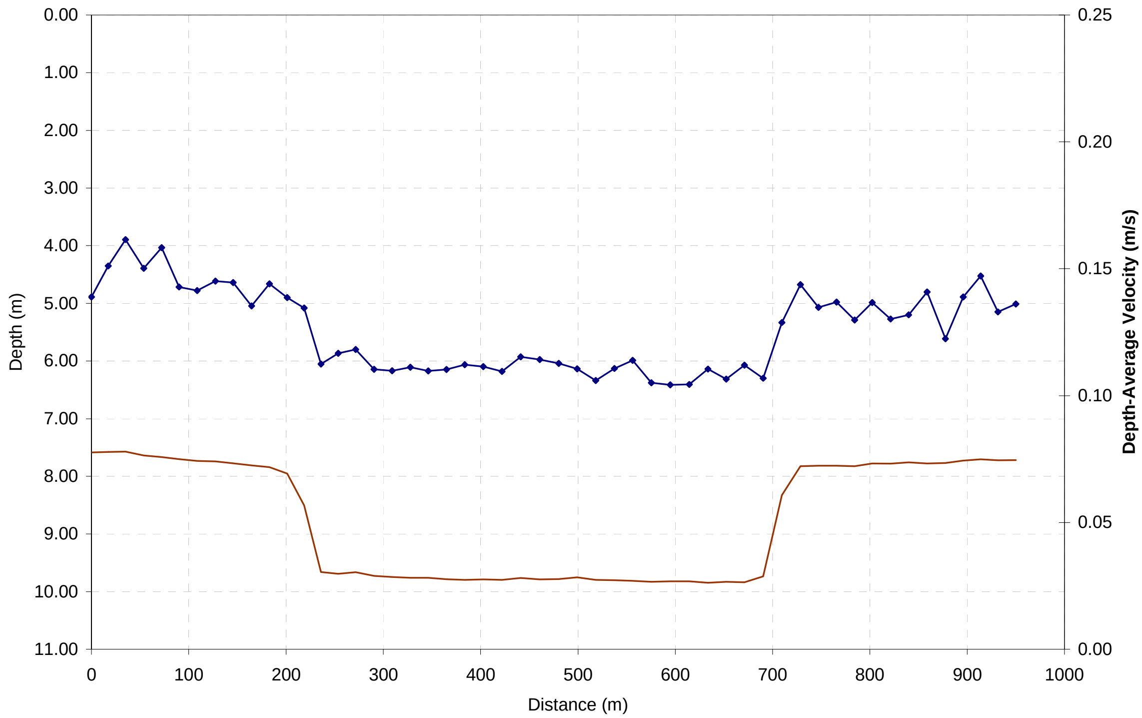

Figure B.2.29 Depth-Average Flow Velocity Change Across East-West Cross-Section (File no. 141039)

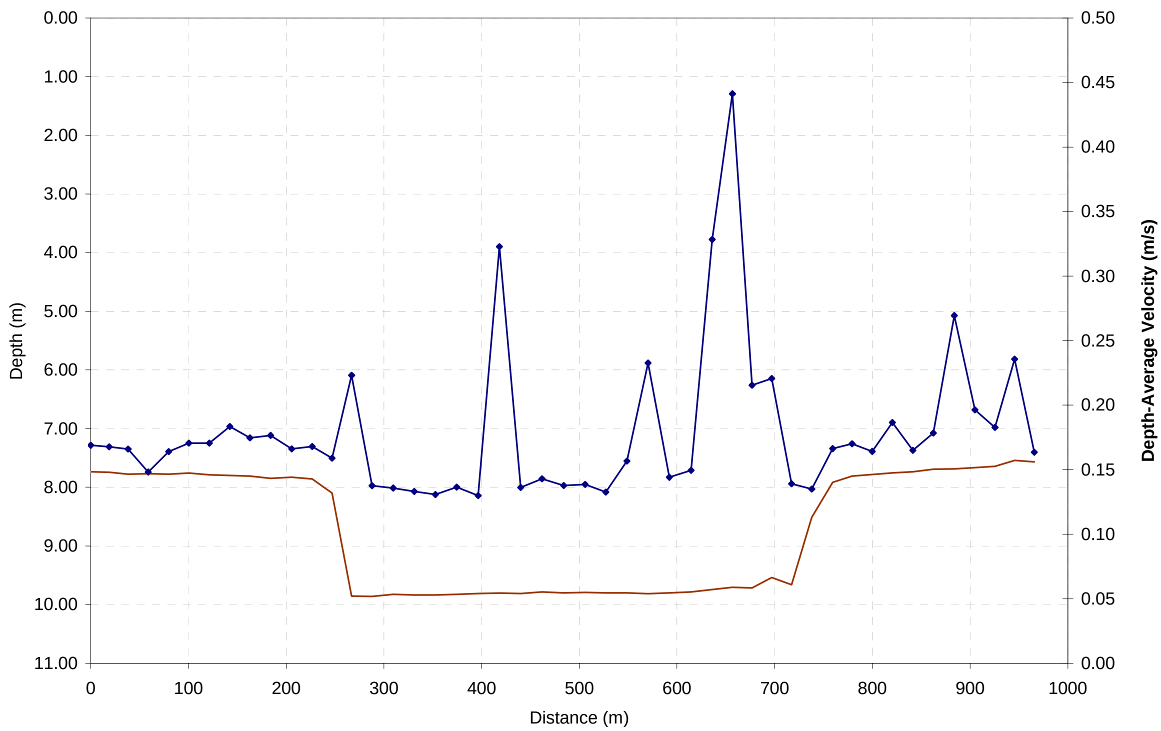

Figure B.2.30 Depth-Average Flow Velocity Change Across East-West Cross-Section (File no. 165500)

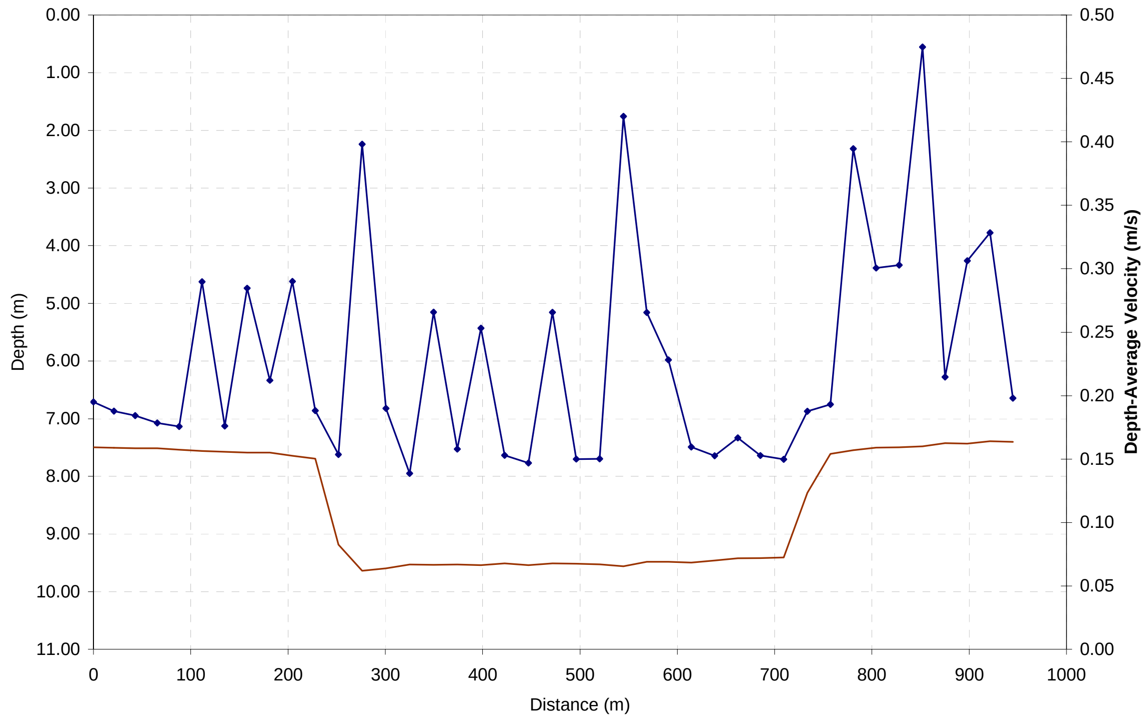

Figure B.2.31 Depth-Average Flow Velocity Change Across East-West Cross-Section (File no. 190058)

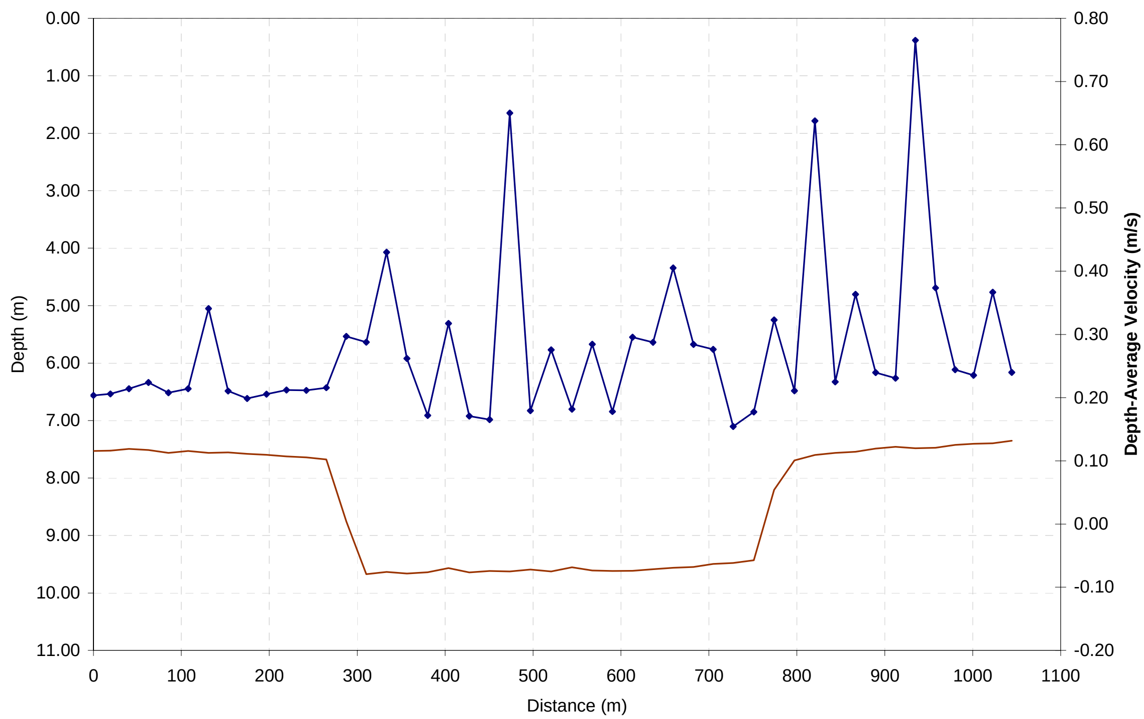

Figure B.2.32 Depth-Average Flow Velocity Change Across East-West Cross-Section (File no. 3629)

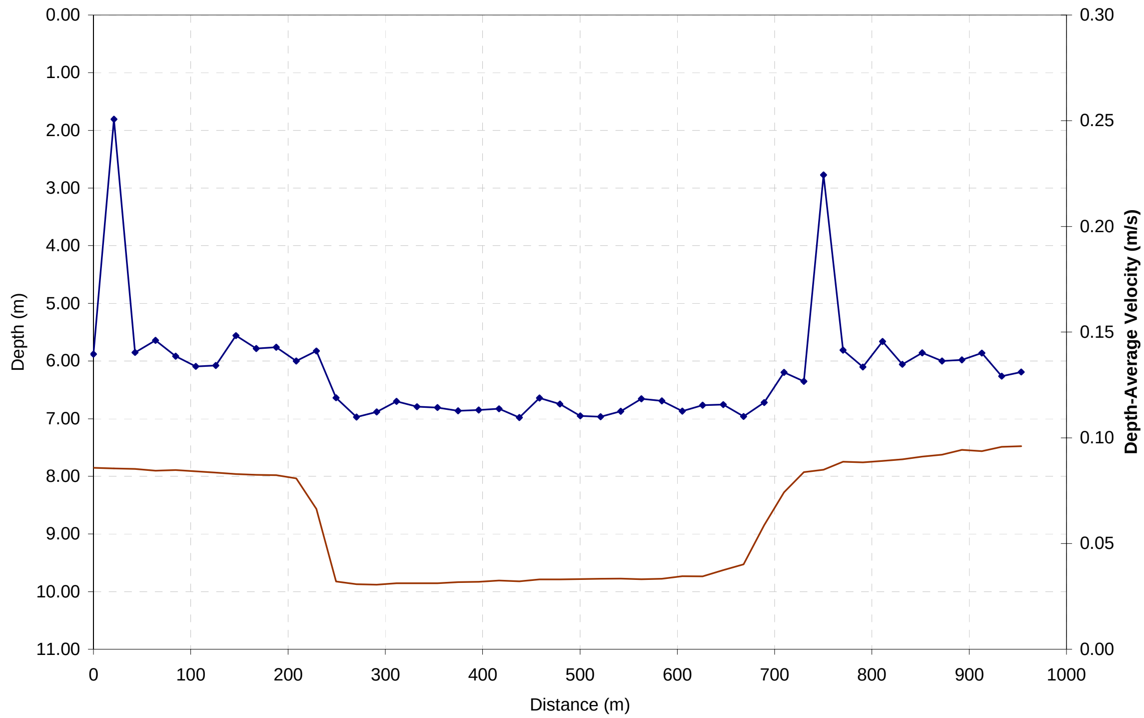

Figure B.2.33 Depth-Average Flow Velocity Change Across Diagonal Cross-Section (File no. 142104)

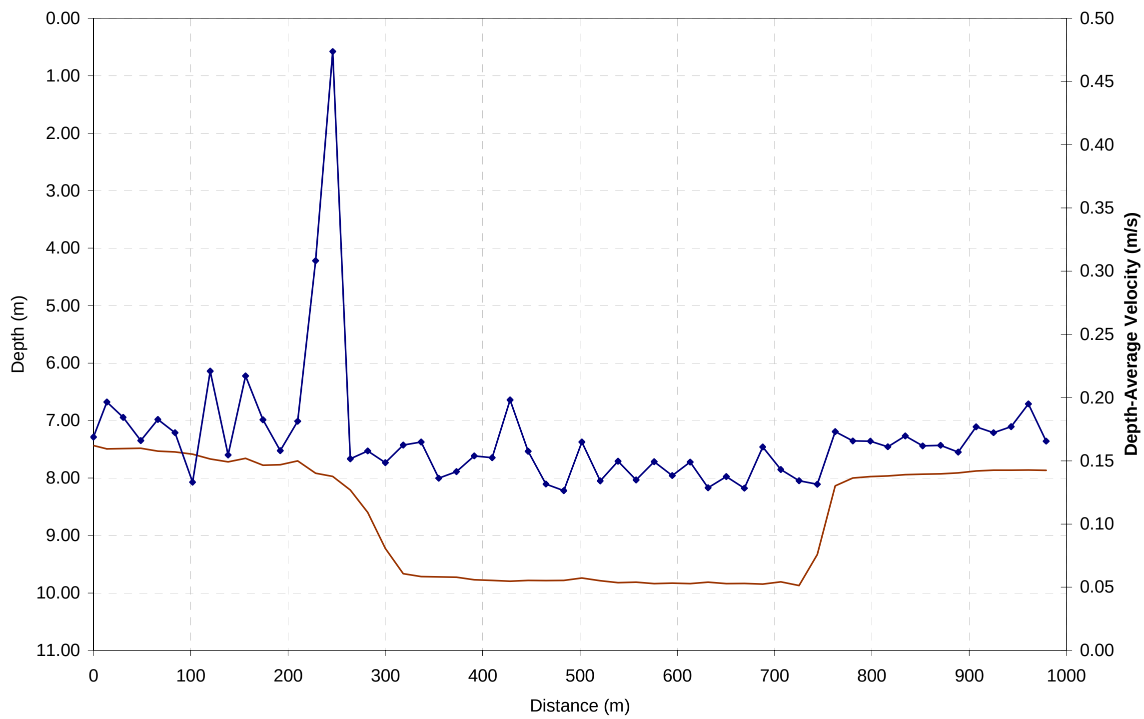

Figure B.2.34 Depth-Average Flow Velocity Change Across Diagonal Cross-Section (File no. 164148)

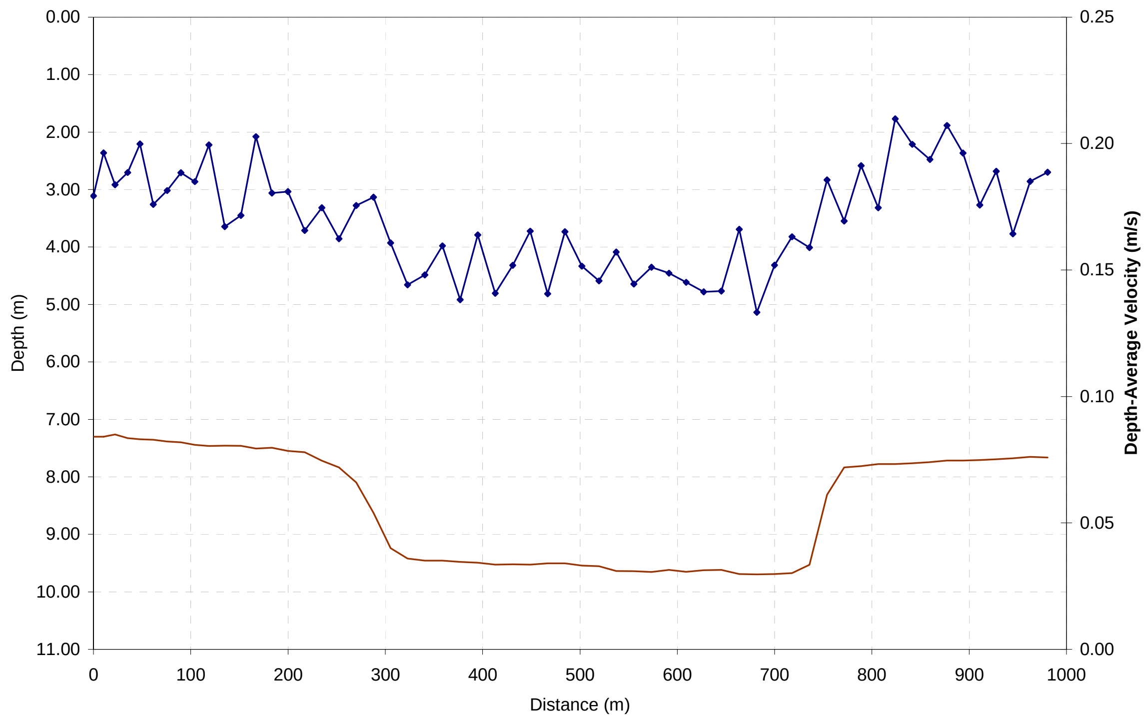

Figure B.2.35 Depth-Average Flow Velocity Change Across Diagonal Cross-Section (File no. 184830)

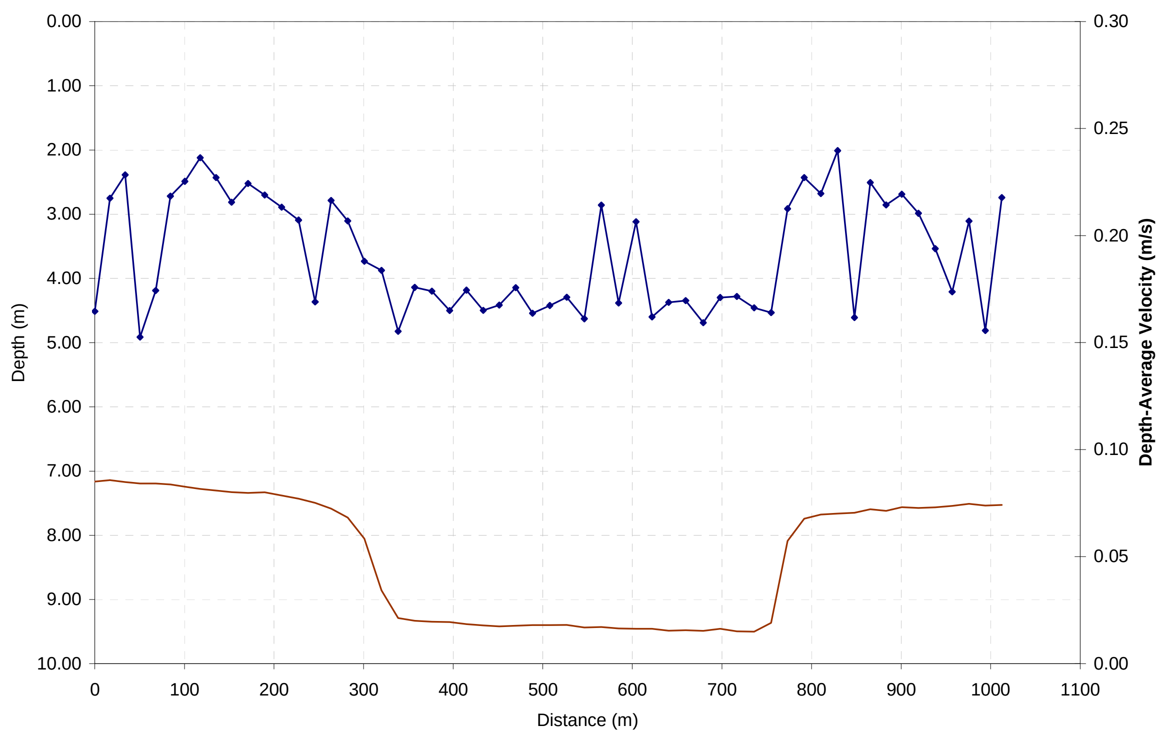

Figure B.2.36 Depth-Average Flow Velocity Change Across Diagonal Cross-Section (File no. 233424)

APPENDIX C:
REPORT ON BENTHIC SAMPLES AND ANALYSIS, TEXAS A & M UNIVERSITY

The Effects of a Dredge Excavation Pit on Benthic Macrofauna in Offshore Louisiana

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The Effects of a Dredge Excavation Pit on Benthic Macrofauna in Offshore Louisiana

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The Effects of a Dredge Excavation Pit on Benthic Macrofauna in offshore Louisiana

Abstract

Over three years after the original creation of a sand excavation pit 8 km off the Louisiana coast, benthic macrofauna communities and sedimentary characteristics are still effected. Macrofaunal communities inside the pit had lower abundance, biomass and diversity than communities outside the pit. This difference however, was only significant compared to some of the stations outside the pit. Results from multi-dimensional scaling and cluster analysis indicate that macrofaunal communities were less than 31 % similar inside the pit to communities outside the pit. The polychaete, *Mediomastus ambiseta*, was the most abundant species outside the excavation pit, but the species was only counted once inside the pit. The most dominant species, which made up over 90% of organisms inside the pit, was the pioneer polychaete, *Paraprionospio pinnata*. Three to five species were found at each station inside the pit as opposed to nine to 27 species at stations outside the pit. Differences in species compositions between inside and outside the pit were due to a loss of species rather than replacement by different species. All species inside the pit were also found outside the pit. Sediment inside the pit contained more silt and clay compared with outside, however no differences in water quality were detected. Sediment in the erosional zone outside the pit and on a dredge disposal mound was coarser than all other sediments sampled. Because the macrofaunal community inside the pit has not recovered within 38 months, it is likely that it will require more time before it resembles the surrounding conditions.

