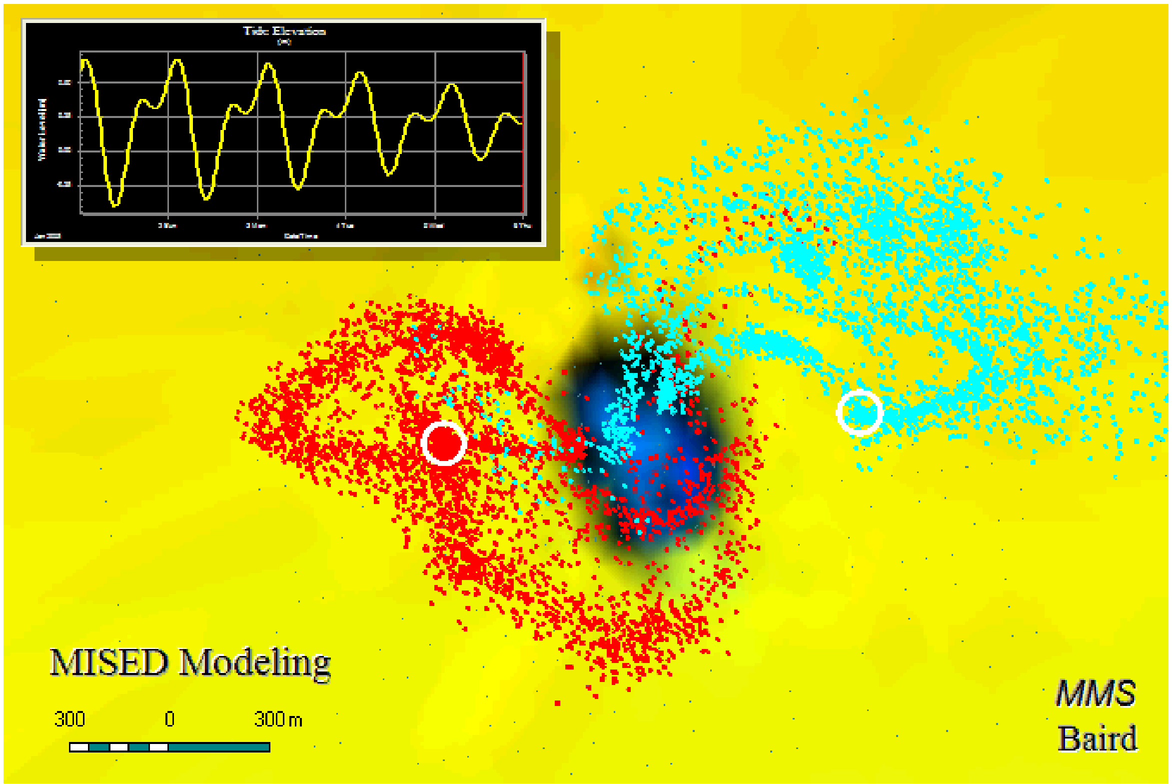
OCS STUDY
MMS 2005-043

A STUDY TO ADDRESS THE ISSUE OF SEAFLOOR STABILITY AND THE IMPACT ON OIL AND GAS INFRASTRUCTURE IN THE GULF OF MEXICO



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U.S. DEPARTMENT OF THE INTERIOR
MINERALS MANAGEMENT SERVICE

U.S. Department of the Interior
Minerals Management Service

OCS Report
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

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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/

The State of Louisiana is looking to MMS to provide access to Federal sand offshore Louisiana for planned barrier island coastal restoration efforts. Material on the OCS represents a prime, compatible source of sand in the volumes required for these efforts. The Louisiana Department of Natural Resources (LA DNR) and the US Environmental Protection Agency (USEPA) have outlined areas on Ship Shoal within which the borrow sites for the New Cut and Whiskey Island projects will be delineated. Geological and geophysical data were collected in 2003 in the support of the design of these borrow sites. The USEPA has identified the South Pelto Block 13 and Ship Shoal Block 88 as the area in which they wish to obtain sand and will identify a more precise location shortly. At the Louisiana Sand Management Working Group (LA SMWG) meeting in New Orleans on 2 February 2005 it was indicated by Syed Khalil of LA DNR that Block 88 had become the preferred deposit for this project. It is planned that sediment for the Pelican Island project will be obtained from the Sandy Point borrow sites off the west flank of the Mississippi delta. At the 2005 LA SMWG meeting Khalil also indicated that only the Southeast borrow deposit at Sandy Point would be targeted owing to the restrictions to the available area for the northeast borrow site associated with a 300 m buffer proposed in a preliminary report by Baird & Associates and Research Planning Inc. (2004).