Introduction

Sand for beach nourishment is often obtained by offshore dredging because of the large volumes of sand required and also because offshore dredging does not have the obvious impacts of nearshore and onshore sand mining (Byrnes *et al.* 2004, Work *et al.* 2004, Finkl and Khalil 2005). Offshore dredging, however still leaves excavation pits that are often physically different from the original and surrounding environment. These physical changes can in turn impact organisms inhabiting the excavated area, especially the benthos. The potential impacts on benthic organisms in an excavated pit can occur by three mechanisms: defaunation of sediment by the dredging process, physical changes to the water column caused by stratification within the pit, and change in sediment size and dynamics in and around the pit (Nairn *et al.* 2004).

Dredging directly causes defaunation of sediment. Colonizers of defaunated sediment are typically dominated by fast growing, opportunistic *r*-selected macrofauna species (Pearson and Rosenberg 1974, Rhoads *et al.* 1978, Thistle 1981, Lu 2000). Benthic colonizers are often small polychaetes, especially from the Spionidae and Capitellidae families (Grassle and Grassle 1974, Pearson and Rosenberg 1978, Montagna and Kalke 1992, Palmer *et al.* 2002). Unless there is subsequent frequent disturbance, succession occurs where colonizers are replaced or joined by a more diverse range of larger *k*-selected species (Pearson and Rosenberg 1978, Ritter *et al.* 2005).

Changes in the water column directly above an excavated dredge pit could inhibit the macrofaunal community from developing into a community that would represent its pre-dredging state. The two mostly likely water column changes are a short-term increase in total suspended solids (TSS) immediately after dredging and the formation of hypoxic (low oxygen) conditions occurring partially as a result of water column stratification in the pit. Hypoxic conditions (low oxygen) are generally defined in the northern Gulf of Mexico as water with less than 2 mg l^{-1} (Pokryfki and Randall 1987, Rabalais *et al.* 2002). The threshold was defined as 2 mg l^{-1} because bottom-dragging trawls do not usually capture shrimp or demersal fish below this concentration (Renaud 1986). At low oxygen levels, pericaridean crustaceans, echinoderms, bivalves and larger fauna are replaced or outlasted by small opportunistic polychaetes (Harper *et al.* 1981, Gaston 1985, Rabalais *et al.* 2002, Montagna and Ritter 2006). It is predicted that there may be limited mixing between the pit and the water column above it. This may cause stratification within the excavation pit. Water column stratification is commonly correlated with hypoxia (Ritter and Montagna 1999, Rabalais *et al.* 2002, Applebaum *et al.* 2005). Low dissolved oxygen levels have been documented in excavation pits in a sand mining study in estuaries (Johnston 1981).

The third potential physical change that may impact macrobenthic communities is a change in sediment grain size distribution. A low-flow zone can occur within a dredge pit, which promotes deposition of fine-grained sediment. Correlations between sediment grain size and benthic organisms are strong and well documented (Young and Rhoads 1971, Rhoads 1974, Mannino and Montagna 1997, Palmer 2006). The in-filling of a dredge excavation pit with finer sediments than the original sediment size was documented in offshore South Carolina (Jutte *et al.* 2002). The deposition of fine-grained sediments is not certain however. Shelf sediments in various locations up to 60 m deep in the northern Gulf of Mexico are frequently reworked due to storms and river discharge (Kennicutt *et al.* 1995).

Approximately 2 million cubic meters (2.5 million cubic yards) was excavated from offshore of the westernmost coastal segment of Louisiana, between Calcasieu and Sabine Passes. The purpose of this excavation was to provide sandy substrate for local beach nourishment at Holly Beach, Louisiana. Louisiana's westernmost coastal segment has been subject to beach erosion since the late 19^{th} century because of decreased supply of sediment to the beaches (Campbell *et al* 2005, Penland *et al.* 2005). This reduction in sediment supply is partially the fault of decreased sediment loading of rivers due to channel and flow alterations and partially because of restrictions in long-shore sediment transport as a result of the construction of 3-km long jetties at Calcasieu Pass and offshore breakwaters at Holly Beach (Campbell *et al* 2005, Penland *et al.* 2005). The purpose of the current study is to investigate the impact created by the dredge excavation pit on macrobenthic communities. There are two hypotheses in this study. The first hypothesis (H_1) is that the sediment and water column will be different in the pit compared to the surrounding area. The second hypothesis (H_2) is that the different physical environment in the pit compared to the surrounding area will result in significant differences in benthic macrofaunal communities.

Methods

Study Design

This study is located in and around a dredge excavation pit located 7 km (4 mi) south of Holly Beach, Louisiana and 28 km (17 mi) east of the Texas-Louisiana border (Figure 1). The original pre-dredging depth was 8 m. The pit was excavated in April 2003. A total of eight stations were sampled between 10 - 11 June 2006, over 3 years after excavation (Table 1, Figure 1). Two sampling stations were located within the pit (stations 1 and 2), one station on the pit edge (station 4), one 20 m from the pit edge (station 5), one 100 m away from the pit edge (station 6), one 200 m from the pit edge (station 3), and two at least 1 km from the edge of the pit (stations 7 and 8). A further four new stations were sampled on 4 March 2007 to compliment the samples taken in June 2006 (Table 1, Figure 1). Of these more recently sampled stations, three were situated outside and one inside the excavation pit. One of these stations was 70 m from the pit edge on a dredge disposal mound and the two other stations were located 100 - 220 m away from the pit, presumably in less disturbed conditions. The only station sampled inside the pit (station 10) was approximately 10 m from a station sampled in June 2006 (station 1). Macrobenthic samples were taken at each station, along with hydrographic measurements in the water column and sediment samples.

Hydrographic Measurements

Vertical hydrographic profiles of the water column were taken at each station that was sampled in June 2006. Measurements were taken at six evenly spaced depth intervals (bottom, surface and 20, 40, 60, 80 % of the total depth) in each profile. Only a mid-depth measurement was taken at the stations that were sampled in March 2007. A multiparameter YSI 600XLM datasonde was used to measure temperature (°C), salinity (psu), dissolved oxygen (mg l^{-1}), and pH at each station.

Macrofauna

Macrofauna samples were collected using SCUBA. Macrofauna were sampled with 6.7-cm diameter core tubes and sectioned at depth intervals of 0 - 3 cm and 3 - 10 cm. Samples were preserved with 5% buffered formalin. Five samples were taken at each of the eight stations that were sampled in June 2006, however only four samples were taken at each of the four stations that were sampled in March 2007. In the laboratory, macrofauna were sorted on 0.5-mm sieves

(Figure A1) and sorted from sediments using a dissecting microscope (Figure A2). Organisms were identified to the lowest taxonomic level possible, usually the species level. Organisms from each sample were pooled into higher taxonomical categories (Crustacea, Mollusca, Polychaeta, and Others) and dried for 24 h at 55 °C to determine dry weight biomass. The dried categories were then weighed to the nearest 0.01 mg (Figure A3). Mollusks were placed in 1 N HCl from a few minutes to an hour until carbonate shells were dissolved, and washed before drying.

Sediment Size Analysis

Sediment samples were collected with 6.7-cm diameter core tubes and sectioned at depth intervals of 0-3 cm and 3-10 cm. Percent contribution by weight was measured for four size classes: rubble and coarse sand (>125 µm), sand (125 - 62.5 µm), silt (62.5 – 3.9 µm), and clay (<3.9 µm). To determine grain size, a 20-cm^3 sediment sample was mixed with 50 ml of hydrogen peroxide and 75 ml of deionized water to digest organic material in the sample. The sample was wet sieved through a 62-µm mesh stainless steel screen using a vacuum pump and a Millipore Hydrosol SST filter holder to separate rubble and sand from silt and clay (Figure A4). After drying, the rubble and sand were separated on a 125-µm screen. In this study rubble is defined as sediment over 125-µm in diameter and is usually composed of shells, gravel, debris and very coarse sand. The silt and clay fractions were measured using pipette analysis (Figure A5). The sediment size analysis follows the methods in Folk (1964).

Statistical Analysis

Species diversity was calculated using Hill's number one (N1) diversity index, which is the exponential form of the Shannon HN diversity index (Hill 1973). Hill's N1 was used because it has units of number of dominant species, and is more interpretable than most other diversity indices (Ludwig and Reynolds 1988).

A one-way analysis of variance (ANOVA) was used to test for differences in macrofauna abundance, biomass and Hill's N1 diversity between stations. Calculations were made after pooling all sections and are reported to a depth of 10 cm. Abundance and biomass were log transformed (log(x+1)) prior to analysis. Where significant differences were detected, Tukey multiple comparison tests were used to find which means were different from one another. The experimentwise error rate for the Tukey tests was maintained at 0.05. Tukey tests were also conducted on log transformed data. All univariate analyses were performed using SAS software (SAS Institute Inc. 1999).

Community structure of infaunal species was analyzed by non-metric multi-dimensional scaling (MDS). MDS is a multivariate statistical tool that can be used to compare many variables from many stations simultaneously. In this study, MDS was used to examine community structure by comparing numbers of individuals of each species at each station. MDS was also used to compare the biomass of each major taxa group at each station. The distance between stations in an MDS plot can be related to community similarities or differences between stations. Differences and similarities among communities were highlighted using cluster analysis using the group average cluster mode. The significance that the clustering structure was not a result of randomization was tested using a similarity profile (SIMPROF) test with a significance level of 5 %. Species abundance data was log transformed prior to analysis and used a Bray-Curtis similarity matrix to create the MDS plot. MDS was performed using Primer software (Clarke and Gorley 2006).

Principal Component Analysis (PCA), a parametric multivariate method, was used to assess relationships between physical variables (sediment grain size, bottom depth, and hydrographic measurements) characteristic of stations. Water quality variables were log-transformed prior to analysis. Sediment sizes were averaged for the two vertical sections, and arcsine root transformed because they were in percentage form. Results are presented in bivariate plots as station scores and as variable loads. The plot of variable loads allow for visualization of the importance of variables in contributing to the loading scores. The PCA station score plots allow for visualization of relationships among the sampling stations. PCA analyses were performed using a rotated covariance model with SAS software (SAS Institute Inc. 1999).

Relationships between macrofauna communities and environmental factors were investigated using the Biota-Environment (BIO-ENV) procedure. The BIO-ENV procedure is a multivariate method that matches biotic (i.e., macrofauna community structure) with environmental variables (Clarke and Warwick 2001). This is carried out by calculating weighted Spearman rank correlations (Δ_w) between sample ordinations from all of the environmental variables and an ordination of biotic variables (Clarke and Ainsworth 1993). Correlations are then compared to determine the best match. The BIO-ENV procedure uses different numbers of abiotic sample variables in calculating correlations to investigate the different levels of environmental complexity. For this study, the macrofauna species abundance MDS ordination was compared with all physical variables. The significance of relationships were tested using RELATE, a non-parametric form of the mantel test. The BIO-ENV and RELATE procedures were calculated with Primer software (Clarke and Gorley 2006).

Relationships between physical and macrofaunal characteristics were also determined by correlating the first two principal components from PCA with macrofaunal abundance, biomass and diversity (N1) using regression analysis. An individual principal component represents a calculated amount of variability within a multivariate dataset and in effect represents a combination of physical variables rather than just one. In this study, if a principal component was found to represent a combination of water quality variables, a linear regression line was used. A Gaussian 3-parameter curve was used in the case that either of the principal components represented only sediment size variables. The peaked curve was used because abundance, biomass and diversity were predicted to peak at minimum disturbance intensities, which was hypothesized to co-occur with relatively moderate grain sizes. Disturbance by accretion was predicted to result in sediment dominated by fines inside the pit, whereas erosion on the dredge disposal mound and excavation pit edges was predicted to leave the sediment dominated by larger grain sizes. Regression analysis was implemented using Sigmaplot software (Systat Software, 2006).

Results

Macrofauna

There were a total of 64 species found in this study (Table 2). The most abundant species overall were *Mediomastus ambiseta* (3,200 m^{-2}, 47 %) followed by *Paraprionospio pinnata* (850 m^{-2}, 12 %), *Spiophanes bombyx* (500 m^{-2},, 7 %) and *Magelona phyllisae* (380 m^{-2}, 6 %). These four most abundant species were all polychaetes. The overall most abundant species, *M. ambiseta* was not present in stations 1, 3, 9 or 10, and occurred only once at station 2. *P. pinnata* occurred at densities greater than 600 m^{-2} at all stations sampled in June 2006 except station 3 where the density was less than 200 m^{-2}. Of the stations sampled in March 2007, *P. pinnata* was found in densities close to 600 m^{-2} at station 12 and less than 200 m^{-2} otherwise. The polychaete *Spiophanes bombyx* was the most abundant species at stations 3 and 11 (1,100 m^{-2} and 4,600 m^{-2} respectively) and was not found at any other stations except station 12 (200 m^{-2}). The total macrofaunal abundance was comprised of 97 - 100 % polychaetes inside the pit as opposed to 14 - 98 % outside the pit (Table 3). Only three species were found at each of station 1 and 2, combining to make a total of four different species. Three out of the four species found at stations 1 and 2 were polychaetes, the most abundant being *P. pinnata* with an abundance of 1400 - 1600 n m^{-2}, out of a total of abundance of 1500 - 1700 n m^{-2} (Table 2). There were only four species found at station 10, the only station sampled inside the pit in March 2007. The species found at station 10 were different to those found in stations 1 and 2 in June 2006, despite the proximity between the three stations.

Macrofauna communities were divided into four significantly different groups based on 40 % similarity among species abundances at each station (Figure 2). The groups were station 3, station 9, stations 1, 2 and 10, and stations 4 to 8. The first group contained only station 9 and was only 15 % similar to the other stations. The second group contained only station 3 and was 24 % similarity to all stations (except station 9). The third group contained stations 1, 2 and 10, the stations located in the dredge excavation pit. Stations 1 and 2 were more similar to each other than station 10 (73 % and 48 % respectively). This excavation pit group was 31 % similar to the remaining group. The fourth group contained stations 4 to 8 and 11 to 12. Stations within this group were 43 to 58 % similar to each other.

Stations were grouped into two groups based on biomass for each taxon at each station (Figure 3). Stations 1, 2 and 10 made up one group and were 26 % different than all of the other stations. The other group was separated into three groups. One group contained stations 5, 6, 11 and 12, another contained stations 3, 4, 7 and 8, while the last group contained only station 9. All stations sampled in June 2006 (stations 1 - 8) contained 87.1 - 99.3 % polychaetes by weight outside the pit, and 99.6 - 100.0 % in the pit (Table 3). In comparison, the percentage of polychaete biomass at the stations sampled in March 2007 was 28.6 - 83.3 % (stations 9, 11 and 12) outside the pit and 100.0 % inside the pit (station 10). Station 9, at the disposal mound had the lowest proportion of polychaetes (28.6 %) and a large proportion of nermertean (52.7 %) and mollusk (18.7 %) biomass.

There were significant differences in total macrofauna abundance, biomass and N1 diversity between stations (Table 4). Stations 1, 2, and 10 inside the pit, as well as station 9 at the dredge disposal mound, had the lowest macrofaunal abundance, and were significantly different from stations 5, 6 and 11, all outside the pit. The stations inside the pit had lower total biomass than all other stations but were only significantly different than stations 6, 11 and 12. N1 diversity at stations 1, 2 and 10 was significantly lower than at stations 11 and 12. Stations 1, 2 and 10 had the lowest total biomass (# 0.26 g m^{-2}), N1 diversity (# 1.5) and among the lowest abundance (#1700 n m^{-2}) out of all of the stations (Table 4).

Physical Variables

All water quality and sediment variables for all stations were merged for Principal Component Analysis (PCA). There was no significant difference between the surface and bottom sections for sediment grain sizes for rubble ($p = 0.11$), sand ($p=0.92$), silt ($p=0.17$), or clay ($p = 0.96$) so the average of both sections was used in the analysis. The first and second principal components (PC1 and PC2) explained 52.0 % and 41.7 % of the variation within the data set respectively for a total 93.6 % (Figure 4). Water quality variables aligned along PC1, where salinity and temperature are both inversely related to pH and dissolved oxygen (Figure 4A). Sediment characteristics aligned along PC2, where the proportion of clay and silt is inversely related to the proportion of sand and rubble in the sediments.

The station scores are divided into two groups along PC1 depending on when they were sampled (Figure 4B). Stations 9 to 10 have in general higher pH and dissolved oxygen values but lower salinity and temperature values than stations 1 to 8 (Table 5). The mean salinities at each of stations 1 to 8 in June 2006 were between 31 and 32 ppt. At the same stations, mean temperature was 28 to 29 °C and pH was 8. In March 2007, mid-water salinities were 23 ppt. In June 2006, mean dissolved oxygen values for the entire water column at the stations (1 and 2) located inside the pit were 4.9 - 5.0 mg l^{-1} as opposed to 5.7 - 6.0 mg l^{-1} at the rest of the stations. Bottom dissolved oxygen values varied only a small amount between stations in June 2006 (3.0 - 3.5 mg l^{-1}). The mean values for temperature, salinity and pH for stations inside the pit were within the range of means calculated for the other stations.

Stations 1, 2, 8 and 10 had the highest proportion of fine sediment (Figure 4B, Table 5). Over 94 % of the sediment at these stations contained either silt or clay. The highest proportion of rubble occurred at stations 5 and 6 (10 - 16 %); however the grain size distributions at these stations were among the most well mixed, as were stations 4, 7, 11 and 12. The sediment at stations 3 and 9 contained 89 to 93 % sand, making it the coarsest and most well sorted sediment in this study.

Linking Macrofauna with Physical Variables

As determined by the BIO-ENV procedure, macrofauna communities were more highly correlated with sediment types rather than any other physical variable (Table 6). The highest correlation with the macrofauna communities was with the combination of sand, silt, clay and dissolved oxygen ($\Delta = 0.720$). The relationship between macrofauna communities and the silt, clay, depth combination had a significance level of $p = 0.001$. Sand, silt and clay concentrations most commonly featured in the highest correlations found by the BIO-ENV procedure.

There were no significant correlation between PC1, which summarized the variability in only water quality variables, and any univariate macrofauna measure (Figure 5). In contrast, PC2, which represents variability in sediment grain size, significantly correlated with abundance and biomass, but not diversity (Figure 6). The lowest abundance and biomass occurred in either coarse (low PC2 score) or fine sediments (high PC2 score). The highest abundance and biomass occurred at stations with a moderate sediment size distribution such as at stations 5 and 6.

Discussion

The first hypothesis (H_1) is that the sediment and water column will be different in the pit compared to the surrounding area. The three stations (1, 2 and 10) inside the pit were approximately 3 meters deeper than the surrounding stations (Table 5). The sediment grain size distribution could be divided into three distinct groups (Figure 4, Table 5). Station 9, on the disposal mound, and stations 3, 180 meters west of the pit had the coarsest sediments of all the stations. Stations 4 to 7 and 11 to 12 had an intermediate grain size distribution. Station 8 and the stations within the pit (1, 2 and 10) had the finest sediment. Sediments at station 8 contained a higher proportion of sand and silt but less clay than the stations inside the pit however. The sediment grain size distributions at the excavated stations (stations 1, 2 and10) contained at least 80 % clay and less than 1 % sand and rubble combined. Sediment at all other stations outside the pit except stations 3 and 9 contained 21 % to 69 % clay and 5 % to 55 % sand. Sediment at stations 3 to 6 is slightly coarser than station 7 and a lot coarser than station 8. The reason for the lower proportion of fine sediments may be because stations 3 to 6 are within the pit's erosion zone (Nairn *et al.* in press). The overlying clay layer in at stations 3 to 6 has been eroded since original excavation, exposing underlying sand. The reason that sediment at stations 3, 5 and 6 is coarser than station 4, is probably because the west side of the pit initially had a thinner layer of clay overlying the sediment than at station 4. The excavation pit filled in approximately 4 m (13 ft) between April 2003 and December 2004 (21 months) and 3.5 m (11 ft) between December 2004 and June 2006 (17 months). This accretion decreased the pit depth from the original 18.5 m to 11 m between April 2003 and June 2006. Lower flow velocities inside the pit favor deposition of finer sediment, which is the dominant reason why sediment inside the pit is finer than outside it. It is possible that the infilling of the excavation pit may be related to the two major hurricanes that hit the dredge pit within nine months prior to June 2006 sampling. Hurricanes Katrina and Rita were both category 5 strength on the Saffir-Simpson scale. While the eye of Hurricane Katrina passed within 400 km east of the study area in August 2005, Hurricane Rita passed directly over the study area in September 2005. During Hurricane Rita, Holly Beach was exposed to a 5 - 6 m (16 - 20 ft) storm surge and consequently suffered beach erosion and severe building destruction (Turner *et al.* 2006, USGS 2005). However predicted accretion rates modeled without the influence of extreme events such as hurricanes by Nairn *et al*. (in press) were similar to the actual accretion rate. Therefore it is likely that the effects of the hurricanes on the pit were minor. Overall, the sediment inside the pit was much finer than outside of it.

Mean water column and bottom temperature, salinity and pH were similar at all stations in June 2006 (Table 5). Only a single mid-water depth was sampled for water quality in March. Therefore there are no bottom data for March 2007. There were minimal differences in mid-water depth water quality between stations sampled in March 2007, but substantial differences between water quality in June 2006 and March 2007. In the week prior to the sampling effort in March 2007, there was excessive rainfall and freshwater inflow, which lowered the salinities in the study area to 23 ppt. The resulting increased inflow also was associated with increased dissolved oxygen and pH relative to the June 2006 samples. The drop in temperature from around 29 °C in June 2006 to 16 °C in March 2007 was a combination of seasonal effects and effects of the increased inflow. Mean vertical profile dissolved oxygen concentrations in June 2006 were 0.7 - 1.1 mg l^{-1} lower at stations inside the pit than the rest of the stations, however bottom dissolved oxygen values inside the pit were within the range of bottom dissolved oxygen values of the undisturbed stations. Bottom dissolved oxygen concentrations both in and out of the dredge pit were between 3.0 and 3.5 mg l^{-1}. There were no anoxic or hypoxic conditions observed as predicted might occur by Baird & Associates (2005). Hypoxia episodically occurs between May and September in the northern Gulf of Mexico with peak occurrences between mid-July and mid-August (Harper *et al.* 1981, Gaston 1985, Rabalais *et al.* 2002). It is estimated that bottom water hypoxia occurred approximately 25 % of the time in mid-summer weeks between 1985 and 2001 in the same area as this current study (Rabalais *et al.* 2002). While hypoxia was not observed in this study, there was strong dissolved oxygen stratification in June 2006, and it is likely that hypoxia does occur in the study area because it is a regional scale phenomenon. There is a high probability that a single bottom sample on a single day would not detect hypoxia in the study area. The single measurement also says nothing about the extent, intensity, duration and frequency of any hypoxic events. Overall, water quality is the same inside and outside the pit.

The second hypothesis (H_2) is that the different physical environment in the pit compared to the surrounding area will result in significant differences in benthic macrofaunal communities. Based on species abundances, macrofauna communities in the pit were 31 % similar to the other stations outside the pit, except for station 3, which had only 24 % similarity with any other station at station 9, which had only 15 % similarity with any other station (Figure 2). Only seven macrofauna species were found inside the pit, four in 2006 and five in 2007 (two occurred in samples from both years). In June 2006, the polychaete *Paraprionospio pinnata* made up over 90 % of all organisms found in the pit, however in March 2007 made up only 33 % (Table 2). Inside the pit, the density of *P. pinnata* decreased from 1400 - 1600 n m^{-2} in June 2006 to 140 n m^{-2} in March 2007. The largest densities of *P. pinnata* outside the pit were stations 4, 7 and 8 (1200 - 2200 n m^{-2}). Stations 4, 7 and 8 also had the finest sediment outside the pit of the stations sampled in 2006 (Figure 4). *P. pinnata* occurred in much lower densities (70 - 600 n m^{-2}) in all stations sampled in 2007 that had comparable grain size distributions (stations 11 and 12).

Tellina sp. was the only mollusk found within the pit and was only found in one sample. The polychaete *Mediomastus ambiseta* occurred in high densities (2,000 - 11,000 n m^{-2}) in all stations outside the pit regardless of sample date except for stations 3 and 9 where none of the species were found. *M. ambiseta* was found in very low densities (0 - 57 n m^{-2}) inside the pit. In a previous study located within 5 - 10 km of the current study, *M. californiensis* (probably misidentified *M. ambiseta* specimens) was found to be sensitive to hypoxia (Gaston 1985). This would support the prediction that the pit experienced more hypoxia or anoxia than the surrounding unexcavated area. However, Mannino and Montagna (1997) found that *M. ambiseta* was more abundant in sandier sediments than other sediment sizes, so the absence of *M. ambiseta* in the pit could be a result of a different sediment size distribution. The macrofaunal community in this current study relates most with the combination of silt and clay concentrations in the sediment and station depth (Table 6). Overall, macrofauna communities are different inside the pit, correlating with the change in sediment size rather than from hypoxia or any other water column variable.

There are two broad mechanisms in which benthic macrofauna populations can become reestablished after a disturbance such as the creation of a dredge excavation pit: (1) lateral encroachment of individuals from the surrounding environment; and (2) recruitment of larvae (adapted from Sousa 2001). The individuals of the one dominant species inside the pit, *P. pinnata* were similar in size to individuals outside the pit; therefore recent recruitment of larvae in the pit is not apparent. Initial mechanisms of recruitment to the pit can not be determined because not enough sampling events occurred over time, however any recent population increases, if any, will have come from lateral encroachment from the area surrounding the pit. The species present inside the pit were a subset of the species present outside the pit. This means that the change in community structure in the pit was caused by a loss of species rather than being replaced by a different set of species and the source of the pit fauna was immigration or recruitment from the surrounding area.

Based on macrofaunal biomass of each taxon, there was a 74 % difference (26 % similarity) between communities inside and outside of the pit (Figure 3). The stations in the pit contained organisms from only 1 or 2 taxa groups compared to 3 to 6 taxa groups at all other stations (Table 3). Polychaetes were still the most dominant taxa by weight at all stations except station 9. The total biomass at station 9 was comprised of only 28.6 % compared with 53.6 - 100 % at all other stations. The greatest proportion of polychaetes biomass relative to the total biomass was inside the pit, at stations 1, 2 and 10 (99.6 - 100 %).

The two stations inside the pit had lower total biomass and N1 diversity than any other station outside the pit, although this relationship was only significant with some of the stations outside of the pit (Table 4). Abundance was also lower inside the pit, with the exception of station 9, on the disposal mound, which had the second lowest total abundance. The lower abundance and diversity in fine sediments compared with sandy sediments is consistent with estuarine studies in a Texas estuary (Mannino and Montagna 1997). The comparatively low abundance, biomass and diversity is also typical of a disturbed area (Pearson and Rosenberg 1978, Gaston 1985, Montagna *et al*. 2002, Palmer *et al.* 2002, Balthis 2006). The constant accretion of sediment of approximately 2.4 m yr^{-1} (8 ft yr^{-1}) inside the dredge pit since excavation in April 2003, in addition to any possible hypoxic events that may occur, will hinder the succession of the macrofaunal community (Rhoads *et al*. 1978, Peterson 1985). The disposal mound at station 9 is probably subject to greater erosion rates than the surrounding area because it protrudes above the rest of the sea floor. Elevated erosion rates will have a similar effect to macrofauna communities as other disturbances such as accretion or hypoxia.

Macrofaunal communities recovered within 30 months of dredging in a series of meter-deep South Carolina dredge pits (Jutte 2002). The original pit excavation depth in the present study was 10 times deeper than the depth in Jutte *et al.* (2002); therefore it is understandable that the recovery was not as rapid. This greater depth will require a longer stabilization and physical recovery time. At the current rate of sedimentation, the pit should be filled up within 1.3 years, however the accretion rate is predicted to slow so that the dredge pit will not be totally full until 2010 or 2011 (Nairn *et al*. in press). Thirty-eight months after excavation (April 2003 - June 2006), the excavation pit is still physically and biologically different from the surrounding area.

Although water quality appeared to be very similar inside and outside the pit at the time of sampling, the water column is temporally dynamic, and a survey over time would be required to prove that water quality played no vital role in the differences in macrofaunal communities. The sediment inside the pit is smaller in size than outside the pit, but is most different from the sediment located at the periphery of the pit. The difference in sediment size between inside and outside of the pit correlated strongly with macrofaunal community differences in the study area. The high accretion rates occurring in the pit are deleterious to many organisms. Predicted reduced accretion rates should allow larger numbers of more diverse organisms to settle and survive in the pit. The macrofaunal community inside the pit is not likely to recover until the sediment inside the pit is similar to that occurring outside the pit and any accretion is more stable.

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Table 1. Station locations in State Plane Projected coordinate system (Louisiana South, feet) and Geographic coordinate system (North American Datum 1983, decimal degrees).

		State Plane		Geographic	
Station	Description	Northing	Easting	Latitude	Longitude
1	Inside the pit - SW portion	440657	2578919	29.69310	93.54418
2	Inside the pit - center	441475	2577027	29.69540	93.54387
3	180 m west of pit edge	437083	2574897	29.69402	93.54551
4	on pit edge on northeast side	441000	2578505	29.69501	93.54852
5	20 m from pit edge on west side	441493	2579033	29.68306	93.55663
6	100 m west of pit edge	441528	2574351	29.69525	93.55862
7	1000 m west of pit edge	441361	2577256	29.69494	93.54947
8	1400 m southwest of pit edge	441378	2577555	29.69525	93.55019
9	70 m northwest of pit edge	441929	2577676	29.69653	93.54818
10	Inside the pit - SW portion	440687	2578895	29.69318	93.54426
11	100 m east of pit edge	440954	2579645	29.69395	93.54192
12	200 m east of pit edge	440952	2580065	29.69397	93.54059

Table 2. Species abundance for each station and as an overall mean. Abundances are in n m $^{-2}$. Taxa groups: P = polychaete, N = nemertean, M = mollusk, C = crustacean, OP = ophiuroid, O = other.

Species name	Taxa Group	Station												Mean	Mean as %	Cum. %
		1	2	3	4	5	6	7	8	9	10	11	12			
Mediomastus ambiseta	P	0	57	0	2,950	10,835	11,459	2,212	1,985	0	0	2,978	6,027	3,209	46.8	46.8
Paraprionospio pinnata	P	1,588	1,418	170	1,418	624	794	2,212	1,191	0	142	71	567	850	12.4	59.2
Spiophanes bombyx	P	0	0	1,135	0	0	0	0	0	0	0	4,609	213	496	7.2	66.5
Magelona phyllisae	P	0	0	0	0	2,042	454	57	57	71	0	1,347	496	377	5.5	72.0
Nemertinea (unidentified)	N	0	0	340	113	908	794	57	170	355	0	213	71	252	3.7	75.7
Cossura delta	P	0	0	57	340	511	340	57	113	0	71	496	851	236	3.5	79.1
Ampharete parvidentata	P	0	0	0	0	57	0	0	0	0	71	780	1,135	170	2.5	81.6
Phoronis architecta	O	0	0	57	0	57	227	0	0.00	496	0	1,064	71	164	2.4	84.0
Sigambra tentaculata	P	57	57	0	340	284	227	113	170	0	71	213	355	157	2.3	86.3
Hobsonia florida	P	0	0	0	0	0	0	0	0	0	0	0	1,773	148	2.2	88.5
Mulinia lateralis	M	0	0	57	0	0	57	0	0	0	0	851	71	86	1.3	89.7
Glycinde solitaria	P	0	0	0	57	284	170	57	0	0	71	71	71	65	0.9	90.7
Tellina sp.	M	57	0	0	0	284	227	0	0	0	0	142	0	59	0.9	91.5
Polinices duplicatus	M	0	0	0	0	0	0	0	0	0	0	496	0	41	0.6	92.1
Diopatra cuprea	P	0	0	0	0	113	340	0	0	0	0	0	0	38	0.6	92.7
Ancistrosyllis sp.	P	0	0	0	0	0	57	0	0	0	0	284	0	28	0.4	93.1
Oligochaetes (unidentified)	P	0	0	0	57	0	57	0	227	0	0	0	0	28	0.4	93.5
Oxyurostylis sp.	C	0	0	0	57	0	0	0	0	0	0	213	71	28	0.4	93.9
Apoprionospio pygmaea	P	0	0	284	0	0	0	0	0	0	0	0	0	24	0.3	94.3
Oweniidae (unidentified)	P	0	0	0	0	0	0	0	0	0	0	284	0	24	0.3	94.6
Gastropoda (unidentified)	M	0	0	0	0	0	0	57	0	0	0	213	0	22	0.3	94.9
Sthenelais sp.	P	0	0	113	0	0	0	0	57	0	0	0	71	20	0.3	95.2
Anaitides longipes	P	0	0	57	0	0	170	0	0	0	0	0	0	19	0.3	95.5
Mysella planulata	M	0	0	0	0	0	0	0	0	0	0	71	142	18	0.3	95.8
Solen viridis	M	0	0	0	0	0	0	0	0	0	0	213	0	18	0.3	96.0
Gyptis vittata	P	0	0	0	0	0	0	0	0	0	0	142	71	18	0.3	96.3
Paguridae juv.	C	0	0	57	0	0	0	0	0	0	0	142	0	17	0.2	96.5
Bivalvia (unidentified)	M	0	0	57	0	0	113	0	0	0	0	0	0	14	0.2	96.7

Species name	Taxa Group	Station												Mean	Mean as %	Cum. %
		1	2	3	4	5	6	7	8	9	10	11	12			
Ampelisca abdita	C	0	0	0	0	57	113	0	0	0	0	0	0	14	0.2	96.9
Ophiuroidea (unidentified)	OP	0	0	0	57	0	113	0	0	0	0	0	0	14	0.2	97.2
Lumbrineridae (unidentified)	P	0	0	0	0	0	57	0	0	0	0	0	71	11	0.2	97.3
Turbellaria (unidentified)	O	0	0	0	57	57	0	0	0	0	0	0	0	9	0.1	97.4
Syllis sp.	P	0	0	0	0	57	0	0	57	0	0	0	0	9	0.1	97.6
Trachypenaeus constrictus	C	0	0	0	0	0	113	0	0	0	0	0	0	9	0.1	97.7
Calappidae (unidentified)	C	0	0	57	0	0	57	0	0	0	0	0	0	9	0.1	97.9
Malmgreniella taylori	P	0	0	0	0	0	0	0	0	0	0	71	0	6	0.1	97.9
Pseudeurythoe sp. A	P	0	0	0	0	0	0	0	0	0	0	71	0	6	0.1	98.0
Amphinomidae (unidentified)	P	0	0	0	0	0	0	0	0	0	0	71	0	6	0.1	98.1
Aglaophamus verrilli	P	0	0	0	0	0	0	0	0	0	0	71	0	6	0.1	98.2
Polydora websteri	P	0	0	0	0	0	0	0	0	0	0	71	0	6	0.1	98.3
Scolelepis squamata	P	0	0	0	0	0	0	0	0	71	0	0	0	6	0.1	98.4
Tharyx sp.	P	0	0	0	0	0	0	0	0	0	0	0	71	6	0.1	98.5
Echiuridae (unidentified)	O	0	0	0	0	0	0	0	0	0	0	71	0	6	0.1	98.5
Anthozoa (unidentified)	O	0	0	0	0	57	0	0	0	0	0	0	0	5	0.1	98.6
Nassarius sp.	M	0	0	0	0	0	0	0	57	0	0	0	0	5	0.1	98.7
Nuculana sp.	M	0	0	0	0	0	0	0	57	0	0	0	0	5	0.1	98.8
Malmgreniella sp.	P	0	0	0	0	0	57	0	0	0	0	0	0	5	0.1	98.8
Paleanotus chrysolepis	P	0	0	0	0	0	57	0	0	0	0	0	0	5	0.1	98.9
Paleanotus sp.	P	0	0	0	0	57	0	0	0	0	0	0	0	5	0.1	99.0
Eurythoe sp.	P	0	0	0	57	0	0	0	0	0	0	0	0	5	0.1	99.0
Ancistrosyllis papillosa	P	0	0	0	0	57	0	0	0	0	0	0	0	5	0.1	99.1
Pilargiidae (unidentified)	P	0	0	0	0	0	0	57	0	0	0	0	0	5	0.1	99.2
Podarke obscura	P	0	0	57	0	0	0	0	0	0	0	0	0	5	0.1	99.2
Websterinereis tridentata	P	0	0	0	0	0	57	0	0	0	0	0	0	5	0.1	99.3
Laeonereis culveri	P	0	0	0	0	0	57	0	0	0	0	0	0	5	0.1	99.4
Nereidae (unidentified)	P	0	0	0	0	0	57	0	0	0	0	0	0	5	0.1	99.4
Dorvillea sp.	P	0	0	0	57	0	0	0	0	0	0	0	0	5	0.1	99.5
Maldanidae (unidentified)	P	0	0	0	0	0	57	0	0	0	0	0	0	5	0.1	99.6
Sabellidae (unidentified)	P	0	0	0	0	0	0	0	57	0	0	0	0	5	0.1	99.7
Callianassa biformis	C	0	0	0	0	57	0	0	0	0	0	0	0	5	0.1	99.7

Species name	Taxa Group	Station												Mean	Mean as %	Cum. %
		1	2	3	4	5	6	7	8	9	10	11	12			
Pinnixa sp.	C	0	0	57	0	0	0	0	0	0	0	0	0	5	0.1	99.8
Oxyurostylis smithi	C	0	0	0	0	57	0	0	0	0	0	0	0	5	0.1	99.9
Corophium sp.	C	0	0	0	0	0	57	0	0	0	0	0	0	5	0.1	99.9
Listriella sp.	C	0	0	57	0	0	0	0	0	0	0	0	0	5	0.1	100.0
Total		1,702	1,532	2,609	5,559	16,451	16,338	4,879	4,198	993	425	15,317	12,197	6,850	100	
Total number of species		3	3	15	12	19	27	9	12	4	5	27	18	12.8		

Table 3. Abundance and biomass of each major taxa group.

Taxa Group	Station												Mean	Mean
	1	2	3	4	5	6	7	8	9	10	11	12		as %
Abundance (n m^2)														
Polychaete	1,645	1,532	1,872	5,219	14,919	14,295	4,765	3,801	142	425	11,629	11,771	6,001	88.0
Nemertean	0	0	340	113	908	851	57	170	0	0	1,985	142	262	3.8
Mollusc	57	0	113	0	284	397	57	113	355	0	213	71	256	3.8
Crustacean	0	0	227	57	170	340	0	0	496	0	1,135	71	184	2.7
Other	0	0	57	57	170	227	0	0	0	0	355	71	102	1.5
Ophiuroid	0	0	0	57	0	113	0	0	0	0	0	0	14	0.2
Total	1,702	1,532	2,609	5,503	16,451	16,224	4,879	4,084	993	425	15,317	12,126	6,820	100.0
% Polychaetes	96.7	100.0	71.7	94.8	90.7	88.1	97.7	93.1	14.3	100.0	75.9	97.1		
Biomass (g m^2)														
Polychaete	0.13	0.26	0.96	1.06	5.45	7.34	1.57	0.66	1.42	0.25	4.88	3.22	2.27	73.2
Mollusc	0.00	0	0.01	0	0.00	0.84	0.00	0.01	0.93	0	3.77	0.01	0.40	12.8
Nemertean	0	0	0.10	0.00	0.19	0.07	0.02	0.03	2.62	0	0.20	0.02	0.27	8.7
Crustacean	0	0	0.03	0.00	0.08	0.1	0	0	0	0	0.14	0.60	0.14	4.4
Other	0	0	0.00	0.00	0.00	0.0	0	0	0	0	0.10	0.01	0.03	0.8
Ophiuroid	0	0	0	0.00	0.00	0.0	0	0	0	0	0.00	0.00	0.00	0.0
Total	0.1	0.3	1.1	1.1	5.7	8.4	1.6	0.7	5.0	0.3	9.1	3.9	3.1	100.0
% Polychaetes	99.6	100.0	87.1	99.3	95.2	87.6	98.6	93.3	28.6	100.0	53.6	83.3		

Table 4. Analysis of variance and Tukey grouping for N1 diversity, biomass and abundance at each station. All analyses were carried out using log transformed data, MS=mean square, *only 4 replicates taken at this station.

Source	Degrees of Freedom	Type III Sum of Squares	Mean Square	F Value	Pr > F
Abundance (n m^{-2})					
Station	11	148.439	13.494	4.95	<0.0001
MS(Error)	44	119.902	2.725		
Biomass (g m^{-2})					
Station	11	24.399	2.218	6.71	<0.0001
MS(Error)	44	14.549	0.331		
Diversity (N1)					
Station	11	159.379	14.489	11.24	<0.0001
MS(Error)	44	56.714	1.289		

Abundance												
Mean (n m^{-2})	16,451	16,224	15,315	12,197	5,503	4,879	4,084	2,609	1,532	1,702	993	425
Station	5	6	11	12	4	7	8	3	2	1	9	10
Tukey groups					—	—	—	—	—	—	—	
	—	—	—	—	—	—	—	—	—			
							—	—	—	—	—	—
				—	—	—	—	—	—	—		
Biomass												
Mean (g m^{-2})	9.11	8.38	3.87	5.72	4.98	1.60	1.10	1.07	0.71	0.26	0.25	0.13
Station	11	6	12	5	9	7	3	4	8	2	10	1
Tukey groups			—	—	—	—	—	—	—			
	—	—	—	—	—							
				—	—	—	—	—	—	—		
		—	—	—	—	—	—	—				
					—	—	—	—	—	—	—	—
N1 Diversity												
Mean	7.69	4.28	4.06	3.87	3.61	3.54	3.31	2.60	1.63	1.50	1.22	1.02
Station	11*	12*	3	4	5	6	8	7	9*	10*	2	1
Tukey groups					—	—	—	—	—	—	—	
		—	—	—	—	—	—	—				
						—	—	—	—	—	—	—
			—	—	—	—	—	—	—	—		

Table 5. Summary of physical parameters measured at each station. Temp = temperature, D.O. = dissolved oxygen. Mean of vertical sections for sediments and vertical profiles for water quality measures.

Station	Date sampled	Mean Rubble (%)	Mean Sand (%)	Mean Silt (%)	Mean Clay (%)	Mean Temp (EC)	Mean Salinity (psu)	Mean D.O. (mg l^{-1})	Mean pH	Bottom Temp (EC)	Bottom Salinity (psu)	Bottom D.O. (mg l^{-1})	Bottom pH	Total Depth (ft)	Total Depth (m)
1	10 Jun 2006	0.0	0.9	19.0	80.1	28.33	31.74	4.92	7.99	27.79	32.22	3.12	7.88	36.4	11.1
2	11 Jun 2006	0.0	0.3	17.3	82.4	28.36	31.74	4.99	7.99	27.73	32.23	3.11	7.87	36.3	11.1
3	11 Jun 2006	5.7	93.1	0.2	1.0	28.86	31.59	5.85	8.04	27.92	32.20	3.32	7.87	26.3	8.0
4	10 Jun 2006	0.2	26.5	18.2	55.2	28.62	31.58	5.70	8.03	27.80	32.20	3.27	7.88	26.8	8.2
5	11 Jun 2006	15.8	54.5	8.7	21.0	28.71	31.57	5.81	8.04	27.91	32.20	3.30	7.87	27.1	8.3
6	11 Jun 2006	10.0	42.1	10.5	37.3	28.81	31.71	5.98	8.04	27.91	32.20	3.30	7.87	26.2	8.0
7	10 Jun 2006	0.3	18.0	16.8	64.9	28.76	31.60	5.71	8.03	27.84	32.22	2.98	7.84	26.0	7.9
8	10 Jun 2006	0.5	5.3	25.7	68.5	28.62	31.48	5.88	8.05	27.93	32.12	3.45	7.89	26.3	8.0
9	04 Mar 2007	8.1	89.1	1.4	1.5	16.06	22.87	11.11	8.26	-	-	-	-	22.0	6.7
10	04 Mar 2007	0.1	0.3	19.8	79.8	16.04	22.91	11.06	8.38	-	-	-	-	35.6	10.9
11	04 Mar 2007	4.6	36.0	15.3	44.0	15.98	23.07	10.74	8.33	-	-	-	-	28.5	8.7
12	04 Mar 2007	2.1	24.7	16.8	56.4	16.00	22.99	11.10	8.42	-	-	-	-	28.5	8.7

Table 6. Environmental variables that correlated highest with macrofaunal communities as determined by the BIO-ENV procedure. The highest correlation had a significant level of $p = 0.001$.