MMS projects the possible use of 20 to 30 million cubic yards or more of Federal sand offshore Louisiana within the next 5 to 10 years. Offshore sand dredging for beach nourishment projects employ hydraulic dredges almost exclusively, which are normally either cutter-head or hopper-type dredges. Together with other factors (including practicality and cost), the distance from borrow site to the beach or coastal area determines the dredging and sand transport method to be used. Two methods of transport are commonly used: (1) a hydraulic cutter suction dredge pumps the material as a fluidized mass (slurry) through a pipeline from the borrow site to the beach, or (2) a hopper dredge, equipped with drag-heads and a hopper, which extracts and transports the collected sand when the hopper is full to the shore for unloading via an offshore pump out shoreline connection, and subsequent placement on the beach.

Regardless of the dredging method employed, the process removes material and creates a depression in the seafloor. There are numerous oil and gas pipelines, platforms, wellheads, and other oil and gas-related infrastructure present on Ship Shoal, in the vicinity of the Sandy Point borrow deposit, throughout the central Gulf of Mexico, in areas which also represent potential future sources of sand for coastal restoration projects.

Sand and gravel mining will create seafloor topography changes that could affect platforms and pipelines. These effects could be manifested directly as seabed topography is modified by dredging the pit or indirectly due to changes to the pit shape in the future caused by the action of waves and currents, and the associated sediment transport processes.

To limit the effect on platforms, MMS currently requires that mining be restricted to areas that are not likely to alter the platform strength or the future platform removal and site clearance (see the RFP for this project issued by MMS). Since the site clearance is required within one-fourth mile (1320 ft) from the platform, mining activity needs to be limited to areas outside the site clearance zone. MMS has recommended that all mining activity be limited to areas at least 1500 ft from all platforms on the OCS. MMS often stipulates avoidance radii ranging between 300 and 1,000 feet around archaeological locations and anomalies in the Gulf of Mexico (MMS, 2003a, b, 2004)

Presently, there is no set or established avoidance distance or buffer zone for other oil and gas infrastructure relative to planned dredging operations. For the recent dredge test lease issued by MMS within South Pelto Block 13, the Gulf of Mexico Region suggested an avoidance distance of 630 ft. For the projects mentioned above which were analyzed presently in an Environmental Assessment, the MMS Gulf of Mexico Region suggested a minimum avoidance distance of 1000 ft. (MMS, 2004a) This buffer is strictly to avoid contact of the dredge head with the pipeline.

Besides the avoidance issue, however, there exists the larger issue of seafloor stability and the potential effect of removing three or more meters of sediment in an area near oil and gas-related infrastructure. Typically, the removal of three or less meters of sediment has not been considered an issue with respect to the influence on adjacent seafloor stability. The possible issues are disruption of sand transport pathways that may supply sand to areas near pipelines or due to the evolution of the dredged pit shape through migration and/or slope flattening as the pit fills in. Spanning of a pipeline could occur if conditions exist such that an excess amount of sediment is removed from beneath a pipeline. In addition, there have been problems with erosion around some of the platforms in the Gulf of Mexico, in the absence of any dredging activity as cited in the MMS RFP issued for this project. During certain instances, concrete filled bags have been placed around platforms to prevent scour.

1.2 Project Goals

The objective of this study is to address the issue of possible seafloor instability created by dredging borrow pits on the outer continental shelf offshore Louisiana and the potential impact on pipelines and other oil and gas infrastructure.

Specifically, there is a need to address the following scientific questions:

1. How do dredged 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? The answers to these questions will address the extent of possible indirect impacts of dredging on oil and gas infrastructure.

2. Given the findings on the characteristics of dredge pit evolution, what is the most appropriate approach to specifying buffers around oil and gas infrastructure to protect them from damage? There are several possibilities with respect to specifying buffer or avoidance zones:

    2.1 Provide a single buffer distance for all conditions and infrastructure types;

    2.2 Provide different buffer zones for different infrastructure types but without variation for local conditions;

    2.3 Provide recommended buffer zones (following 2.1 or 2.2 above) and methodology to determine whether these can be reduced for given situations;

    2.4 Provide a set of rules for determining buffer zone width based on the various factors related to local conditions and infrastructure types.