No. Of Variables	Pearson Correlation (Δ_w)	Variables Selected
4	0.720	Sand, Silt, Clay, Dissolved Oxygen
1	0.719	Sand
4	0.714	Sand, Silt, Clay, Salinity
2	0.713	Sand, Clay
4	0.710	Sand, Silt, Clay, Temperature
3	0.707	Sand, Silt, Clay
1	0.703	Clay
3	0.699	Sand, Clay, Dissolved Oxygen
2	0.696	Sand, Silt
5	0.694	Rubble, Sand, Silt, Clay, Dissolved Oxygen

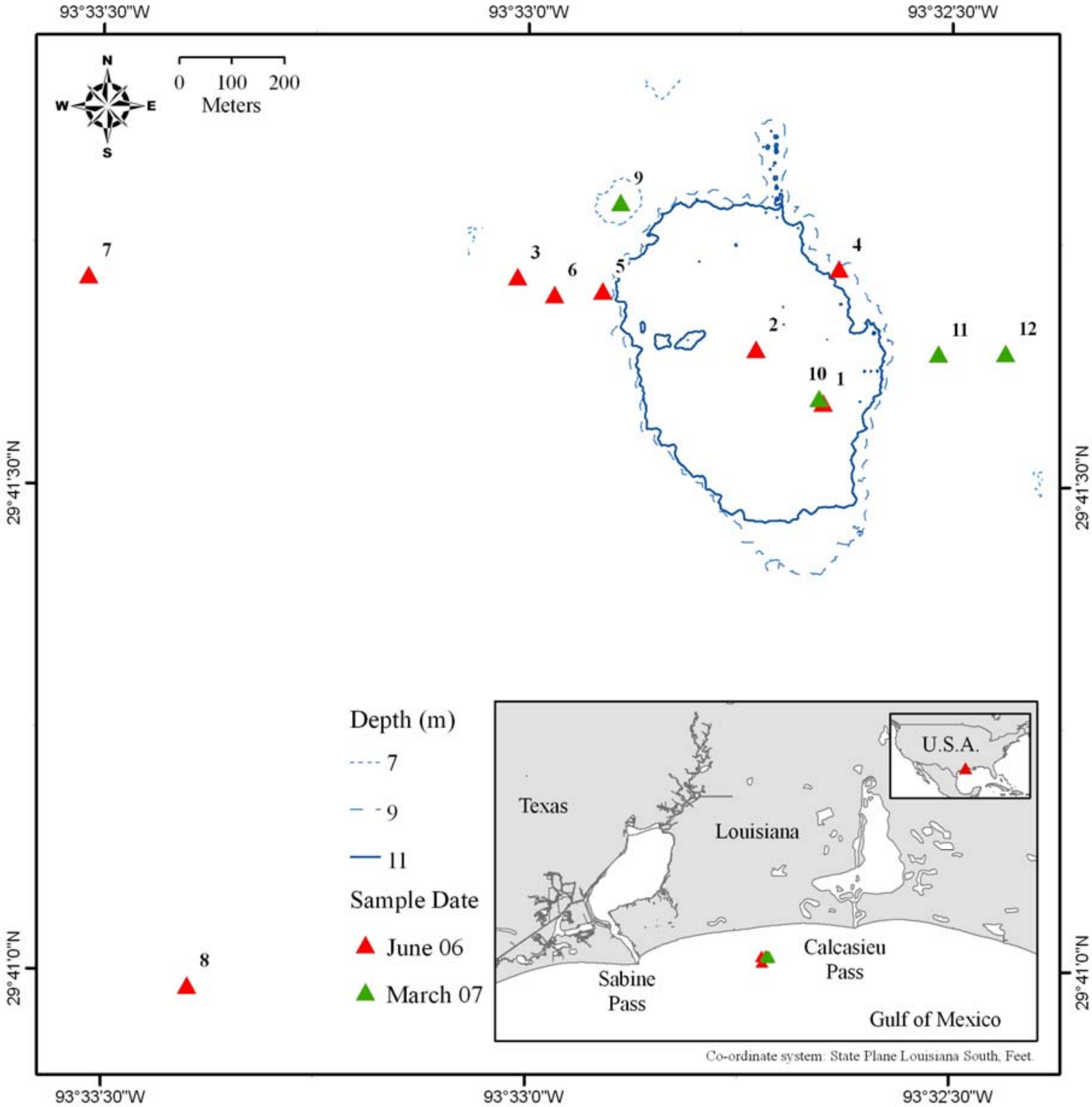

Figure 1. Locations of sampling stations. Bathymetry is derived from a June 2006 survey.

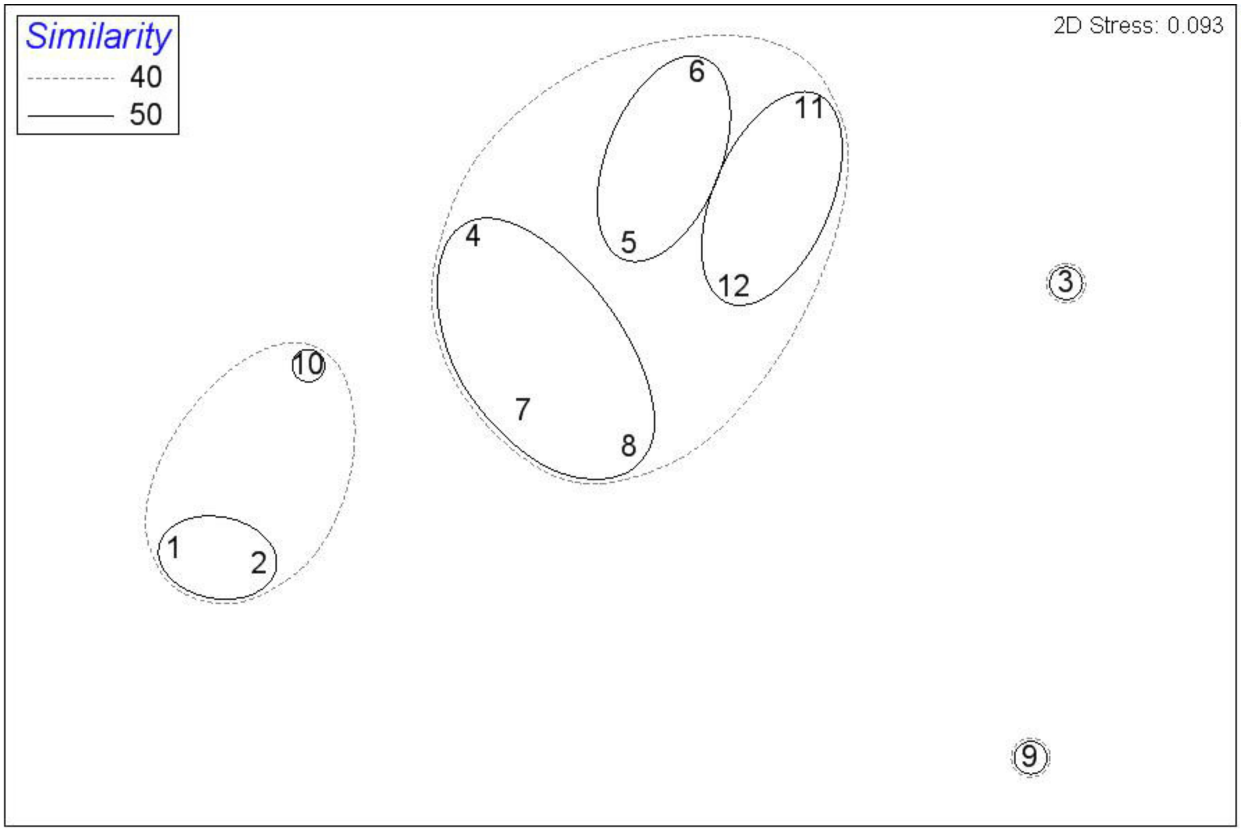

Figure 2. Non-metric Multi-Dimensional Scaling analysis of species abundances at each station.

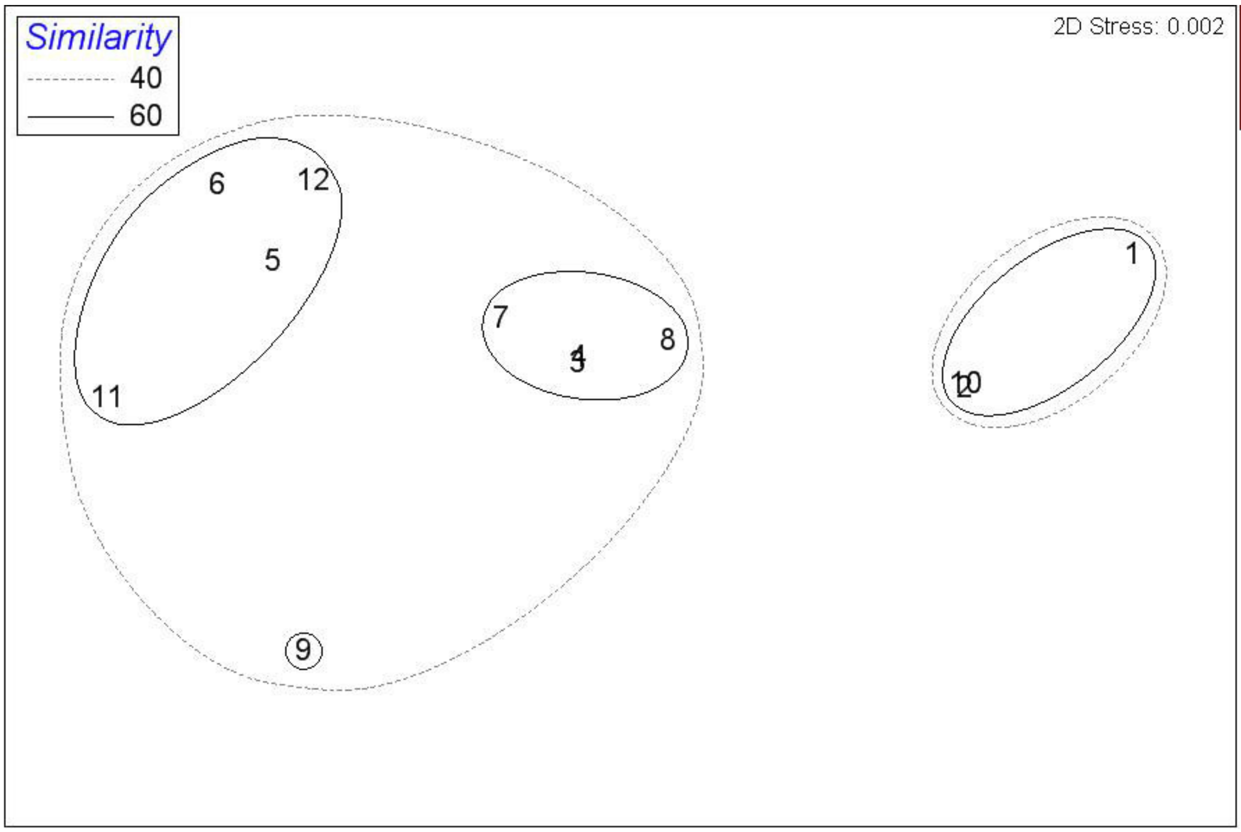

Figure 3. Non-metric Multi-Dimensional Scaling analysis of biomass of each taxa at each station. Samples 3 and 4 lie on top of one another as do samples 2 and 10.

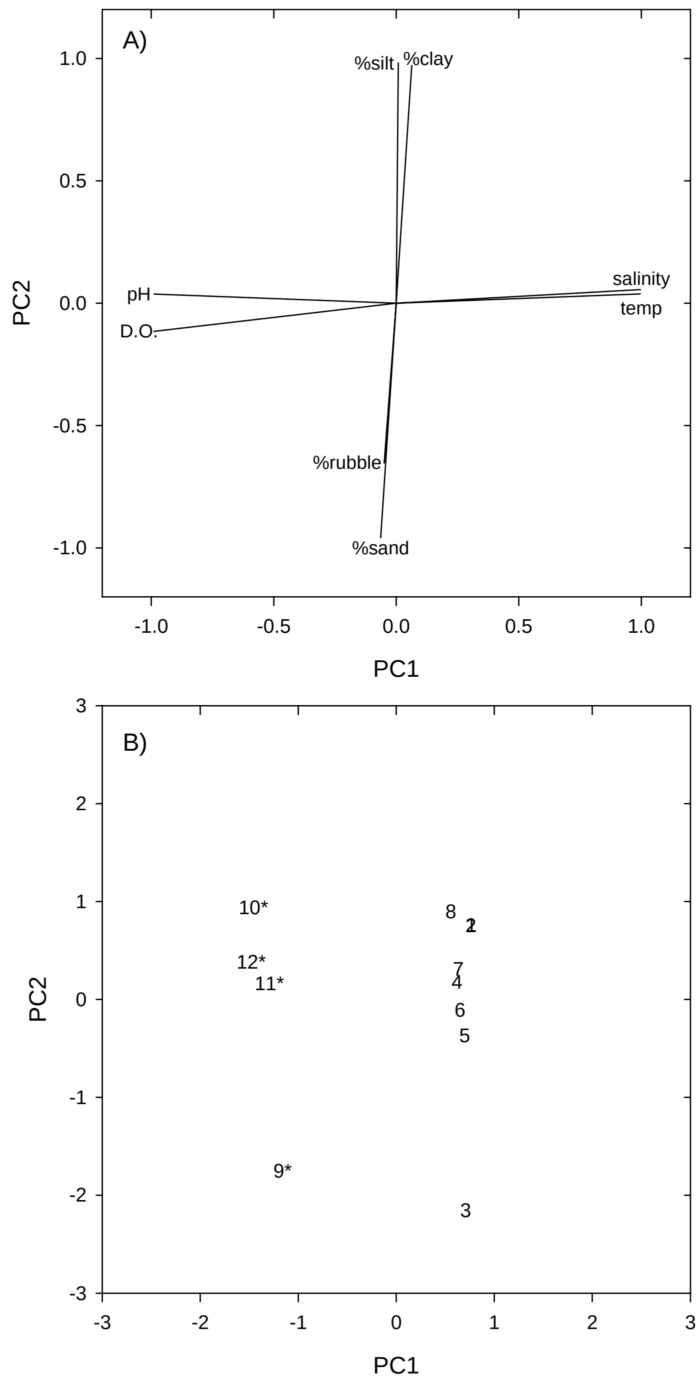

Figure 4. Plots of the first two principal components (PC) resulting from analysis of sediment data. A) PC variable loadings and B) PC station scores. D.O. = Dissolved Oxygen, *denotes that station was sampled on March 2007 rather than June 2006.

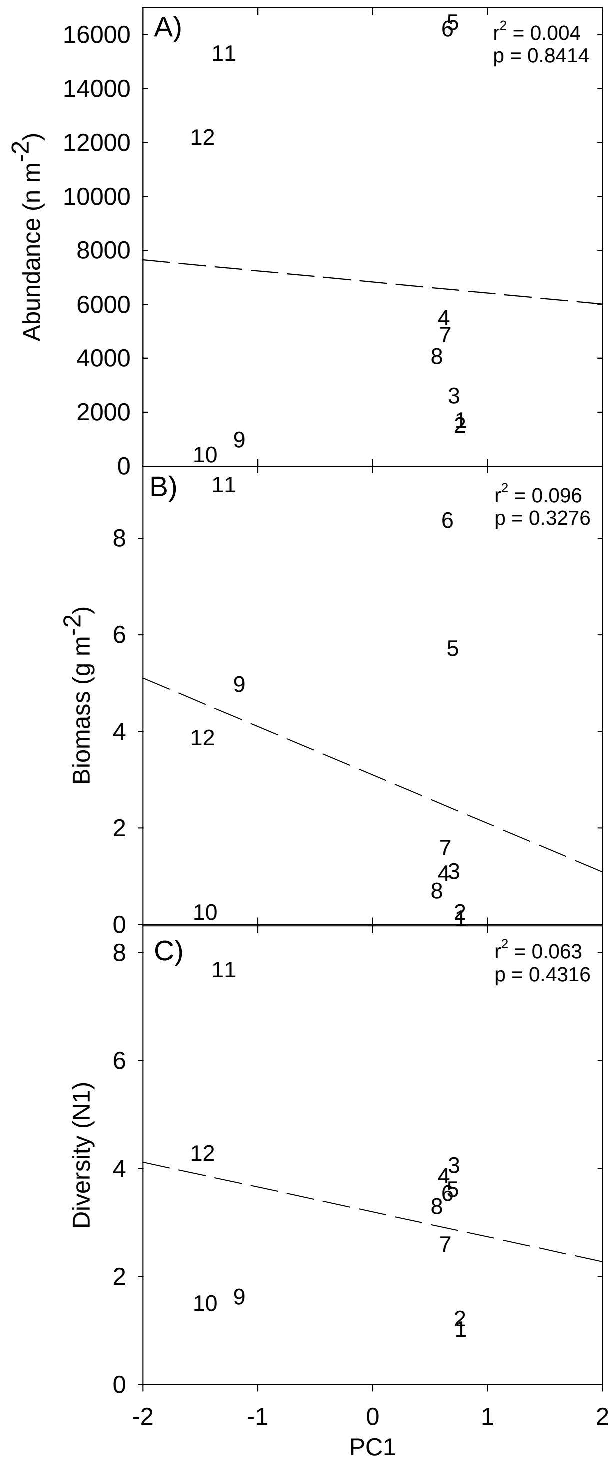

Figure 5. Plots of the first principle component (PC1) versus A) abundance, B) biomass and C) N1 diversity. Dashed line indicates line of best fit.

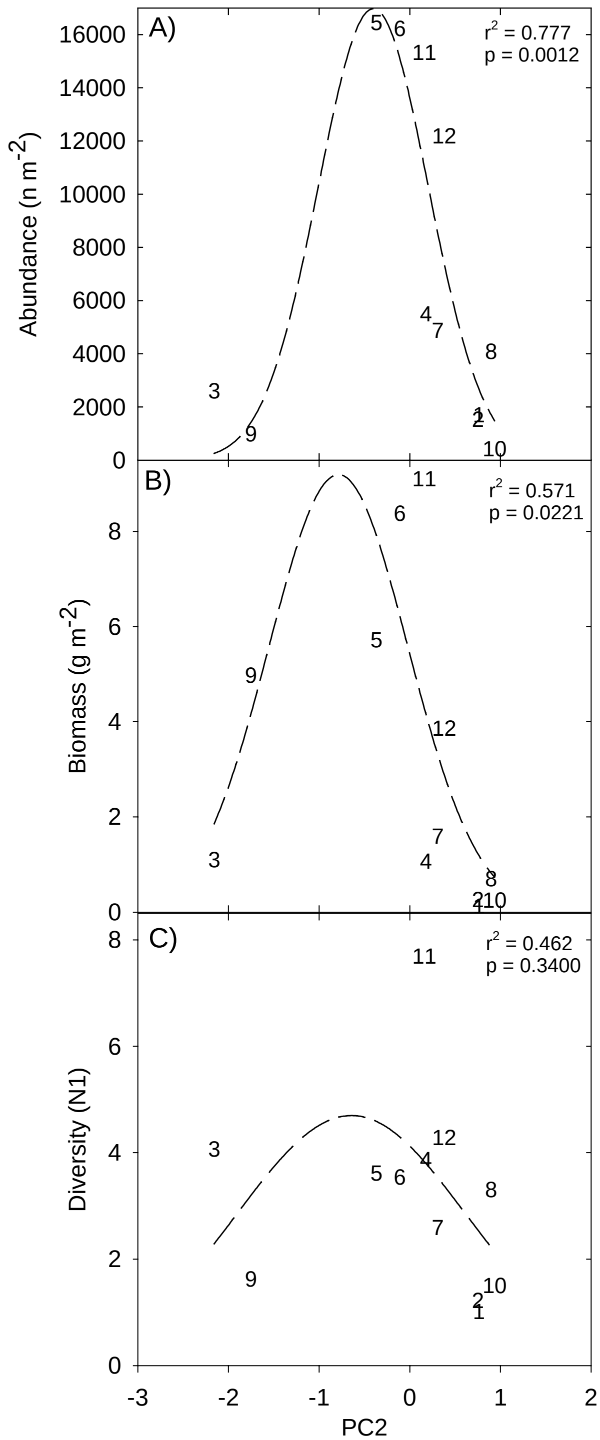

Figure 6. Plots of the second principle component (PC2) versus A) abundance, B) biomass and C) N1 diversity. Dashed line indicates line of best fit.

Appendix: Photographs of Methods

Figure A1 Sieving sediment on a 0.5 mm sieve

Figure A2 Identifying and enumerating macrofauna under a dissecting microscope

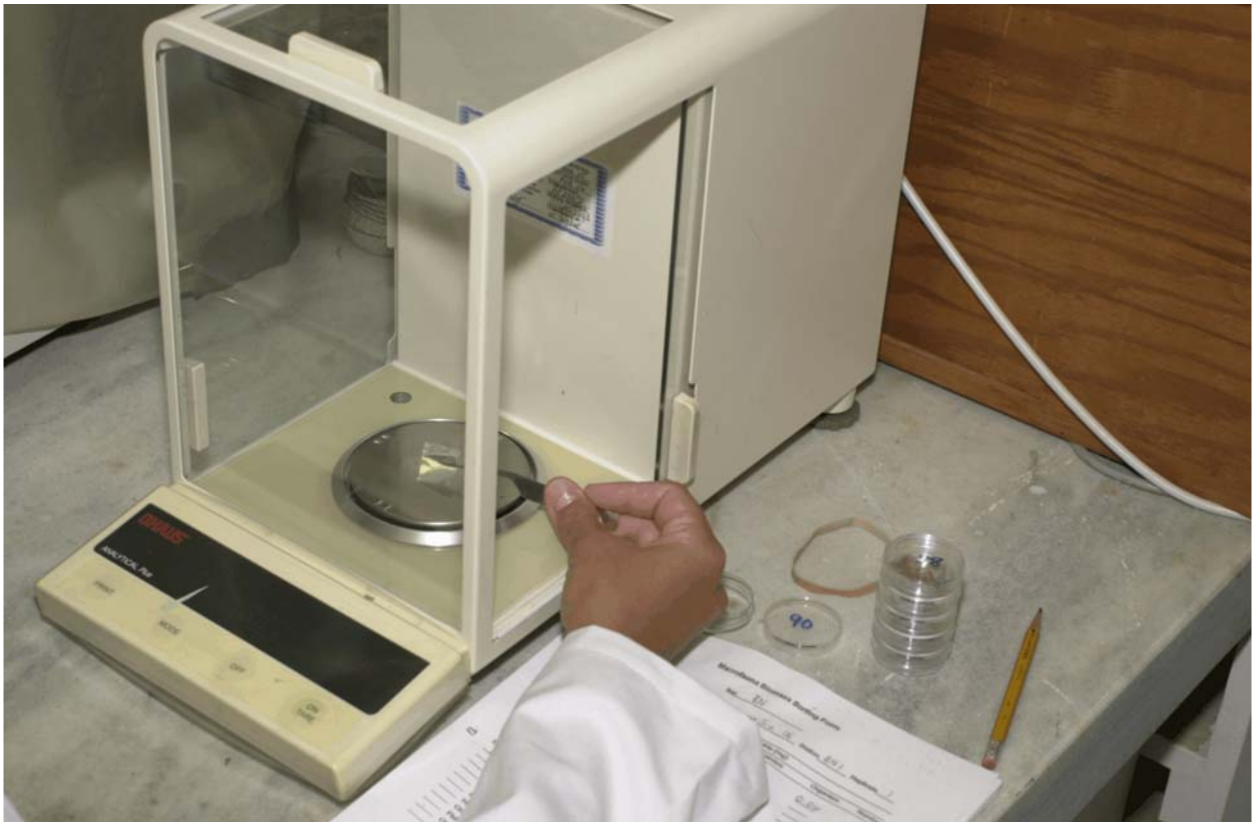

Figure A3 Weighing aluminum trays for biomass measurements

Figure A4 Wet sieving sediment using a vacuum pump and a Millipore Hydrosol SST filter holder

Figure A5 Mixing silt and clay as part of pipette analysis to determine silt and clay contents

APPENDIX D:
REPORT ON THE BIOLOGICAL IMPACTS ON HIGHER TROPHIC LEVELS, UNIVERSITY OF SOUTH ALABAMA

Review of Biological Resources and Water Quality Conditions for the Gulf of Mexico and Atlantic Coasts: implications for biological impacts from dredging of buried sand deposits

Powers, S.P.

Review of Biological Resources and Water Quality Conditions for the Gulf of Mexico and Atlantic Coasts: implications for biological impacts from dredging of buried sand deposits

Prepared by:

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University of South Alabama

Final Report

June 1, 2007

Scope of work

The purpose of this document is to review the existing scientific research (both peer reviewed as well as technical reports) regarding the potential impact to marine biological resources that may result from the dredging of buried sand deposits. Areas targeted for potential sand mining operations consist of mud/fine sand bottom habitats that lack significant topographic features. Consequently, I limit the scope of this review to biological resources in such areas found in nearshore environments (within the 25 m isobath) along the South Atlantic (Florida) and the Gulf of Mexico (Florida to Texas). Because many of the potential impacts of dredging may result from the interaction between changes in seabed geomorphology and water quality (i.e., the probability of stratification and low dissolved oxygen), I also review aspects of water quality conditions over the same region. Because the nature of the disturbance (i.e., changes in bottom habitat) will result in greater impacts to bottom dwelling fauna than to pelagic fauna, the majority of this review focuses on benthic and demersal fish and invertebrates. Contractually, this report is written for completion of task 1.4, *Review of Biological resources and Water Quality Conditions for the Gulf of Mexico and Atlantic,* and the initial phase of task 2.6, *Evaluation of Generic Biological Impacts*, as outlined in the technical proposal prepared for the Minerals Management service by W.F. Baird and Associates. Finally, this review and synthesis is augmented by a detailed assessment of the potential effects of the Holly Beach excavation pit on demersal fish and mobile invetebrates.

Background

As the need to restore and replenish highly eroded areas of the U.S. coastline continues to increase, so does the demand for sand from nearshore areas. Historically, state and local municipalities have relied on sand deposits within state waters to accomplish local beach renourishment projects. As these sand resources become depleted, expansion further offshore into federally managed outer continental shelf areas seas will be necessary to locate suitable sand recourses (Nairn et al. 2004). The extraction of this sand will result in negative impacts to the local benthic community. Because the benthic community represents a critical link in coastal foodwebs, impacts to the benthic community have the potential to radiate out to other components of the ecosystem. Here, I review (1) the linkages between marine benthic communities and demersal fish and crabs, (2) the potential biological and water quality impacts of dredging of sand in areas of the inner continental shelf, and (3) the potential implications of these impacts on biological resources of the Gulf of Mexico and Atlantic coasts.

Linkages between benthic habitats and fisheries

Nearshore areas of the U.S. Gulf of Mexico and Atlantic coasts are highly productive systems that support an abundance of demersal (bottom feeding) and pelagic (water column) species, many of which provide the basis for valuable fisheries (Chesney and Baltz 2001). In 2004, commercial fishermen landed 730 million kg of finfish and shellfish worth $683 million from the Gulf of Mexico. Commercial landings in the South Atlantic were 88 million kg and worth $153 million (National Marine Fisheries Service, 2005). With the notable exception of Gulf and Atlantic menhaden, the majority of these fish and shellfish utilize bottom habitats for feeding and/or shelter at some point in their life cycle (demersal). The rich abundance of benthic invertebrates that reside within (benthic infauna) or on the surface (benthic epifauna) of bottom sediments of the inner continental shelf areas of the Gulf of Mexico and Atlantic coasts provide an abundant and accessible prey base for these demersal consumers. The productivity of this abundant benthic invertebrate community is maintained in turn by riverine or coastal inputs of nutrients and organic matter that stimulate high primary production (Rowe 1971; Turner and Rabalais 1991). Because the input of nutrients and thus primary production decreases with distance from the coast, a distinct gradient of secondary productivity also exists along the shelf regions: secondary production decreases with distance from the shoreline and depth. For example, over 60% of shellfish and almost 1/3 of finfish harvest in the Gulf of Mexico and Atlantic coasts occur within 3 miles of the shoreline (National Marine Fisheries Service, 2005). The vast majority of the remaining shellfish and finfish are harvest between 3 and 200 miles from the coast.

The tight linkages between water column conditions, benthic invertebrates, and demersal fish in nearshore areas provide the mechanism by which changes in water quality or benthic habitat quality are transferred to higher trophic levels (Peterson et al. 2000; Powers et al. 2005). Although the nature of the disturbance event varies, marine benthic communities normally follow a similar trajectory of recovery following a disturbance event. The successional model for benthic communities described by Rhoads et al. (1978), and later illustrated for dredging studies by Newell et al. (1998), describes a series of stages in the recovery of a typical marine benthic community. Following the end of the disturbance, or in the case of chronic disturbance (such as high sedimentation rates) a relaxation of the disturbance event, the benthic community is rapidly colonized by small opportunistic infauna, generally small polychaetes and nematodes). In the absence of disturbance, succession should proceed with small infaunal clams as well as amphipod crustaceans colonizing bottom habitat. During later stages of succession, deeper burrowing, larger invertebrates colonize the habitat and inhibit the settlement of the small opportunistic species. The species composition and duration of different succesional stages may also influence trophic transfer during the recovery process and affect the condition and relative abundance of mobile consumers (Peterson et al. 2000). The benthic community characteristic of early successional stages or those that persist under chronic disturbance provides an ideal food source for small shrimp that feed on deposit feeding polychaetes (Figure 1). During the latter successional stages, bivalve and large tube dwelling polychaetes provide a prey resource for portunid crabs and fishes of the family Sciaenidae (croaker and drums).

The timing and duration of these various successional stages as well as species composition will be dictated by a variety of factors including, larval supply (Santos and Simon 1980; Powers et al., 2002; Lundquist et al. 2004), resuspension of nearby adult populations (Commito et al., 1995; Thrush et al. 2003), local species richness, and the spatial scale of disturbance (Thrush et al. 2005). Chief among these factors are the temporal duration and spatial extent of habitat degradation. Chronic disturbance may cause the benthic community to remain in an early successional stage (dominated by small opportunistic polychaetes). Small scale disturbances (cm – m's) may require relatively short time periods for recovery (days – weeks) because adult migration via passive or active redispersal of macrofauna can facilitate recovery. In contrast, larger scale disturbances (km's) that require larval recruitment to replenish the macrobenthic community will require extended periods of time (months – years) for full recovery to occur.

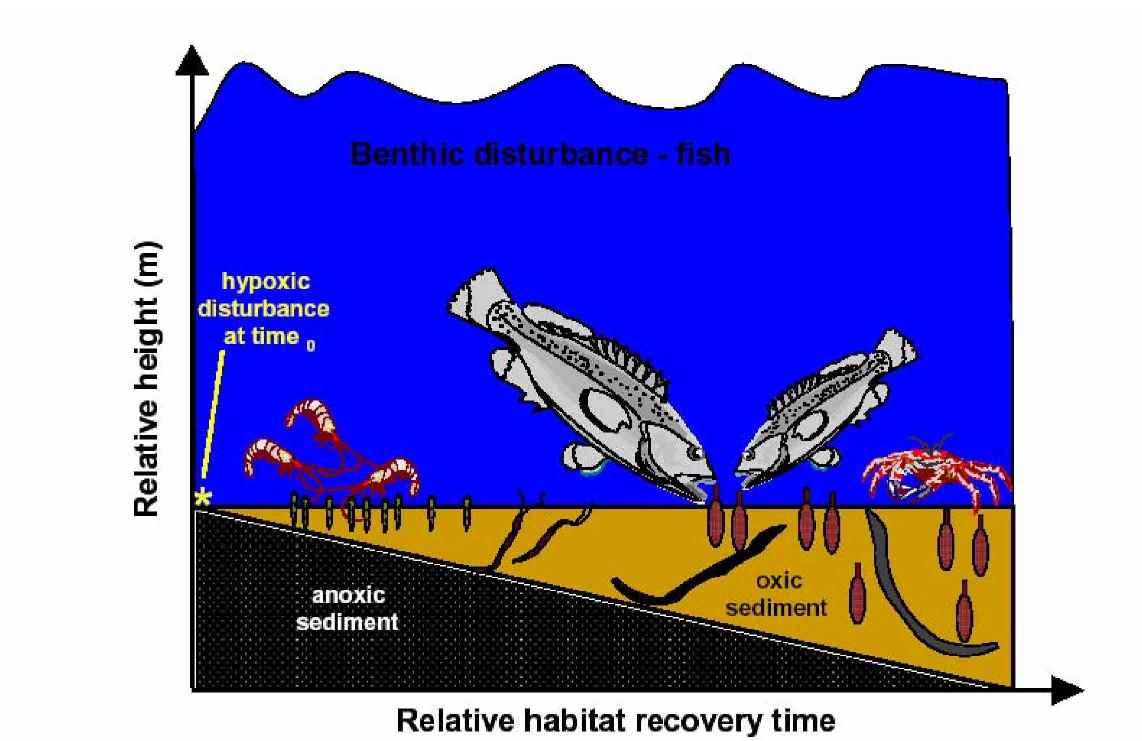

Figure 1. Conceptual diagram of benthic recovery following a disturbance event indicating changes in both benthic infauna and demersal fish and crab communities.

Potential impacts of sand mining on benthic and pelagic resource.

Negative impacts to marine benthic communities that result from dredging marine bottom sediments are well documented throughout estuarine and coastal areas (Hall 1994; Newell et al. 1998, 2004; Boyd et al. 2005). Reductions in species richness of 30 - 70%, individual abundance, and biomass of 40 – 95% are all common impacts of dredging operations (see Table 1). The most pronounced effects of this habitat degradation are usually limited to the immediate vicinity of the dredged area (Newell et al. 2004). Impacts to adjacent, non-dredged areas will vary in relation to the size and advection of any plume created by the dredging activities, the quantity of dredge material discarded in adjacent areas and modification to the local hydrodynamic environment that result from creation of deep pits or channels. The degree to which adjacent area experience elevated suspended solid concentrations in the water column, sediment deposition, organic enrichment from resuspension or discard of dredged sediments will influence the degree of impact. The presence of a dredge plume has been detected at distances from 3 to 8 km away from the actual dredge operation (Dickson and Rees 1998; Hitchcock et al. 2002). In general, adjacent areas will experience substantially less loss of benthic species richness and biomass than dredged areas and this "spill-over" impact will quickly decrease with distance.

Recovery of the benthic community in the dredged area and adjacent non-dredged but impacted areas is of considerable importance when examining the potential for transfer of impacts to other components of the foodweb. The rate of recovery is dependent to a large extent on the type of substrate dredged (Newell and Seiderer 2003), the degree to which the post-dredging substrate matches the original substrate (Newell et al., 1998), the persistence of bathymetric changes (Blake et al. 1996), as well as the spatial scale of disturbance (Thrush et al. 2005). Recovery is relatively easy to assess when the substrate remaining after dredging activities cease is similar to the pre-dredge condition or return to pre-dredge substrate type occurs after some period of particle resorting (Newell et al. 1998). Newell and Seiderer (2003) reviewed 19 dredging studies that examined recovery of the benthic invertebrate community and found that recovery, which was generally defined by 80% return of species richness or biomass, occurred most rapidly (< 1yr) for estuarine and freshwater habitats with muddy substrates. Substrates composed of courser material (sand, gravel or shell material), required an average of 2 – 4 yrs to recover, although a large range (2-12 years) existed (Table 2). Recovery is more difficult to evaluate for dredged areas whose substrate is permanently altered. Changes in sediment type, normally replacement of course material with fine particles, result in substantially different species composition. Because reestablishment of a benthic community similar to the pre-dredging environment does not occur, other metrics (e.g., similar biomass) must be used to gauge "recovery" and the effect of the new community on higher trophic levels must also to be examined and considered (Nairn et al. 2004).

Table 1. Summary of impacts on benthic invertebrate populations within dredged areas for selected studies (from Newell and Seiderer 2003).

LOCALITY	**HABITAT TYPE**	**% REDUCTION AFTER DREDGING**			**SOURCE**
		Species	**Individuals**	**Biomass**	
Chesapeake Bay	Coastal Embayment Muds-sands	70	71	65	Pfitzenmeyer, 1970
Goose Creek, Long Island, NY	Shallow Lagoon Mud	26	79	63-79	Kaplan *et al*, 1975
Tampa Bay, Florida	Oyster shell	40	65	90	Conner & Simon, 1979
Moreton Bay, Queensland, Australia	Sand	51	46	-	Poiner & Kennedy, 1984
Dieppe, France	Sands-gravels	50-70	70-80	80-90	Desprez, 1992
Klaver Bank, Dutch Sector, North Sea	Sands-gravels	30	72	80	van Moorsel, 1994
Lowestoft, Norfolk, UK	Gravels	62	94	90	Kenny & Rees, 1994
Hong Kong	Sands	60	60	-	Morton, 1996
Lowestoft, Norfolk, UK	Sands-gravels	34	77	92	MESL, 1997
Dieppe, France	Sands-gravels	80	90	90	Desprez, 2000
Bayou Texar, Florida	Mud	55	77	-	Lewis *et al*, 2001
North Nab, UK	Gravels	66	87	80-90	Newell *et al*, 2001b; 2003 Hitchcock *et al*, 2002
Area 408, North Sea.	Sandy gravel	0	0	82	Newell *et al*, 2002

Of specific interest for this review is the impact associated with dredging of sand deposits for beach replenishment. Such projects have generally targeted nearby surficial areas of course sand in order to match the grain size of beach sand. Because these surficial areas normally experience high current velocities, accumulation of finer sediment particles is not expected and rapid filling of the excavated pit is anticipated. However, examples of depressions and pits left by dredging activities filling with fine sediments (see Van Dolah et al. 1998 and Blake et al. 1996) and/or not filling after several years (Blake et al. 1996) do exist. In their study of relatively shallow pits (1 to 3 m in depth) dredged from sand sheets off South Carolina, Van Dolah et. al. (1998) found that pits filled in with finer sediment and that this change is sediment composition resulted in an altered benthic community. Blake et. al. (1996) found little or no change in grain size, minimal pit infilling and no clear evidence of change to benthic communities for pits dredged offshore of Tampa Bay from a sand sheet setting for beach nourishment purposes. In contrast to excavation of sandy surficial areas, mining of sand deposits buried under layers of fine sediment particles (mud caps) would be expected to require an extended time period to fill and would likely fill with fine sediments, although these latter sediments would presumably match the adjacent substrates. Sandy pits generally expand and infill through flattening of the pit slopes and may migrate if there is a net direction of sand transport. In contrast, based on their experience with surveying and modeling the Holly Beach dredge pit offshore the west coast of Louisiana, Baird showed that muddy-capped pits evolve differently. These pits feature very little slope change (primarily because of the greater stability of partially consolidated cohesive sediment underwater). Muddy capped pits fill through deposition from the general background turbidity and from erosion of the pit margins (i.e. beyond the pit edge). Given the results of Blake et al. (1996, Van Dolah et al. (1998) and Newell and Seiderer (2003) that changes in bathymetry and sediment type greatly influence the trajectory of recovery for benthic communities, the possibility of negative impacts from mining of buried sand deposits does exist.

Table 2. Summary of recovery time for selected dredging studies (from Newell and Seiderer 2003).

LOCALITY	HABITAT TYPE	RECOVERY TIME	SOURCE
James River, Virginia	Freshwater semi-liquid muds	±3 weeks	Diaz, 1994
Coos Bay, Oregon	Disturbed muds	4 weeks	McCauley *et al*, 1977
Gulf of Cagliari, Sardinia	Channel muds	6 months	Pagliai *et al*, 1985
Mobile Bay, Alabama	Channel muds	6 months	Clarke *et al*, 1990
Chesapeake Bay	Muds-sands	18 months	Pfitzenmeyer, 1970
Goose Creek, Long Island, NY	Lagoon muds	>11 months	Kaplan *et al*, 1975
Klaver Bank, Dutch Sector, North Sea	Sands-gravels	1-2 years (ex-bivalves)	van Moorsel, 1994
North Sea (Area 408)	Sands-gravels	1 year	Newell *et al*, 2002
English Channel (North Nab)	Coarse gravel	>2 years	Newell *et al*, 2001b Hitchcock *et al*, 2002
Dieppe, France	Sands-gravels	>2 years	Desprez, 1992
Lowestoft, Norfolk, UK	Gravels	>2 years	Kenny & Rees, 1994, 1996
Dutch Coastal Waters	Sands	3 years	de Groot, 1979, 1986
Tampa Bay, Florida	Oyster shell (complete defaunation)	>4 years	US Army Corps of Engineers, 1974
Tampa Bay, Florida	Oyster shell (incomplete defaunation)	6-12 months	Conner & Simon, 1979
Boca Ciega Bay, Florida	Shells-sands	10 years	Taylor & Saloman, 1968
Beaufort Sea	Sands-gravels	12 years	Wright, 1977
Florida	Coral reefs	>7 years	Courtenay *et al*, 1972
Hawaii	Coral reefs	>5 years	Maragos, 1979
Area 222 Isle of Wight, English Channel	Gravel	>4 years	Boyd *et al,* 2003

Predicting the overall magnitude of impacts to benthic and demersal biological resources resulting from mining of buried sand deposits is challenging because such impacts will likely vary based on a number of physical factors associated with the dredging operation as well as site-specific environmental variables. Further, differences in the physical recovery between surficial sand deposits and buried sand deposits as illustrated in the previous paragraph limit the applicability of previous studies to the current assessment. Factors likely to be determinants of recovery are the depth of the dredge pit, size of the pit, rate of infilling from the pit, as well as the potential for low dissolved oxygen to occur within the pit. Assuming that fine muds are present above the buried sand and the adjacent area is dominated by similar fine muds (as is the case in many areas of buried sand deposits) differences in sediment grain size between pre and post-recovery conditions are not likely. Over time the pit should fill, however, the time period for this will be determined by the rate of sediment deposition within the pit. A rapid deposition rate will result in a relatively short infilling period, but greatly inhibit benthic fauna from colonizing the area. Conversely, a reduced deposition rate may allow for benthic fauna to colonize the pit throughout an extended recovery period. The persistence of a deep pit may also increase the frequency or duration of low dissolved oxygen events. Because these deep pits have experience limited horizontal and vertical mixing they are prone to stratification and may become hypoxic or anoxic when deposition of organic matter from surface water is high (Stanley and Nixon 1992, Diaz and Rosenberg 1995, Paerl et al. 1998). The occurrence of low oxygen conditions would be expected to further limit the ability of benthic organisms to colonize the recovering area.

Based on the analysis of previous studies of the impact of sand mining on benthic communities as well as inclusion of those issues of particular concern for excavation of buried sand deposits discussed earlier, the biological impacts of dredging buried sand deposits may be separated into six specific areas listed below (see Nairn et al. 2004).

1. Removal of the original substrate and defaunation of the associated benthic community is the most obvious biological impact for both raised topographic and nontopographic deposits. Because the deposits intended for excavation are buried, an impact unique to muddy pits results from dumping of muddy sediment from the stripping process, covering and likely destroying adjacent benthic communities.

2. Water column impacts include elevated levels of TSS during the dredging operation (short term) and the potential for hypoxic (oxygen levels less than 2 or 4

mg/l) anoxic (oxygen levels of 0 mg/l) conditions to develop in the pit (long-term). Eventually, as the pit fills in this impact will be diminished or eliminated.

3. In the case of deep pits, high sedimentation rates may delay or prevent the recovery of the benthic community. High rate of sedimentation will results in constant burial of the benthic organisms that recruit to the area. Although some small, rapidly burrowing invertebrates may survive in such habitats depending on the fluidity of the substrate, overall species diversity and biomass will be suppressed for some time. As the pit fills in, the rate of sedimentation will slow and allow for greater colonization of benthic invertebrates.

4. Another potential biological impact that is unique to dredged pits in muddy deposits is the margin erosion. Benthic organisms that colonize these higher elevation areas formed by the removal and deposition of the mud cap may be subject to erosion and scour. High rates of erosion could prevent establishment of many benthic organisms and prolong recovery. Although this can occur at the margin of sandy pits, it is usually limited to a smaller area and may not occur at all due to the lower mobility of sands compared to muddy sediment for similar depths of water.

5. For pits in relatively sandy settings the main biological concern will be the change in substrate from coarse sand to finer sediment.

6. Finally, impacts to the benthic community could be transferred to other components of the food web. The removal and delayed recovery of the benthic community as a result of sedimentation, erosion or low dissolved oxygen represents a loss of prey base for demersal fish and crabs. Changes in benthic community structure as a result of differing sediment type may also represent a potential loss of feeding opportunities for some demersal consumers, although other consumers may experience enhanced feeding. Further, some areas may have previously served as spawning grounds or habitat for juvenile and adult

stages, the loss and/or degradation of these areas may result in decreased production of these higher trophic levels (Eby et al. 2004; Powers et al. 2005).

Review of relevant water quality conditions in the Gulf of Mexico and Atlantic

The potential for dredged pits to become hypoxic or anoxic exists in many areas of the Gulf of Mexico and Atlantic coasts, particularly for deeper pits in muddy areas near river plumes, and may represent a significant impact to demersal fish and crabs. Low oxygen conditions may develop and be sustained as long as the pit remains below some critical depth where sufficient stratification can occur and be maintained (i.e. without mixing with the water column above). Low dissolved oxygen concentrations are a symptom of declining water quality in a growing number of estuarine and coastal environments worldwide (Cooper and Brush 1991, Diaz and Rosenberg 1995; Paerl et al. 1998, Rabalais et al. 2002). Changing land use patterns (such as riparian wetland conversion and the growth of industrial animal farming operations) and other consequences of increasing human development (such as sewage spills and polluted stormwater runoff) are resulting in increased nutrient (primarily N) loading of coastal waters. This intensifies eutrophication and the frequency, duration, and spatial scale of hypoxic and anoxic events (Officer et al. 1984, Rosenberg 1985, Cooper and Brush 1991, Rabalais et al. 1994). Periods of severe hypoxia and anoxia are a natural result of water column stratification in conjunction with a high sediment oxygen demand caused by the presence of decomposing organic matter (Stanley and Nixon 1992, Diaz and Rosenberg 1995). Meteorological conditions (wind, temperature, large storms) and freshwater runoff directly affect the strength of stratification and, depending on the nutrient load of the runoff, can also stimulate algal blooms (Officer et al. 1984, Seliger et al. 1985). As a large amount of organic matter (phytoplankton and/or terrestrial detritus) sinks and begins aerobic microbial decomposition, the resultant elevated rates of microbial oxygen consumption can cause rapid depletion of dissolved oxygen near the sediment-water interface (Stanley and Nixon 1992, Diaz and Rosenberg 1995, Paerl et al. 1998). When combined with strong water column stratification, which prevents mixing with well-oxygenated surface waters, aerobic degradation in bottom sediments can result in prolonged periods of hypoxia and/or anoxia.

Several nearshore areas of the Gulf of Mexico and Atlantic coasts experience episodic and/or prolonged periods of hypoxia and anoxia due to high levels of primary production coinciding with periods of stratification (Table 3). Hypoxia and anoxia are frequent occurrences in the Northwestern and Central Gulf of Mexico (Texas to Alabama) and shallow bay systems of the entire Gulf of Mexico (e.g., Harper et al. 1981; Diaz and Rosenberg 1995; Ritter and Montagna 1999; Rabalais et al. 2002). Hypoxic and anoxic areas along the Florida coastline are restricted primarily to estuarine areas along the Gulf of Mexico and Atlantic Coast (e.g., Perdido Bay [Livingston 2001]; Ft. Charlotte Harbor [Pierce et al. 2004]; St. John's River [Mason 1998]). Along the U.S. Atlantic coast, hypoxic coastal areas have been reported in the New York bight (offshore New Jersey, Swanson and Parker 1988) and within Long Island Sound (Anderson and Taylor 2001). Small areas of coastal hypoxia may occur near the mouths of major estuaries such as Chesapeake Bay or Pamlico Sound, although the majority of hypoxia occurs within the estuary.

Along both the Gulf of Mexico and Atlantic, hypoxic and anoxic areas are usually associated with river plumes. The most widely cited examples being the influence of the Mississippi and Atchafalaya Rivers on the Louisiana shelf hypoxic zone (Rabalais et al. 1994, 2002) and the influence of the Hudson River plume on the New York bight hypoxic zone (Falkowski et al. 1980; Swanson and Parker 1988). Freshwater inflow is also one of the principal drivers of hypoxia within estuarine systems (Ritter and Montagna 1999; Buzelli et al. 2002). The timing of hypoxic zones reflects the role of freshwater inflow as well as high surface water temperatures. Along the U.S. Atlantic and Gulf of Mexico coastal hypoxic/anoxic bottom zones appear in the summer when high discharge of freshwater from rivers, high atmospheric temperatures and low wind stress enhance water column stratification, although hypoxia on the Louisiana shelf has been reported as early as February and as late in the year as October (Rabalais et al. 2002). Size of the hypoxic area off the Louisiana shelf also appears to be correlated with riverine discharge: years of higher discharge tend to have the largest volume of hypoxic waters (Rabalais et al. 2002). Although variable in size (4,000 – 20,000 km^2 over 1990 –

2001), several areas particularly those west of the Mississippi and Atchafalaya Rivers appear to be within the hypoxic zone in most years (see Figure 2).