1.3 Study Approach

The project approach was comprised of the following three 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 data on environmental conditions both regionally and at each site describing such factors as: bathymetry (different snapshots through time); pipeline routes; satellite images; seabed sediment type and geology; tide levels and currents; and waves and turbidity levels (or total suspended sediment). Key literature reviewed included: specification of buffers for other jurisdictions and agencies; reports and articles associated with the European Community $5 million SANDPIT study on dredged pits that concluded in 2005; information on the characteristics and condition of pipelines in the Gulf of Mexico; a review of underwater slope stability; a contribution by Louisiana DNR on dredged pit stability; and other studies related to dredged pits and channels and their evolution.

2. The second area of study included analysis and numerical modeling of several examples of dredged pits. These included the existing Holly Beach Dredge Pit located offshore western Louisiana in federal waters; the proposed Block 88 borrow site on Ship Shoal and the proposed Sandy Point site offshore the west flank of the Mississippi River delta. Other pits considered in the analysis and review phase were: the Mobile Bay Channel in Alabama; dredged pits offshore Tampa Bay; dredged pits offshore Delray Beach on Florida's southeast coast; dredged pits offshore South Carolina and a dredged channel for a new LNG facility on the Nile River Delta. The analysis and modeling focused on understanding the characteristics of dredged pit evolution for different environmental settings similar to the conditions offshore the Louisiana and central Gulf of Mexico coast.

3. The final phase of the investigation consisted of the interpretation of findings on dredged pit evolution and the development of approaches to specify appropriate and reasonable buffers for oil and gas infrastructure in different settings.

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

- Dick Christensen, Ph.D., Baird & Associates
  Geotechnical Engineer

- Phil Hanley, Environmental and GIS Consultants
  Hydrographic Surveyor

- Mr. John Hines, Pegasus International
  Pipeline Engineer

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

1.5 Report Structure

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

2. Field Survey Results and Review of Background Information
3. Analysis and Numerical Modeling
4. Guidelines for Buffers to Prevent Direct and Indirect Impacts of Dredging
5. Conclusions and Recommendations
6. References Cited

2.0 FIELD SURVEY RESULTS AND REVIEW OF BACKGROUND INFORMATION

This section provides an overview of all the background data collected or surveyed in addition to the literature reviewed.

2.1 Holly Beach Dredge Pit Bathymetry Survey

The Marine Minerals Branch of MMS and LA DNR suggested that a survey of the Holly Beach (or Peveto Channel) Dredge Pit would provide actual field data from a representative Gulf of Mexico site (albeit in state waters) on dredged pit evolution.

Before and after stripping and dredging surveys were completed for the Holly Beach Dredge Pit located in federal waters offshore western Louisiana midway between Calcasieu Ship Channel and Sabine Pass in April 2003 (see Figure 2.1). This pit was located approximately 7 km offshore in 8 m of water. The pit has dimensions of 400 m (alongshore) by 600 m (cross-shore) and was about 8 m deep immediately after dredging. A limited interim survey of the pit was completed by LA DNR in July 2004.

At the suggestion of LA DNR, the Scope of Work for this project was amended to include a new hydrographic survey of the Holly Beach Dredge Pit to provide another snapshot of its continuing evolution. The survey was completed on December 18, 2004 and January 8, 2005 by the firm of Environmental and GIS Consultants (ERIS) under contract to Baird & Associates. The hydrographic survey was completed using dual beam acoustic sounder Odem Mk.3 ECHO-TRACT. The survey vessel sailed from Port Arthur on the first trip and from Calcasieu Pass in Cameron, LA on the second trip. The horizontal 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 0.186 m higher than MLLW.

The hydrographic survey of the Holly Beach Dredge Pit included 57 east-west lines and 42 north-south lines each spaced at approximately 15 m (50 ft) intervals for a total of 48 km. The lines were located so as to re-occupy the post dredge survey lines from April 2003 to allow direct profile comparisons in addition comparisons of surfaces based on data interpolation (see Figure 2.2).