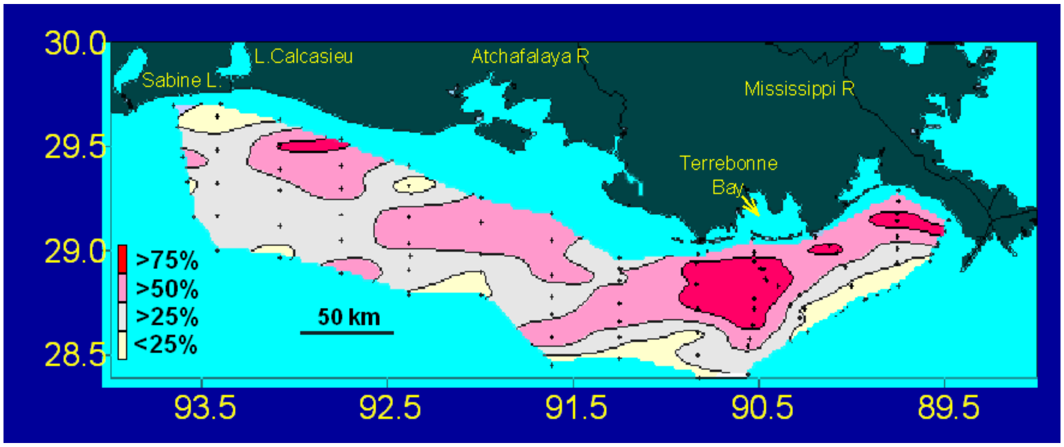

Figure 2. Distribution of the frequency of occurrence of bottom water hypoxia from 1985-2001 (From Rabalais et al. 2002). The map presents the percent of annual surveys conducted in mid-summer where hypoxic conditions were detected at a specific station (black dots). The survey area is restricted to Louisiana coastal waters, hypoxic areas have been reported west of the study area (Harper et al. 1981); however, no annual survey is conducted off the Texas coast.

Review and analysis of biological resources at risk

Direct and indirect effects on benthic invertebrates and demersal fish and invertebrates are likely to result from the dredging of sand deposits (Nairn et al. 2004). Direct impacts include loss of benthic organisms as a result of excavation and/or burial and the delay in recovery as a result of increased erosion, high sedimentation or low dissolved oxygen. Direct impacts to demersal species include loss of foraging habitat, nursery habitat and/or loss of spawning habitat. Because of their mobility several impacts resulting from dredging operation may have relatively minor effects on demersal and pelagic fish. For example fish may avoid areas of increased turbidity during dredge operations thereby reducing there exposure to potentially harmful particles in the water column. However, visual predators that remain in the area may experience decreased foraging success as a result of turbidity (Benfield and Minello 1996). The direct impact of hypoxic or anoxic waters will also vary as a function of mobility of the organism. Mobile consumers of benthic macroinvertebrates usually emigrate out of areas where dissolved oxygen concentrations reach hypoxic levels (Pihl et al. 1991, Rabalais et al. 2001). If low-oxygen conditions are relatively mild, some of these demersal consumers may remain in the area and exploit stunned or moribund benthic prey resources not normally available (Pihl et al.1992, Pihl 1994). Most animals can tolerate some moderate duration of hypoxia (hours to days depending on the species), but few animals can persist for long in anoxic conditions (partly as a response to hydrogen sulfide produced by bacteria in these conditions, which is poisonous). Consequently, fish or crabs that cannot migrate from hypoxic water generally suffer high mortality (Rabalais et al. 2001).

In order to evaluate the potential importance of the possible direct and indirect effects resulting from sand dredging, I assembled a matrix of demersal fish and invertebrate species likely to occur in nontopographic sand/mud habitat along the inner continental shelf of the Gulf of Mexico and Atlantic. Next, I reviewed information regarding their life history and foraging behavior to determine the potential susceptibility of each to one of the three potential impacts: (1) loss and or modification to benthic prey resources, (2) degradation of nursery or spawning area and (3) susceptibility to the bottom water hypoxia (evaluated based on mobility). Information on species distribution, relative abundance and life history was assembled following an extensive review of relevant journal articles, technical reports and agency databases. In the event that specific information was lacking, I relied either upon my knowledge of the species in question or the expertise of colleagues from the National Marine Fisheries Service (MS Laboratory). Potential impacts were ranked as none (no possibility) or on a scale of low, medium or high. A low ranking indicates there is some possibility of an affect on an individual of that species; however, habitat and or foraging preferences would likely result in minimal impacts. In contrast, a ranking of high indicates than individual of that species has habitat or foraging preferences that make it vulnerable to impacts. The ranking does not account for the scale of disturbance, simply the potential for an adverse impact. If the spatial extent of the disturbance is small and sufficient resources area available in the surrounding non-impacted area, then the resulting impact may be inconsequential. Ultimately both the spatial extent of the impact and the mobility of the organisms will largely determine the impact on benthic and demersal animals.

Several groups of fish or invertebrates were classified as susceptible to one of the three categories of impacts. Table 4 lists 154 species of fish and sharks and 40 species of epibenthic (echinoderms) or mobile invertebrates (shrimps and crabs) that are likely to occur along inner continental shelf areas (5 – 30 m). Species distribution data came principally from seven sources: Darnell et al. (1983, 1987), Williams 1984; Murdy et al. (1997) Hoese and Moore (1998) Schwartz (2003) and the National Marine Fisheries Service southeast area monitoring and assessment program (NMFS SEAMAP). NMFS SEAMAP performs semi-annual bottom trawl and long-line surveys in selected areas throughout the Southeast. Information on regional and site specific abundances (CPUE) can be obtained from the SEAMAP data set that extends from 1983 to the present. The majority of fish identified as likely to occur in areas of non-topographic features along the inner shelf were judged to have fairly low susceptibility to the direct impacts of low dissolved oxygen. The majority of these fish and all sharks exhibit sufficient mobility to avoid low oxygen areas. For fish, worm and cusk eels along with tonguefishes probably lack sufficient mobility to escape large areas of hypoxic bottom water, although these species would be expected to have some tolerance to hypoxia of relatively modest duration. In contrast to the majority of fishes, most species of invertebrates were determined to have medium to high risk because of their limited mobility. These classifications could be refined to a greater degree when data on the dynamics of low oxygen water masses in dredged pits (level of oxygen depletion, frequency, and spatial extent) is obtained. Additionally, information regarding the dynamics of low oxygen conditions could also be used to determine the potential for the formation of sulfide compounds in and around pit areas (Cooper and Morse 1996).

Impacts to spawning/nursery grounds are difficult to assess for many taxa because significant gaps exist in our knowledge of the early history of many fish – particularly those of limited commercial or recreational value. Of those species whose life history is reasonably well documented, members of the family Sciaenidae (drums, croakers, weakfish) could potentially be impacted since many of these species utilize offshore and nearshore sandy habitat near tidal inlets to spawn (e.g. Wilson and Nieland 1994;

Roumillat and Brouwer 2004). The majority of sciaenids recruit to estuarine habitats as juveniles, so impact to nursery areas would be minimal with the exception of kingfish and stardrum, which do utilize nearshore habitat as nursery grounds. Several flounder and eel species would also be expected to use offshore sand/mud habitat as nursery grounds; consequently, their potential impact under the spawning/nursery ground category is ranked as medium to high.

The most probable mechanisms by which higher trophic levels are impacted is through the loss prey resources or changes in the prey base (Table 4). This impact occurs directly through removal or burial of sediments during the dredging process. Loss of prey resource may extend for some time in the impacted area due to the occurrence of low dissolved oxygen within the pit and/or high levels of sedimentation inhibiting colonization. While conceptually this linkage is easy to appreciate, quantifying the effect of habitat degradation on mobile consumers is difficult. Bioenergetic approaches that assume static trophic transfer efficiency could be used to translate the loss in benthic organisms to higher trophic levels (French McCay and Rowe 2003). Such an approach requires measurement of the difference in benthic biomass (from either before dredging or from a reference area – biomass after dredging) and uses published estimates of trophic efficiency and demographic rates. Alternatively, direct measurements of changes in consumer diets as a result of habitat degradation could be conducted by sampling demersal consumers at the post-dredging area. Utilizing data collected by Montagana and Palmer (2007) for the Holly Beach excavation pit, we demonstrate how the former approach can be utilized to quantify potential effects of dredge pits on demersal fishes and invetebrates.

Holly Beach Dredge Pit Study: Quantifying potential impacts on demersal fish and mobile invertebrate production.

The most applicable approach to estimate how decreases in benthic biomass will affect demersal fish and mobile invertebrates is the bioenergetic method proposed by French-McCay and Rowe (2003). The method requires several parameters be estimated: (1) decrease in benthic production per unit area, (2) the total area affected, (3) the expected time to no impact is apparent (recovery rate), and (4) a bioenergetic efficiency (or trophic efficiency). For the Holly Beach dredge pit study, we can estimate the decrease in production per unit area utilizing data from Montagana and Palmer (2007). The study measured benthic community structure 38 months after the dredging of buried sand from a mud capped borrow pit. Eight stations were sampled: two sampling stations were located within the pit (stations 1, 2 and 10), two 20 m from the pit edge (stations 4 and 5), one 100 m away from the pit edge (station 6), one 200 m from the pit edge (station 3), and two at least 1 km from the edge of the pit (stations 7 and 8). An additional four station were sampled 47 months after pit exacavation: three were situated outside the pit at distance of 70 m (on a disposal mound), 100 m and 220 m and one inside (Station 10) the excavation pit. Macrobenthic samples were taken at each station, along with hydrographic measurements in the water column and sediment samples. Using the average biomass at stations 3, 6, 7, 8, 11 and 12 as the reference value for a non-dredged area and the average biomass at stations 1, 2 and 10 as the value for dredged sites, the average decrease in benthic biomass resulting from the pit was 94% or 3.78 g m^{-2}. Using the highest and lowest value we can quantify the range of potential benthic degradation. The minimum decrease in biomass is estimated at 57.2% or 0.4 g m^{-2} (using 0.3 g m^{-2} at station 2 or 10 and 0.7 g m^{-2} at station 8) and the maximum at 99% or 9.0 g m^{-2} (using 0.1 g m^{-2} at station 1 and 9.1 g m^{-2} at station 11). Because biomass represents only a measure of current standing stock, biomass would underestimate the degree to which prey is reduced for demersal consumers. Production (P), which takes into account future growth and mortality, can be estimated from standing biomass (B) if there is some prior knowledge of both growth (G) and mortality rates (Z) (Kneib 2003). These vital rate can be related to production with the equation $P = GB \{(e^{G-Z} - 1)/(G-Z)\}$. Several published estimate of P/B relationship exists for benthic macrofauna. Applying a P/B ratio of 2.2 yr^{-1} (based on 120 studies that reported polychaete P/B ratios in Cusson and Bourget 2005 and averaging those that were conducted in mud/sand environments), we can express the potential loss of prey into an annual estimate: average = 8.3 g m^{-2} yr^{-1} with a range of 0.9 g m^{-2} yr^{-1} to 19.8 g m^{-2} yr^{-1}.

For the second data requirement, the total area effected, surveys of the borrow pit can be used to estimate the spatial extent of disturbance. Total surface area of the excavated pit is 190,600 m^2 (Steve Langendyk, pers. comm). Multiplying this to our estimate of benthic productiviton loss, the average loss is 1,582 kg yr^{-1} with a range of 172 to kg yr^{-1} to 3,774 kg yr^{-1}.

Estimating the recovery rate of the benthic community to pre-dredge or reference site values will allow determination of the total loss over multiple years. In their study, Montagana and Palmer (2007) reported decreased abundance, biomass and diversity of benthic infauna within the Holly Beach dredge pit after 38 and 47 months. The original pit was dredged to a depth of 15 to 18 m beneath the sediment surface in April 2003. Post-dredge bathymetry collected 20 months later reported a pit depth of 14.6 m and 11.6 m by June 2006. Based on these observed filling rates and the application of the MISED 3D numerical model, Nairn et al. 2007 predicted complete filling of the pit between 2010 and 2011. If we assume that total recovery of the benthic community will occur when the pit is filled, then the recovery time should be approximately 9 yrs. More than likely, this represents an underestimate of the recovery time because sufficient time will need to elapse for physical sorting of surficial pit sediments to match the pre-existing sediment condition. Montagana and Palmer (2007) noted distinct difference in sediment types between samples collected within the pit and those collected from reference areas. Sediments within the pit were much finer (i.e. more clay) than those at most reference areas. Specifically, clay constituted at least 80% of the sediment in the excavated pit with less than 1% sand. In contrasts, stations located outside the pit had 1 – 69% clay and 5 – 93% sand. Because the bottom area experience relatively low current velocities, sorting of the finer sediments at the pit surface would be expected to proceed slowly. Influence from major tropical storms, a common occurrence during 2004 and 2005, would presumably quicken the process and results in substantial uncertainty in predicting a time to complete sediment matching. If we assume another 2 yrs are required for sorting of sediments to match pre-dredge or reference area sediment grain sizes, the recovery time is 11 yrs. Applying this recovery time to our annual estimate of loss benthic invertebrate production gives a total average loss from the time of dredging of 17,402 kg with a range of 1,892 to 41,415 kg.

This loss of benthic invertebrate production can be expressed in terms of the subsequent higher trophic level (potential loss of demersal fish and mobile invertebrate) by multiplying the benthic invertebrate loss by an ecological or trophic transfer efficiency. Estimates of ecological efficiency, predator production per unit production of prey, for fish and mobile invertebrate predators feeding on invertebrate prey range from 3 – 30 % (McCay and Rowe 2003). Ecological efficiency of 10% is the most commonly applied value (Pauly & Christensen 1995, ECOPATH). Taxonomic (fish vs. non-insect invertebrate) and size differences are key factors in explaining variability in trophic efficiency. Efficiencies are generally higher for non-insect invertebrates than for fish and higher for smaller fish than larger fish. Based on their review of ecological efficiencies, McKay and Rowe (2003) applied a value of 20% for invertebrates and fish < 200 g. They used an efficiency of 10% for fish between 200 and 1000 g and 4% for fish > 1000g. Based on a review of the NMFS SEMAP trawl survey in this area of the Gulf of Mexico, the majority of predators on the polychaete prey base are most likely invertebrates (shrimp and crabs) and juvenile fish (< 200 g). Consequently, the efficiency of 20% is probably more reflective of this predator community. Applying this value to the calculated loss of benthic invertebrate production, the average loss of demersal fish and invertebrate production is estimated at 3,480 kg (0.2 x 17, 402 kg) with a range of 378 to 8,283 kg over an 11 year recovery period. On an annual basis the average loss of demersal fish and invertebrate production would be 316 kg yr^{-1}.

The estimated loss of benthic production and subsequent bioenergetic calculations for equivalency to demersal fish and mobile invertebrates derived from the above data make several assumptions that affect the magnitude of loss. First and foremost, this estimate assumes that all benthic invertebrate production would have been consumed by predators. Although 100% loss to predators is high, benthic invertebrates in soft-sediment habitats that lack structural refuge have been documented to experience extremely high predation rates (e.g., Olafsson et al. 1995). Field and tethering experiments conducted in nearshore areas often demonstrate 90-100% mortality (e.g., Summerson and Peterson 1984; Heck et al. 2003). Hypoxic conditions, which appear in the Holly Beach dredge pit area, approximately once every four years (Rabalais et al. 2002; Montagana and Palmer 2007), would cause considerable mortality and prevent transfer of some fraction of the annual benthic invertebrate production to higher trophic levels (Baird et al. 2004; Powers et al. 2005). Consequently, some fraction of this benthic invertebrate production would be loss periodically whether the pit was dredged or not. A second assumption is that the level of benthic prey reduction is constant throughout the recovery process. It is plausible that biomass may increase over time within the pit as the pit continues to fill reaching values near the reference station prior to complete infilling. This potential overestimate of benthic invertebrate prey loss in later years of the recovery period is balanced to some degree by applying the value measured at 38 – 47 months to the annual loss estimate of prior years. Finally, a critical assumption of this analysis is that predators realize a decrease in food consumption as a result of the loss of benthic invertebrate prey in the excavated pit. Because these demersal predators are mobile, they have the ability to forage in nearby unaffected areas. The assumption that this migration would result in increased densities of predators in surrounding, unaffected areas and hence decreased prey availability for the community is one that needs to be further explored. Studies documenting a similar negative growth response of estuarine demersal fish to benthic defaunation caused by hypoxia provide support for this assumption (Eby and Crowder 2002; Eby et al. 2005; Powers et al. 2005).

Finally, the estimate of loss of benthic production does not compensate the public for the delay in restoring complete functionality of the habitat. In a compensatory context, a discounting factor (usually 3% annually, French-McCay and Rowe 2003) would be used to compensate for this delay and uncertainty in recovery estimates. Application of this discounting factor has substantial implications on recommendations for pit dredging. Figure 3 illustrates loss of production over time with and without the application of the discounting factor. If discounting is used to adjust for the delay in recovery, then shallow pits, even over a greater surface area would be preferential to deeper pits over a smaller surface area because of the longer time necessary for full recovery.

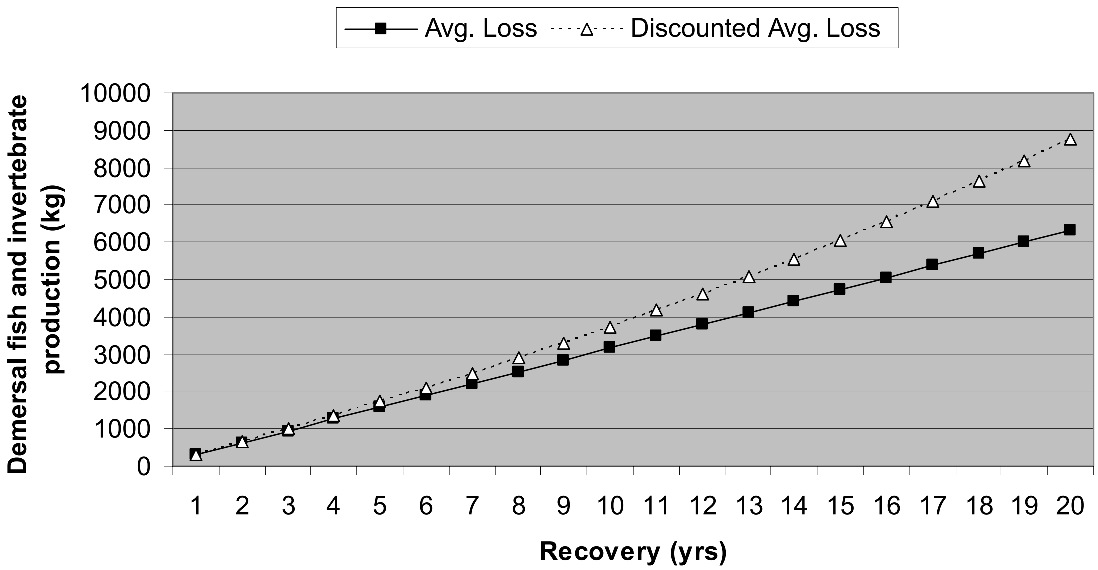

Figure 3. Cumulative estimated loss of demersal fish and invertebrate production resulting from loss of benthic invertebrate production within the Holly Beach dredge pit. Recovery time is estimate at 9-11 years although a wide range is included for illustration.

Our average annual estimate of demersal fish loss is relatively small (316 kg yr^{-1}) when one considers the harvest levels of many of the commercially important species in the area. For example, the harvest of penaeid shrimp from Louisiana coastal waters (including the continental shelf) has averaged around 52 million kg over the last 25 years (National Marine Fisheries Statistics). Although our estimate pales in comparison, it does point to tangible effects of the loss of benthic invertebrate production resulting from the extraction of sand resources from the pit. Below we offer 2 recommendations that would minimize these impacts or minimize the uncertainty associated with the potential impact.

Recommendations

(1) Substantial uncertainty in quantifying the effect of the loss of benthic prey resources exists because the recovery time is not known. Continued monitoring of the Holly Beach pit as well as similar mud-capped pits excavated in the future would greatly aid at decreasing this uncertainty.

(2) The maximum depth of an excavated pit should be based on an anticipated recovery time of less than 5 years. This timing would minimize the loss of ecosystem services and would decrease the uncertainty associated with quantifying effects on biological resources. While twice the bottom area would be potentially impacted, the benefits associated with a more rapid recovery would make this a preferable option to dredging twice the depth and doubling the recovery time.

Table 3. Hypoxic or Anoxic areas along the Gulf of Mexico and Atlantic Coast (excluding estuarine systems).

System	Hypoxic type	Hypoxia level [a]	Areal extent	Reference
Eastern Texas shelf	Aperiodic	Severe- moderate	> 400 km^2	Harper et al. 1981
Louisiana shelf	Seasonal	Severe	20,700 km^2	Rabalais et al. 2002
Chesapeake Bay	Seasonal	moderate-severe		Seliger 1985
New York Bight, New Jersey	Aperiodic	Severe	8,600 km^2	Swanson and Parker 1988
Long Island Sound, New York	Seasonal	moderate	130 km^2	Anderson and Taylor 2001

a Severe - periods of hypoxia or anoxia last for several days or weeks. Moderate - hypoxic conditions occur for relatively short time periods (hours - days).

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic Grouping	**Common Name**	**Foraging Impact**	**Hypoxia Impact**	**Spawn/Nursery Impact**	**Depth Range/ Shelf Distribution[1]**	**Benthic Habitat**
Cartilaginous Fishes						
Ginglymostomatidae	NURSE SHARKS					
Ginglymostoma cirratum	nurse shark	LOW	NONE	NONE	inner shelf	ubiquitous
Caracharhinidae	REQUIEM SHARKS					
Carcharhinus acronotus	blacknose shark	LOW	NONE	LOW	estuary/inner shelf	coarse sand-shell
Carcharhinus brevipinna	spinner shark	LOW	NONE	LOW	estuary/inner shelf	ubiquitous
Carcharhinus isodon	finetooth shark	LOW	NONE	LOW	estuary/inner shelf	ubiquitous
Carcharhinus leucas	bull shark	LOW	NONE	LOW	estuary/inner shelf	ubiquitous
Carcharhinus limbatus	blacktip shark	MED	NONE	LOW	estuary/inner shelf	ubiquitous
Rhizoprionodon terraenovae	Atlantic sharpnose shark	MED	NONE	LOW	estuary/inner shelf/mid shelf	ubiquitous
Sphyrnidae	HAMMERHEAD SHARKS					
Sphyrna tiburo	bonnethead	MED	NONE	LOW	estuary/inner shelf	ubiquitous
Triakidae	DOGFISHES					
Mustelus canis	smooth dogfish	MED	NONE	LOW	estuary/inner shelf	ubiquitous
Mustelis norrisi	Florida smooth hound	MED	NONE	LOW	inner shelf	ubiquitous
Rhinobatidae	GUITARFISHES					
Rhinobatos lentiginosus	Atlantic guitarfish	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Narcinidae	LESSER ELECTRIC RAYS					
Narcine brasiliensis	lesser electric ray	LOW	LOW	LOW	estuary/inner shelf	ubiquitous
Rajidae	SKATES					
Raja eglanteria	clearnose skate	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Raja teevani (Raja floridana)	Caribbean skate	MED	LOW	LOW	inner shelf/mid shelf	ubiquitous
Raja texana	roundel skate	MED	LOW	LOW	inner shelf/mid shelf	ubiquitous
Dasyatidae						
Dasyatis americana	southern stingray	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Dayatis centroura	roughtail stingray	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Dasyatis sabina	Atlantic stingray	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Dasyatis say	bluntnose stingray	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Gymnuridae						
Gymnura micrura	smooth butterfly ray	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Myliobatidae						
Rhinoptera bonasus	cownose ray	MED	NONE	LOW	estuary/inner shelf	ubiquitous

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic Grouping	Foraging Habits	Occurrence (absent/rare/sporadic/common/abundant)	Citation[2]
Cartilaginous Fishes			
Ginglymostomatidae			
Ginglymostoma cirratum	mollusks/crustaceans/urchins/squids/bony fish	ATL/GOM - sporadic	A,E,F
Caracharhinidae			
Carcharhinus acronotus	bony fish	ATL/GOM - sporadic/ FLA common	A,B,C,E,F
Carcharhinus brevipinna	squids/octopus/sharks/bony fish	ATL/GOM - sporadic	A,E,F,G
Carcharhinus isodon	squids/bony fish	ATL/GOM - sporadic	A,E,F
Carcharhinus leucas	mollusks/crustaceans/squids/sharks/bony fish	ATL/GOM - common	A,D,E,F
Carcharhinus limbatus	crustaceans/squids/sharks/bony fish	ATL/GOM - abundant	A,B,C,E,F,G
Rhizoprionodon terraenovae	polychaetes/mollusks/crustaceans/bony fishes	ATL/GOM - abundant	A,B,C,D,E,F,C
Sphyrnidae			
Sphyrna tiburo	mollusks/crustaceans/squids/bony fish	ATL/GOM - common	A,B,C,D,E,F
Triakidae			
Mustelus canis	mollusks/crustaceans/squids/urchins/bony fish	ATL/GOM - abundant	A,B,C,D,E,F
Mustelis norrisi	crustaceans/bony fish	ATL/NEGOM to West GOM - sporadic	A,E,F
Rhinobatidae			
Rhinobatos lentiginosus	crustaceans/bony fish	ATL/GOM - common	A,B,C,E,F
Narcinidae			
Narcine brasiliensis	crustaceans/bony fish	ATL-common/GOM -sporadic	A,B,C,E,F,G
Rajidae			
Raja eglanteria	polychaetes/amphipods/crustaceans/bony fish	ATL/NE GOM - common/NW GOM - rare	A,C,D,E,F
Raja teevani (Raja floridana)	polychaetes/amphipods/crustaceans/bony fish	ATL-absent/GOM-sporadic	D,E,F
Raja texana	polychaetes/amphipods/crustaceans/bony fish	TL-absent/NWGOM-abundant/NEGOM-commo	A,B,C,G
Dasyatidae			
Dasyatis americana	mollusks/polychaetes/crustaceans/bony fish	ATL/GOM - common	A,C,D,E,F,G
Dayatis centroura	mollusks/polychaetes/crustaceans/bony fish	ATL/GOM - common	B,D
Dasyatis sabina	polychaetes/crustaceans/bony fish	ATL/GOM - abundant	A,B,C,D,E,F,C
Dasyatis say	mollusks/polychaetes/crustaceans/bony fish	ATL/GOM - common	A,B,C,D,E,F
Gymnuridae			
Gymnura micrura	mollusks/crustaceans/bony fish	ATL/GOM - common/LA shelf - sporadic	A,B,C,D,E,F
Myliobatidae			
Rhinoptera bonasus	mollusks/crustaceans	ATL/GOM - abundant	A,B,C,D,E,F,C

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic		Foraging	Hypoxia	Spawn/Nursery	Depth Range/	
Grouping	**Common Name**	**Impact**	**Impact**	**Impact**	**Shelf Distribution[1]**	**Benthic Habitat**
Bony Fishes						
Megalopidae	TARPONS					
Megalops atlanticus	tarpon; silver king	LOW	NONE	LOW	estuary/inner shelf	ubiquitous
Elopidae	LADYFISHES					
Elops saurus	ladyfish; skipjack	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Albulidae	BONEFISHES					
Albula vulpes	bonefish	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Muraenidae	MORAYS					
Gymnothorax nigromarginatus	blackedge moray	MED	MED	NONE	estuary/inner shelf	?
Nettastomatidae	DUCKBILL EELS					
Hoplunnis macrura	freckled pike-conger	MED	MED	NONE	inner shelf/mid shelf	?
Congridae	CONGER EELS					
Rhynochoconger flavus	yellow conger	MED	MED	NONE	inner shelf/mid shelf	mud
Ophichthidae	SNAKE EELS					
Myrophis punctatus	speckled worm eel	HIGH	HIGH	?	estuary/inner shelf/mid shelf	mud
Ophichthus gomesi	shrimp eel	HIGH	HIGH	?	estuary/inner shelf/mid shelf	mud
Synodontidae	LIZARDFISHES					
Saurida brasiliensis	largescale lizardfish	HIGH	HIGH	?	inner shelf/mid shelf	ubiquitous
Saurida normani	shortjaw lizardfish	HIGH	HIGH	?	inner shelf/mid shelf	ubiquitous
Synodus foetens	inshore lizardfish	HIGH	HIGH	MED	estuary/inner shelf/mid shelf	sand/mud/shell/grass
Synodus intermedius	sand diver	HIGH	HIGH	?	inner shelf/mid shelf	ubiquitous
Trachinocephalus myops	snakefish	HIGH	HIGH	?	inner shelf/mid shelf	coarse sand
Ariidae	SEA CATFISHES					
Arius felis	hardhead catfish	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Bagre marinus	gafftopsail catfish	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Batrachoididae	TOADFISHES					
Opsanus beta	gulf toadfish	MED	MED	LOW	estuary/inner shelf	sand/mud/shell/grass
Opsanus tau	oyster toadfish	MED	MED	LOW	estuary/inner shelf	sand/mud/shell/grass
Porichthys plectrodon	Atlantic midshipman	HIGH	MED	MED	inner shelf/mid shelf	sand
Gobiesocidae	CLINGFISHES					
Gobiesox strumosus	skilletfish	MED	MED	LOW	estuary/inner shelf	sand/mud/shell/grass
Atennariidae	FROGFISHES					
Antennarius ocellatus	ocellated frogfish	LOW	LOW	?	inner shelf/mid shelf	?
Antennarius radiosus	singlespot frogfish	LOW	LOW	?	inner shelf/mid shelf	?

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic Grouping	Foraging Habits	Occurrence (absent/rare/sporadic/common/abundant)	Citation[2]
Bony Fishes			
Megalopidae			
Megalops atlanticus	bony fish/crabs/shrimp	SEATL/NWGOM-sporadic/NEGOM-common	A,D
Elopidae			
Elops saurus	crustaceans/bony fish	ATL/GOM - abundant	A,D
Albulidae			
Albula vulpes	polychaetes/mollusks/crustaceans/bony fish	SEATL/NEGOM- common/NWGOM-rare	A,D
Muraenidae			
Gymnothorax nigromarginatus	crustaceans/polychetes/mollusks/bony fish	ATL/GOM - common	A,C,G
Nettastomatidae			
Hoplunnis macrura	crustaceans/polychetes/mollusks/bony fish	ATL/NWGOM - common/NEGOM - rare	A,B,C,G
Congridae			
Rhynochoconger flavus	crustaceans/polychetes/mollusks/bony fish	ATL/NWGOM - common/NEGOM - rare	A,C
Ophichthidae			
Myrophis punctatus	polychaetes/amphipods/crustaceans	ATL/GOM - common	A,B,C
Ophichthus gomesi	polychaetes/amphipods/crustaceans	ATL/GOM - common	A,C,G
Synodontidae			
Saurida brasiliensis	crustaceans/bony fish	ATL/GOM - common	A,B,C,G
Saurida normani	crustaceans/bony fish	ATL/GOM - common	A,G
Synodus foetens	crustaceans/bony fish	ATL/GOM - common	A,B,C,D,G
Synodus intermedius	crustaceans/bony fish	ATL/GOM - common	A,B,C
Trachinocephalus myops	crustaceans/bony fish	ATL/GOM - common	A,B,C,G
Ariidae			
Arius felis	polychaetes/crustaceans/bony fish	ATL - common /GOM - abundant	A,B,C,D,G
Bagre marinus	polychaetes/crustaceans/bony fish	GOM-abundant	A,B,C,D,G
Batrachoididae			
Opsanus beta	crustaceans	GOM-abundant	A,C
Opsanus tau	crustaceans	ATL-abundant	A,C,D
Porichthys plectrodon	crustaceans	GOM-common	A,B,C,G
Gobiesocidae			
Gobiesox strumosus	polychaetes/crustaceans	ATL/GOM - abundant	A,C,D
Atennariidae			
Antennarius ocellatus	jellyfish/squid/crustaceans/bony fish	ATL/GOM - sporadic	A,C,G
Antennarius radiosus	jellyfish/squid/crustaceans/bony fish	ATL/GOM - sporadic	A,B,C,G

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic Grouping	**Common Name**	**Foraging Impact**	**Hypoxia Impact**	**Spawn/Nursery Impact**	**Depth Range/ Shelf Distribution[1]**	**Benthic Habitat**
Ogcocephalidae	BATFISHES					
Halieutichthys aculeatus	pancake batfish	LOW	LOW	?	inner shelf/mid shelf	?
Ogcocephalus spp.	batfishes	LOW	LOW	?	inner shelf/mid shelf	?
Gadidae	CODFISHES					
Urophycis cirrata	gulf hake	HIGH	HIGH	?	inner shelf/mid shelf	sand/mud/shell/grass
Urophycis floridana	southern hake	HIGH	HIGH	?	estuary/inner shelf/mid shelf	sand/mud/shell/grass
Urophycis regia	spotted hake	HIGH	HIGH	HIGH	inner shelf/mid shelf	sand/mud/shell/grass
Ophidiidae	CUSK-EELS					
Brotula barbata	bearded brotula	HIGH	HIGH	?	inner shelf/mid shelf	mud
Lepophidium graellsi	blackedge cusk-eel	HIGH	HIGH	?	inner shelf/mid shelf	?
Lepophidium jeannae	mottled cusk-eel	HIGH	HIGH	?	inner shelf/mid shelf	?
Ophidion grayi	blotched cusk-eel	HIGH	HIGH	?	inner shelf/mid shelf	?
Ophidion holbrooki	bank cusk-eel	HIGH	HIGH	?	inner shelf/mid shelf	?
Ophidion welshi	crested cusk-eel	HIGH	HIGH	?	inner shelf/mid shelf	?
Otophidium omostigmum	polka-dot cusk-eel	HIGH	HIGH	?	inner shelf/mid shelf	?
Syngnathidae	PIPEFISHES					
Hippocampus erectus	lined seahorse	LOW	LOW	LOW	estuary/inner shelf	sand/grass/sponge
Hippocampus zosterae	dwarf seahorse	LOW	LOW	LOW	estuary/inner shelf	grass/sponge
Micrognathus criniger	fringed pipefish	LOW	LOW	LOW	estuary/inner shelf	sand/grass/sponge
Syngnathus floridae	dusky pipefish	LOW	LOW	LOW	estuary/inner shelf	grass/sponge
Syngnathus louisianae	chain pipefish	LOW	LOW	LOW	estuary/inner shelf	sand/grass/sponge
Syngnathus scovelli	gulf pipefish	LOW	LOW	LOW	estuary/inner shelf	sand/grass/sponge
Centropomidae	SNOOKS					
Centropomus undecimalis	common snook	LOW	LOW	LOW	estuary/inner shelf	ubiquitous
Moronidae	STRIPED BASSES					
Morone saxatilis	striped bass	MED	LOW	MED	estuary/inner shelf	ubiquitous
Serranidae	SEA BASSES					
Centropristis philadelphica	rock sea bass	LOW	LOW	LOW	inner shelf/mid shelf	sand/mud
Centropristis stiata	black sea bass	LOW	LOW	LOW	estuary/inner shelf	sand/shell
Diplectrum bivittatum	dwarf sand perch	MED	LOW	LOW	inner shelf/mid shelf	sand/shell
Dipelctrum formosum	sand perch	MED	LOW	LOW	inner shelf/mid shelf	coarse sand
Myctoperca microlepis	gag	LOW	LOW	LOW	estuary/inner shelf	nd/shell/grass/structu
Serranus atrobranchus	blackear bass	LOW	LOW	LOW	inner shelf/mid shelf	sand/shell
Serranus subligarus	belted sandbass	MED	LOW	LOW	inner shelf/mid shelf	sand/shell

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic Grouping	**Foraging Habits**	**Occurrence (absent/rare/sporadic/common/abundant)**	**Citation[2]**
Ogcocephalidae			
Halieutichthys aculeatus	crustaceans/bony fish	ATL/GOM - sporadic	A,B,C,G
Ogcocephalus spp.	crustaceans/bony fish	ATL/GOM - sporadic	A,B,C,D,G
Gadidae			
Urophycis cirrata	crustaceans/squid/bony fish	NEGOM/FLA-common/NWGOM-sporadic	A,B,C
Urophycis floridana	crustaceans/squid/bony fish	ATL/GOM-abundant	A,B,C
Urophycis regia	crustaceans/squid/bony fish	ATL-common/NEGOM-common	A,B,C,D
Ophidiidae			
Brotula barbata	polychaetes/crustaceans/bony fish	GOM-common	A,B,C
Lepophidium graellsi	polychaetes/crustaceans/bony fish	GOM-abundant	A,B,C,G
Lepophidium jeannae	polychaetes/crustaceans/bony fish	SEATL-sporadic/NEGOM-common	A,C
Ophidion grayi	polychaetes/crustaceans/bony fish	ATL/NEGOM-sporadic	A,C
Ophidion holbrooki	polychaetes/crustaceans/bony fish	GOM-common	A,B,C
Ophidion welshi	polychaetes/crustaceans/bony fish	ATL/GOM - abundant	A,B,C,G
Otophidium omostigmum	polychaetes/crustaceans/bony fish	ATL/NEGOM-sporadic	C
Syngnathidae			
Hippocampus erectus	zooplankton/crustaceans	ATL/GOM-common	A,C,D,G
Hippocampus zosterae	zooplankton/crustaceans	ATL/GOM-common	A,C
Micrognathus criniger	zooplankton/crustaceans	ATL/NEGOM-sporadic/NWGOM-absent	A,C
Syngnathus floridae	zooplankton/crustaceans	ATL/GOM-sporadic	A,C,D
Syngnathus louisianae	zooplankton/crustaceans	ATL/GOM-abundant	A,C,D
Syngnathus scovelli	zooplankton/crustaceans	ATL/GOM-common	A,C
Centropomidae			
Centropomus undecimalis	crustaceans/squids/mollusks/polychaetes/bony fish	subtropical ATL/GOM-common	A,D
Moronidae			
Morone saxatilis	crustaceans/squids/mollusks/polychaetes/bony fish	ATL-common/GOM-sporadic	A,D
Serranidae			
Centropristis philadelphica	crustaceans/mollusks/squid/bony fish	ATL/GOM-common	A,B,C,G
Centropristis stiata	crustaceans/mollusks/squid/bony fish	ATL/GOM-common	A,B,C
Diplectrum bivittatum	crustaceans/mollusks/squid/bony fish	ATL/GOM-sporadic	A,B,C,G
Dipelctrum formosum	crustaceans/mollusks/squid/bony fish	ATL-common/GOM-sporadic	A,B,C,G
Myctoperca microlepis	crustaceans/mollusks/squid/bony fish	ATL/GOM-common	A,C,D
Serranus atrobranchus	crustaceans/mollusks/squid/bony fish	NEGOM/NWGOM-sporadic	A,B,C,G
Serranus subligarus	crustaceans/mollusks/squid/bony fish	ATL/GOM-common	A,C

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic Grouping	Common Name	Foraging Impact	Hypoxia Impact	Spawn/Nursery Impact	Depth Range/ Shelf Distribution[1]	Benthic Habitat
Pomatomidae	BLUEFISHES					
Pomatomus salatrix	bluefish	MED	LOW	MED	estuary/inner shelf	ubiquitous
Rachycentridae	COBIAS					
Rachycentron canadum	cobia	LOW	LOW	HIGH	estuary/inner shelf	ubiquitous
Carangidae	JACKS					
Caranx hippos	crevalle jack	MED	LOW	LOW	estuary/inner shelf/mid shelf	sand/shell/structure
Chloroscombrus chrysurus	Atlantic bumper	MED	LOW	MED	estuary/inner shelf	ubiquitous
Seriola dumerili	greater amberjack	MED	NONE	NONE	inner shelf/mid shelf	sand/shell/structure
Trachinotus carolinus	Florida pompano	MED	LOW	MED	estuary/inner shelf	sand
Trachinotus falcatus	permit	MED	LOW	MED	estuary/inner shelf	sand
Lutjanidae	SNAPPERS					
Lutjanus campechanus	red snapper	LOW	LOW	LOW	inner shelf/mid shelf	sand/shell/structure
Lutjanus griseus	gray snapper	LOW	LOW	LOW	estuary/inner shelf/mid shelf	nd/shell/grass/structu
Gerreidae	MOJARRAS					
Eucinostomus argenteus	spotfin mojarra	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Eucinostomus gula	silver jenny	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Haemulidae	GRUNTS					
Haemulon macrostomum	Spanish grunt	LOW	LOW	LOW	estuary/inner shelf	nd/shell/grass/structu
Orthopristis chrysoptera	pigfish	MED	LOW	MED	estuary/inner shelf	nd/shell/grass/structu
Sparidae	PORGIES					
Archosargus probatocephalus	sheepshead	MED	MED	MED	estuary/inner shelf	nd/shell/grass/structu
Calamus arctifrons	grass porgy	LOW	LOW	LOW	estuary/inner shelf	nd/shell/grass/structu
Diplodus holbrooki	spottail pinfish	MED	MED	MED	estuary/inner shelf	nd/shell/grass/structu
Lagodon rhomboides	pinfish	MED	MED	HIGH	estuary/inner shelf	ubiquitous
Stenotomus caprinus	longspine porgy	LOW	LOW	LOW	inner shelf/mid shelf	ubiquitous
Sciaenidae	DRUMS					
Bardiella chrysoura	silver perch	HIGH	LOW	HIGH	estuary/inner shelf	ubiquitous
Cynoscion arenarius	sand seatrout	HIGH	LOW	HIGH	estuary/inner shelf	ubiquitous
Cynoscion nebulosus	spotted seatrout	HIGH	LOW	HIGH	estuary/inner shelf	ubiquitous
Cynoscion nothus	silver seatrout	HIGH	LOW	HIGH	estuary/inner shelf	ubiquitous
Cynoscion regalis	weakfish	HIGH	LOW	HIGH	estuary/inner shelf	ubiquitous
Larimus fasciatus	banded drum	HIGH	LOW	LOW	inner shelf/mid shelf	sand
Leiostomus xanthurus	spot	HIGH	MED	HIGH	estuary/inner shelf	ubiquitous
Menticirrhus americanus	southern kingfish	HIGH	MED	HIGH	estuary/inner shelf	sand

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic Grouping	Foraging Habits	Occurrence (absent/rare/sporadic/common/abundant)	Citation[2]
Pomatomidae			
Pomatomus salatrix	bony fish	TL-abundant/NEGOM-sporadic/NWGOM-abse	A,B,C,D,G
Rachycentridae			
Rachycentron canadum	crustaceans/squid/bony fish	ATL/GOM-common	A,C,D,G
Carangidae			
Caranx hippos	crustaceans/squid/bony fish	ATL/GOM-abundant	A,B,C,D,G
Chloroscombrus chrysurus	crustaceans/squid/bony fish	ATL/GOM-common	A,B,C,D,G
Seriola dumerili	crustaceans/squid/bony fish	ATL/GOM-common	A,C,D,G
Trachinotus carolinus	crustaceans/mollusks/squid	ATL/GOM-abundant	A,B,D
Trachinotus falcatus	crustaceans/mollusks/squid/bony fish	ATL/GOM-sporadic	A,D
Lutjanidae			
Lutjanus campechanus	crustaceans/bony fish	ATL/GOM-abundant	A,B,C,G
Lutjanus griseus	crustaceans/bony fish	ATL/GOM-abundant	A,B,C,D
Gerreidae			
Eucinostomus argenteus	epibenthic inverts/polychaetes	ATL/GOM-abundant	A,B,C,D
Eucinostomus gula	epibenthic inverts/polychaetes	ATL/GOM-abundant	A,B,C,D,G
Haemulidae			
Haemulon macrostomum	polychaetes/mollusks/crustaceans/bony fish	ATL-sporadic/FLA-abundant/GOM-abundant	A,C
Orthopristis chrysoptera	polychaetes/mollusks/crustaceans/bony fish	ATL/GOM-abundant	A,B,C,D,G
Sparidae			
Archosargus probatocephalus	mollusks/crustaceans	ATL/GOM-abundant	A,B,C,D
Calamus arctifrons	plants/sponges/hydroids/polychaetes	ATL-rare/NEGOM-common/NWGOM-rare	A,C
Diplodus holbrooki	plants/sponges/hydroids/polychaetes	ATL/NEGOM-abundant/NWGOW-sporadic	A,C,D
Lagodon rhomboides	plants/sponges/hydroids/polychaetes	ATL/GOM-abundant	A,B,C,D,G
Stenotomus caprinus	plants/sponges/hydroids/polychaetes	ATL/NEGOM-rare/NWGOM-common	A,B,C,G
Sciaenidae			
Bardiella chrysoura	crustaceans/polychaetes/bony fish	ATL/GOM-abundant	A,B,C,D,G
Cynoscion arenarius	crustaceans/bony fish	ATL-absent/GOM-abundant	A,B,C,G
Cynoscion nebulosus	crustaceans/bony fish	ATL/GOM-abundant	A,B,C,D,G
Cynoscion nothus	crustaceans/bony fish	ATL/GOM-abundant	A,B,C,D,G
Cynoscion regalis	crustaceans/bony fish/squid	ATL-abundant/GOM-absent	D
Larimus fasciatus	crustaceans	ATL/GOM-abundant	A,B,C,D,G
Leiostomus xanthurus	polychaetes/crustaceans/mollusks	ATL/GOM-abundant	A,B,C,D,G
Menticirrhus americanus	crustaceans/polychaetes	ATL/GOM-abundant	A,B,C,D,G