An analysis of the changes to the Holly Beach Dredge Pit through time and numerical modeling of these processes are presented in Section 3.1

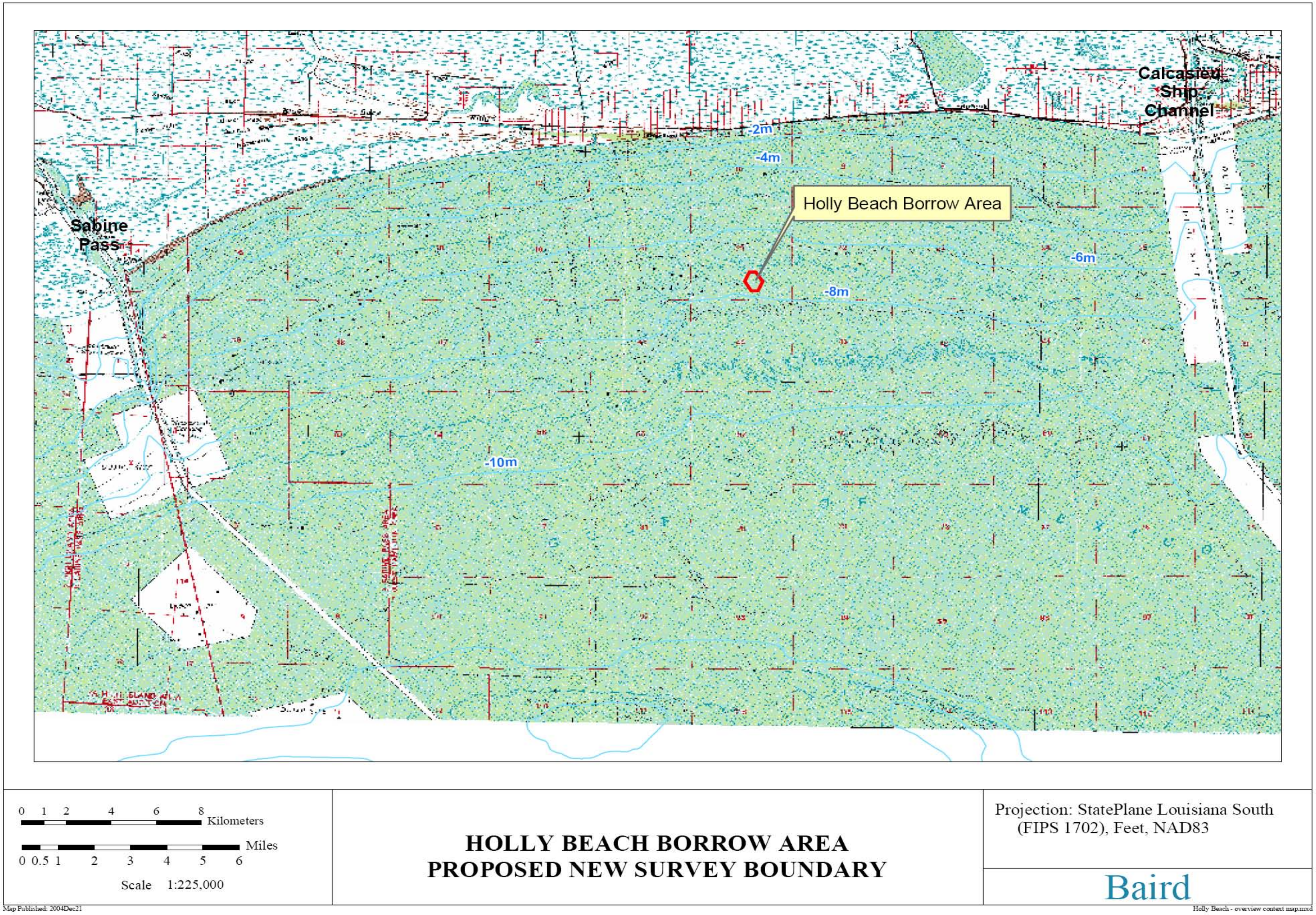
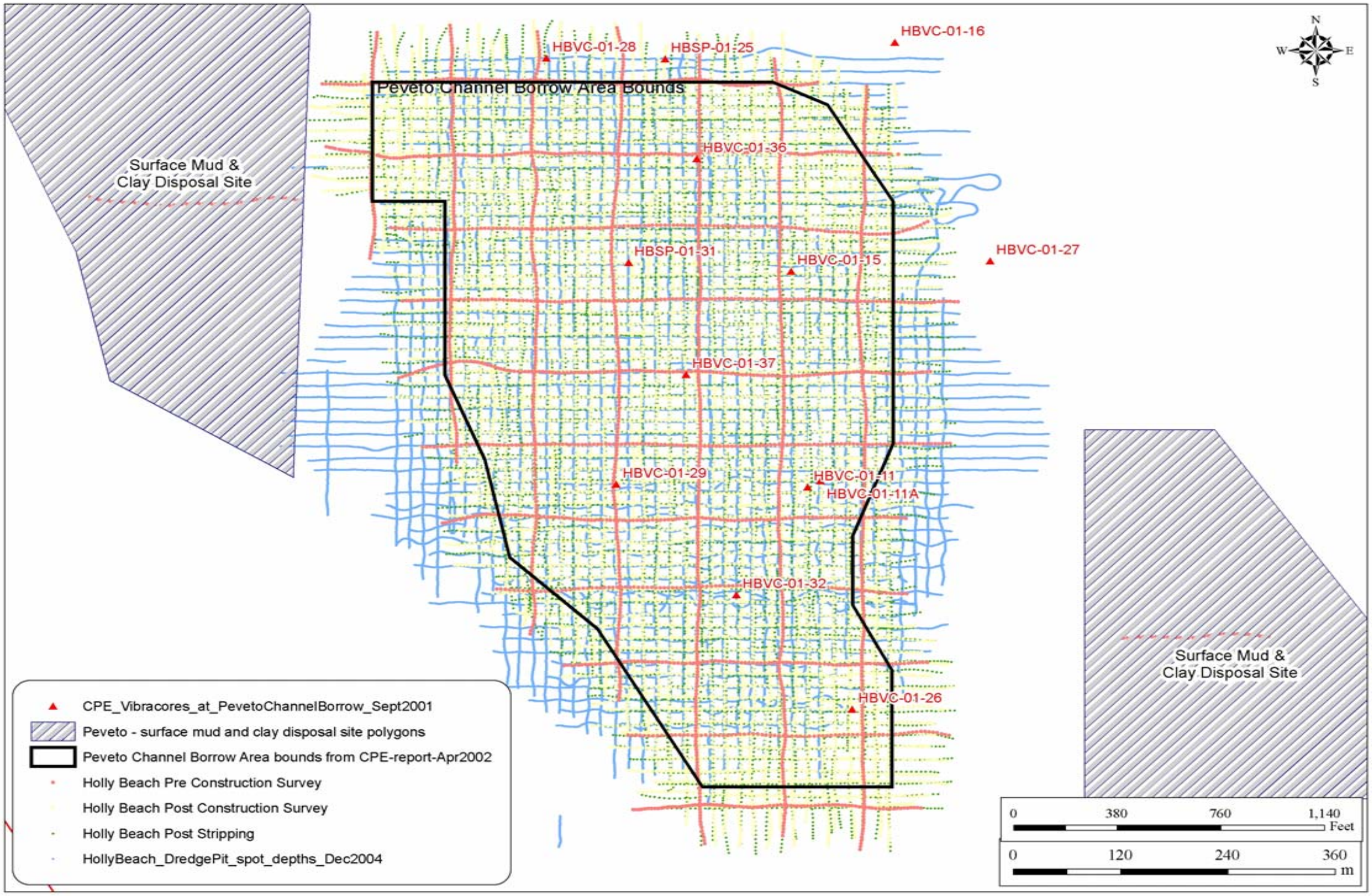