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic Grouping	**Common Name**	**Foraging Impact**	**Hypoxia Impact**	**Spawn/Nursery Impact**	**Depth Range/ Shelf Distribution[1]**	**Benthic Habitat**
Menticirrhus littoralis	gulf kingfish	HIGH	MED	HIGH	estuary/inner shelf	sand
Menticirrhus saxatilis	northern kingfish	HIGH	MED	HIGH	estuary/inner shelf	sand
Micropogonias undulatus	Atlantic croaker	HIGH	MED	HIGH	estuary/inner shelf	ubiquitous
Pogonias cromis	black drum	HIGH	MED	HIGH	estuary/inner shelf	ubiquitous
Sciaenops ocellatus	red drum	HIGH	LOW	HIGH	estuary/inner shelf	ubiquitous
Stellifer lanceolatus	star drum	HIGH	LOW	HIGH	inner shelf/mid shelf	sand
Mullidae	GOATFISHES					
Upeneus parvus	dwarf goatfish	LOW	LOW	?	inner shelf	?
Ephippidae	SPADEFISHES					
Chaetodipterus faber	Atlantic spadefish	LOW	LOW	?	estuary/inner shelf	ubiquitous
Labridae	WRASSES					
Hemipteronotus novacula	pearly razorfish	MED	MED	?	inner shelf	sand-coarse sand
Mugilidae	MULLETS					
Mugil cephalus	striped mullet	LOW	LOW	LOW	estuary/inner shelf	ubiquitous
Polynemidae	THREADFINS					
Polydactylus octonemus	Atlantic threadfin	MED	MED	MED	estuary/inner shelf	sand
Uranoscopidae	STARGAZERS					
Astroscopus y-graecum	southern stargazer	HIGH	HIGH	HIGH	inner shelf	sand
Blenniidae	COMBTOOTH BLENNIES					
Chasmodes saburrae	Florida blenny	MED	MED	LOW	estuary/inner shelf	sand/grass/shell
Hypleurochilus geminatus	crested blenny	MED	MED	LOW	estuary/inner shelf	sand/grass/shell
Hypsoblennius hentzi	feather blenny	MED	MED	LOW	estuary/inner shelf	mud/grass/shell
Gobiidae	GOBIES					
Bollmannia communis	ragged goby	MED	MED	LOW	estuary/inner shelf	mud
Gobiosoma robustum	code goby	MED	MED	LOW	estuary/inner shelf	sand/mud/grass
Stromateidae	BUTTERFISHES					
Peprilis alepidotus	harvestfish	LOW	LOW	MED	estuary/inner shelf	sand
Peprilis burti	gulf butterfish	LOW	LOW	MED	estuary/inner shelf	sand
Scorpaenidae	SCORPIONFISHES					
Pontinus longispinis	longspine scorpionfish	MED	LOW	LOW	inner shelf/mid shelf	mud
Scorpaena brasiliensis	barbfish	MED	LOW	LOW	estuary/inner shelf/mid shelf	?
Scorpaena calcarata	smoothhead scorpionfish	MED	LOW	LOW	inner shelf	?
Triglidae	SEAROBINS					
Prionotus ophyras	bandtail searobin	MED	LOW	LOW	inner shelf/mid shelf	ubiquitous

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic Grouping	**Foraging Habits**	**Occurrence (absent/rare/sporadic/common/abundant)**	**Citation[2]**
Menticirrhus littoralis	crustaceans/polychaetes	ATL/GOM-abundant	A,B,C,D
Menticirrhus saxatilis	crustaceans/polychaetes	ATL/GOM-abundant	A,C,D
Micropogonias undulatus	polychaetes/crustaceans/bony fish	ATL/GOM-abundant	A,B,C,D,G
Pogonias cromis	crustaceans/bony fish/mollusks	ATL/GOM-abundant	A,C,D
Sciaenops ocellatus	crustaceans/bony fish	ATL/GOM-abundant	A,B,C,D,G
Stellifer lanceolatus	epibenthic crustaceans	ATL/GOM-abundant	A,B,C,D,G
Mullidae			
Upeneus parvus	?	ATL/GOM-common	A,B,C,G
Ephippidae			
Chaetodipterus faber	hydroids/polychaetes/amphipods/jellyfish	ATL/GOM-abundant	A,B,C,D
Labridae			
Hemipteronotus novacula	polychaetes/crustaceans	ATL-sporadic/GOM-common	A,B,C
Mugilidae			
Mugil cephalus	detritus/zooplankton/algae	ATL/GOM-abundant	A,B,C,D
Polynemidae			
Polydactylus octonemus	zooplankton/epibenthic inverts	ATL/GOM-abundant	A,B,C,D,G
Uranoscopidae			
Astroscopus y-graecum	crustaceans/bony fish	ATL/GOM-common	A,B,C
Blenniidae			
Chasmodes saburrae	epibenthic inverts/mollusks/tunicates	ATL-absent/NEGOM-sporadic/NWGOM-absent	A,C
Hypleurochilus geminatus	epibenthic inverts/mollusks/tunicates	ATL/GOM-common	A,C
Hypsoblennius hentzi	epibenthic inverts/mollusks/tunicates	ATL/GOM-common	A,C,D
Gobiidae			
Bollmannia communis	epibenthic inverts/mollusks/tunicates	ATL-absent/NWGOM-sporadic/NEGOM-rare	A,B,C,G
Gobiosoma robustum	epibenthic inverts/mollusks/tunicates	ATL/GOM-common	A,C,D
Stromateidae			
Peprilis alepidotus	jellyfish/crustaceans/polychaetes/bony fish	ATL/GOM-common	A,B,C,D,G
Peprilis burti	jellyfish/crustaceans/polychaetes/bony fish	ATL/GOM-common	A,B,C,D,G
Scorpaenidae			
Pontinus longispinis	crustaceans/bony fish	ATL/GOM-sporadic	A,B,C
Scorpaena brasiliensis	crustaceans/bony fish	ATL/NWGOM-sporadic/NEGOM-common	A,B,C,G
Scorpaena calcarata	crustaceans/bony fish	ATL/GOM-common	A,B,C,G
Triglidae			
Prionotus ophyras	crustaceans/polychaetes/squid	ATL/GOM-sporadic	A,B,C,G

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic Grouping	Common Name	Foraging Impact	Hypoxia Impact	Spawn/Nursery Impact	Depth Range/ Shelf Distribution[1]	Benthic Habitat
Prionotus paralatus	Mexican searobin	MED	LOW	LOW	inner shelf/mid shelf	ubiquitous
Prionotus alatus	spiny searobin	MED	LOW	LOW	inner shelf/mid shelf	ubiquitous
Prionotus rubio	blackwing searobin	MED	LOW	LOW	inner shelf	ubiquitous
Prionotus scitulus	leopard searobin	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Prionotus tribulus	bighead searobin	MED	LOW	LOW	estuary/inner shelf	ubiquitous
Bothidae	LEFTEYE FLOUNDERS					
Ancylopsetta quadrocellata	ocellated flounder	MED	LOW	MED	estuary/inner shelf/mid shelf	ubiquitous
Bothus robinsi	twospot flounder	MED	LOW	MED	inner shelf	ubiquitous
Citharichthys macrops	spotted whiff	MED	MED	MED	inner shelf/mid shelf	coarse sand/shell
Citharichthys spilopterus	bay whiff	MED	MED	MED	estuary/inner shelf	ubiquitous
Cyclopsetta chittendeni	Mexican flounder	MED	LOW	?	inner shelf/mid shelf	ubiquitous
Etropus crossotus	fringed flounder	MED	LOW	MED	inner shelf	ubiquitous
Etropus microstomus	smallmouth flounder	MED	LOW	?	estuary/inner shelf	mud
Etropus rimosus	gray flounder	MED	LOW	?	estuary/inner shelf	ubiquitous
Paralichthys albigutta	gulf flounder	MED	LOW	MED	estuary/inner shelf	sand/grass
Paralichthys dentatus	summer flounder	MED	MED	MED	estuary/inner shelf	ubiquitous
Paralichthys lethostigma	southern flounder	MED	MED	MED	estuary/inner shelf	ubiquitous
Paralichthys squamilentus	broad flounder	MED	LOW	MED	estuary/inner shelf/mid shelf	ubiquitous
Syacium gunteri	shoal flounder	MED	LOW	LOW	inner shelf/mid shelf	ubiquitous
Syacium papillosum	dusky flounder	MED	LOW	LOW	inner shelf/mid shelf	ubiquitous
Soleidae	SOLES					
Achirus lineatus	lined sole	MED	MED	MED	estuary/inner shelf	ubiquitous
Gymnachirus texae	fringed sole	MED	MED	MED	inner shelf/mid shelf	mud
Gymnachirus melas	naked sole	MED	MED	MED	inner shelf/mid shelf	mud
Trinectes maculatus	hogchoker	MED	MED	MED	estuary/inner shelf	ubiquitous
Cynoglossidae	TONGUEFISHES					
Symphurus civitatus	offshore tonguefish	HIGH	HIGH	MED	inner shelf	ubiquitous
Symphurus diomedianus	spottedfin tonguefish	HIGH	HIGH	MED	inner shelf	ubiquitous
Symphurus plagiusa	blackcheek tonguefish	HIGH	HIGH	MED	estuary/inner shelf	ubiquitous
Balistidae	LEATHERJACKETS					
Aluterus schoepfi	orange filefish	LOW	LOW	LOW	estuary/inner shelf	sand/shell/grass
Aluterus scriptus	scrawled filefish	LOW	LOW	LOW	estuary/inner shelf	sand/shell/grass
Balistes capriscus	gray triggerfish	LOW	LOW	LOW	estuary/inner shelf	sand/shell/structure
Monacanthus ciliatus	fringed filefish	LOW	LOW	LOW	estuary/inner shelf	sand/shell/grass

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic		**Occurrence**	
Grouping	**Foraging Habits**	**(absent/rare/sporadic/common/abundant)**	**Citation[2]**
Prionotus paralatus	crustaceans/polychaetes/squid	TL-absent/NEGOM-sporadic/NWGOM-abunda	A,B,C,G
Prionotus alatus	crustaceans/polychaetes/squid	ATL/NEGOM-abundant/NWGOM-absent	A,G
Prionotus rubio	crustaceans/polychaetes/squid	ATL/GOM-common	B,C,D,G
Prionotus scitulus	crustaceans/polychaetes/squid	ATL/GOM-common	A,B,C,D,G
Prionotus tribulus	crustaceans/polychaetes/squid	ATL/GOM-abundant	A,B,C,D,G
Bothidae			
Ancylopsetta quadrocellata	crustaceans/polychaetes/bony fish	ATL/GOM-common	A,B,C,G
Bothus robinsi	crustaceans/polychaetes/bony fish	ATL/NWGOM-absent/NEGOM-sporadic	A,C
Citharichthys macrops	crustaceans/polychaetes/bony fish	ATL/NEGOM-common/NWGOM-rare	A,B,C,G
Citharichthys spilopterus	crustaceans/polychaetes/bony fish	ATL/GOM-abundant	A,B,C,D,G
Cyclopsetta chittendeni	crustaceans/polychaetes/bony fish	ATL-absent/GOM-common	A,B,C,G
Etropus crossotus	crustaceans/polychaetes/bony fish	ATL/GOM-sporadic	A,B,D,G
Etropus microstomus	crustaceans/polychaetes/bony fish	ATL-common/GOM-absent	C,D
Etropus rimosus	crustaceans/polychaetes/bony fish	ATL/NWGOM-absent/NEGOM-sporadic	B,C,D
Paralichthys albigutta	crustaceans/polychaetes/bony fish	ATL/GOM-common	A,B,C
Paralichthys dentatus	crustaceans/polychaetes/bony fish	ATL-abundant/GOM-absent	D
Paralichthys lethostigma	crustaceans/polychaetes/bony fish	ATL/GOM-abundant	A,B,C,D,G
Paralichthys squamilentus	crustaceans/polychaetes/bony fish	ATL/GOM-sporadic	A,B,C,G
Syacium gunteri	crustaceans/polychaetes/bony fish	ATL-absent/GOM-common	A,B,C,G
Syacium papillosum	crustaceans/polychaetes/bony fish	ATL/NEGOM-common/NWGOM-rare	A,B,C
Soleidae			
Achirus lineatus	crustaceans/polychaetes	ATL/GOM-abundant	A,B,C
Gymnachirus texae	crustaceans/polychaetes	ATL/NEGOM-absent/NWGOM-common	A,B,G
Gymnachirus melas	crustaceans/polychaetes	ATL/NEGOM-common/NWGOM-absent	A,C
Trinectes maculatus	crustaceans/polychaetes	ATL/GOM-abundant	A,B,C,D,G
Cynoglossidae			
Symphurus civitatus	crustaceans/polychaetes	ATL/GOM-common	A,B,C
Symphurus diomedianus	crustaceans/polychaetes	ATL/GOM-sporadic	A,B,C
Symphurus plagiusa	crustaceans/polychaetes	ATL/GOM-abundant	A,B,C,D,G
Balistidae			
Aluterus schoepfi	plants/algae	ATL/GOM-common	A,B,C,D,G
Aluterus scriptus	epibenthic inverts	ATL/GOM-common	A,C
Balistes capriscus	crabs/mollusks/sea urchins/corals	ATL/GOM-abundant	A,B,C,D,G
Monacanthus ciliatus	pibenthic inverts/mollusks/polychaetes/sea urchin	ATL/NEGOM-common/NWGOM-absent	A,B,C

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic Grouping	**Common Name**	**Foraging Impact**	**Hypoxia Impact**	**Spawn/Nursery Impact**	**Depth Range/ Shelf Distribution[1]**	**Benthic Habitat**
Monacanthus hispidus	planehead filefish	LOW	LOW	LOW	estuary/inner shelf	sand/shell/grass
Ostraciidae	BOXFISHES					
Lactophrys quadricornis	scrawled cowfish	LOW	LOW	LOW	estuary/inner shelf	sand/shell/grass
Tetraodontidae	PUFFERS					
Lagocephauls laevigatus	smooth puffer	MED	MED	MED	estuary/inner shelf/mid shelf	ubiquitous
Sphoeroides dorsalis	marbled puffer	MED	MED	LOW	inner shelf	ubiquitous
Sphoeroides nephelus	southern puffer	MED	MED	MED	estuary/inner shelf	ubiquitous
Sphoeroides parvus	least puffer	MED	MED	MED	estuary/inner shelf	ubiquitous
Diodontidae	PORCUPINEFISHES					
Chilomycterus schoepfi	striped burrfish	LOW	LOW	LOW	estuary/inner shelf	ubiquitous
MacroInvertebrates						
Shrimps						
Farfantepenaeus aztecus	brown shrimp	HIGH	HIGH	MED	estuary/inner shelf/mid shelf	ubiquitous
Farfantepenaeus duorarum	pink shrimp	HIGH	HIGH	MED	estuary/inner shelf/mid shelf	d/shell-sand/muddy s
Gibbesia neglecta	mantis shrimp	HIGH	HIGH	MED	inner shelf/mid shelf	mud bottoms
Litopenaeus setiferus	white shrimp	HIGH	HIGH	MED	estuary/inner shelf	ubiquitous
Parapenaeus longirostris	deepwater pink shrimp	HIGH	HIGH	LOW	inner shelf/mid shelf	ubiquitous
Sicyonia brevirostris	brown rock shrimp	HIGH	HIGH	MED	estuary/inner shelf/mid shelf	sand/shell-sand
Sicyonia dorsalis	lesser rock shrimp	HIGH	HIGH	LOW	estuary/inner shelf/mid shelf	mud/shell
Sicyonia laevigata	rock shrimp	HIGH	HIGH	LOW	estuary/inner shelf	nud/muddy sand/shel
Sicyonia typica	Kinglet rock shrimp	HIGH	HIGH	MED	inner shelf/mid shelf	and/muddy sand/shel
Solenocera atlantidis	dwarf humpback shrimp	HIGH	HIGH	MED	inner shelf/mid shelf	ubiquitous
Squilla chydaea	mantis shrimp	HIGH	HIGH	MED	inner shelf/mid shelf	mud bottoms
Squilla empusa	mantis shrimp	HIGH	HIGH	MED	estuary/inner shelf/mid shelf	mud bottoms
Trachypenaeus constrictus	roughneck shrimp	HIGH	HIGH	MED	inner shelf/mid shelf	and/muddy sand/shel
Trachypenaeus similis	broken neck shrimp	HIGH	HIGH	MED	inner shelf/mid shelf	and/muddy sand/shel
Xiphopeneus kroyeri	seabob	HIGH	HIGH	HIGH	estuary/inner shelf	ubiquitous
Crabs						
Arenaeus cribrarius	speckled crab	HIGH	HIGH	HIGH	estuary/inner shelf	sand
Calappa flammea	box crab	HIGH	HIGH	HIGH	inner shelf	sand
Calappa sulcata	shame face crab	HIGH	HIGH	HIGH	inner shelf	sand
Callinectes sapidus	blue crab	HIGH	HIGH	HIGH	estuary/inner shelf	ubiquitous

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic		Occurrence	
Grouping	**Foraging Habits**	**(absent/rare/sporadic/common/abundant)**	**Citation[2]**
Monacanthus hispidus	pibenthic inverts/mollusks/polychaetes/sea urchin	ATL/GOM-abundant	A,B,C,D,G
Ostraciidae			
Lactophrys quadricornis	pibenthic inverts/mollusks/polychaetes/sea urchin	ATL/GOM-common	A,B,C
Tetraodontidae			
Lagocephauls laevigatus	ponge/crustactean/sea urchin/polychaetes/hydroid	ATL/GOM-common	A,B,C,D,G
Sphoeroides dorsalis	ponge/crustactean/sea urchin/polychaetes/hydroid	ATL/GOM-sporadic	A,B,C
Sphoeroides nephelus	ponge/crustactean/sea urchin/polychaetes/hydroid	ATL/GOM-common	A,C
Sphoeroides parvus	ponge/crustactean/sea urchin/polychaetes/hydroid	ATL/GOM-common	A,B,C,G
Diodontidae			
Chilomycterus schoepfi	hermit crabs	ATL/GOM-common	A,B,C,G
MacroInvertebrates			
Shrimps			
Farfantepenaeus aztecus	detritus/epiphytes/infaunal inverts	ATL/GOM-abundant	C,D,G,H
Farfantepenaeus duorarum	detritus/epiphytes/infaunal inverts	ATL/NWGOM-abundant/NEGOM-common	C,D,G,H
Gibbesia neglecta	mollusks/crustaceans/bony fishes	ATL/GOM-sporadic	G
Litopenaeus setiferus	detritus/epiphytes/infaunal inverts	ATL/GOM-abundant	C,D,G,H
Parapenaeus longirostris	detritus/epiphytes/infaunal inverts	ATL/GOM-sporadic	D
Sicyonia brevirostris	detritus/epiphytes/infaunal inverts	ATL/NWGOM-common/NEGOM-abundant	C,D,G,H
Sicyonia dorsalis	detritus/epiphytes/infaunal inverts	ATL-common/GOM-abundant	C,G,H
Sicyonia laevigata	detritus/epiphytes/infaunal inverts	ATL/GOM-common	C,D,H
Sicyonia typica	detritus/epiphytes/infaunal inverts	ATL/GOM-common	C,H
Solenocera atlantidis	detritus/epiphytes/infaunal inverts	ATL/GOM-common	D,H
Squilla chydaea	mollusks/crustaceans/bony fishes	SEATL/GOM-common	G
Squilla empusa	mollusks/crustaceans/bony fishes	ATL/GOM-abundant	G
Trachypenaeus constrictus	detritus/epiphytes/infaunal inverts	ATL/GOM-common	C,D,G,H
Trachypenaeus similis	detritus/epiphytes/infaunal inverts	ATL/GOM-common	C,G
Xiphopeneus kroyeri	detritus/epiphytes/infaunal inverts	ATL/NEGOM-sporadic/NWGOM-common	D,H
Crabs			
Arenaeus cribrarius	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-abundant	G,H
Calappa flammea	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-abundant	G,H
Calappa sulcata	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Callinectes sapidus	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-abundant	G,H

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic Grouping	Common Name	Foraging Impact	Hypoxia Impact	Spawn/Nursery Impact	Depth Range/ Shelf Distribution[1]	Benthic Habitat
Callinectes similus	portunid crab	HIGH	HIGH	HIGH	estuary/inner shelf	ubiquitous
Collodes robustus	spider crab	HIGH	HIGH	?	estuary/inner shelf	ubiquitous
Dromidia antillensis	hairy sponge crab	HIGH	HIGH	HIGH	estuary/inner shelf	ubiquitous
Hepatus epheliticus	calico box crab	HIGH	HIGH	HIGH	estuary/inner shelf	sand
Libinia emarginata	portly spider crab	HIGH	HIGH	HIGH	estuary/inner shelf	ubiquitous
Neopanope sayi	mud crab	HIGH	HIGH	MED	estuary/inner shelf	mud/shell/grass
Ovalipes floridanus	Florida lady crab	HIGH	HIGH	?	estuary/inner shelf	sand
Pagurus pollicaris	flatclaw hermit crab	HIGH	HIGH	MED	estuary/inner shelf	ubiquitous
Parthenope granulata	bladetooth elbow crab	HIGH	HIGH	?	inner shelf/mid shelf	ubiquitous
Persephona crinita	pink purse crab	HIGH	HIGH	?	estuary/inner shelf	mud/shell
Persephona mediterranea	mottled purse crab	HIGH	HIGH	?	estuary/inner shelf	mud/shell
Portunus gibbsei	portunid crab	HIGH	HIGH	HIGH	estuary/inner shelf	mud/sand/shell
Portunus spinicarpis	portunid crab	HIGH	HIGH	HIGH	inner shelf	mud/sand/shell
Portunus spinimanus	blotched swimming crab	HIGH	HIGH	HIGH	inner shelf	sand/muddy sand
Starfish						
Luidia alternata	banded sea star	HIGH	HIGH	HIGH	inner shelf/mid shelf	sand
Luidia clathrata	sand star fish	HIGH	HIGH	HIGH	inner shelf/mid shelf	sand
Ophiolepis elegans	elegant brittle star	HIGH	HIGH	HIGH	estuary/inner shelf/mid shelf	ubiquitous

1 Notes: Estuary refers to within semi-eclosed coastal embayments
Inner shelf includes areas from the coastline to the 50 m isobath
Mid shelf includes areas from the 50 m isobath to 500m isobath.

Table 4. Fish and crab species common on nearshore sand/mud bottom habitat in the GOM and Atlantic. Individual susceptibility to one of three potential impacts from sand dredging is estimated on a scale of low to high (see text for details).

Species/Taxonomic Grouping	**Foraging Habits**	**Occurrence (absent/rare/sporadic/common/abundant)**	**Citation[2]**
Callinectes similus	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-abundant	G,H
Collodes robustus	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Dromidia antillensis	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Hepatus epheliticus	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Libinia emarginata	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-abundant	G,H
Neopanope sayi	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-abundant	G,H
Ovalipes floridanus	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G
Pagurus pollicaris	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-abundant	G,H
Parthenope granulata	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Persephona crinita	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-sporadic	G
Persephona mediterranea	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Portunus gibbsei	epiphytes/infaunal inverts/mollusks/crustactans	ATL/NEGOM-common/NWGOM-rare	G,H
Portunus spinicarpis	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Portunus spinimanus	epiphytes/infaunal inverts/mollusks/crustactans	ATL/GOM-common	G,H
Starfish			
Luidia alternata	epiphytes/detritus/mollusks/echinoderms/tunicates	ATL/GOM-common	G
Luidia clathrata	epiphytes/detritus/mollusks/echinoderms/tunicates	ATL/GOM-common	G
Ophiolepis elegans	epiphytes/detritus	ATL/GOM-common	G

1 Notes: Estuary refers to within semi-eclosed coastal embayments
Inner shelf includes areas from the coastline to the 50 m isobath
Mid shelf includes areas from the 50 m isobath to 500m isobath.

2 Citations

A = Hoese and Moore 1998

B = Darnell et al 1983 NWGOM MMS
C = Darnell et al 1987 NEGOM MMS
D = Murdy et al. 1997
E = Schwartz 2003
F = Collette and Klein MacPhee 2002
G = SEAMAP 2004
H = Williams 1984

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APPENDIX E:
SPATIAL AND TEMPORAL DATA FILES