FIGURE 2.1. Location of the Holly Beach Dredge Pit.



All Surveys Overview

Survey Lines for the Recent and Historic Surveys of the Holly Beach Dredge Pit Area.

FIGURE 2.2.

2.1b Existing Spatial and Temporal Data

2.1.1 Spatial Data

During the course of this study spatial datasets were acquired from many different sources. The list below identifies each dataset and provides a brief description.

Pipeline Infrastructure

The website of the MMS Gulf of Mexico Region Products Geographic Mapping Data in Digital Format (http://www.gomr.mms.gov/homepg/pubinfo/repcat/arcinfo/index.html) was the source of the pipelines dataset. The ArcInfo E00 version was updated 17 November 2003 and contains the points and arcs of the pipelines in the GOM, and all pipelines existing in the databases are included.

Federal Lease Blocks

The website of the MMS Gulf of Mexico Region Products Geographic Mapping Data in Digital Format was the source of the Federal lease blocks dataset. The ArcInfo E00 version was updated 24 May 2001 and contains information that defines the Federal lease blocks for the GOM OCS Region.

Bathymetry – Recent

Multiple detailed surveys at the Holly Beach site were conducted by Weeks Marine Inc., including post stripping borrow area, pre-construction borrow area, and post construction borrow area. These datasets were provided to us via Coastal Planning & Engineering, Inc. (CP&E), Boca Raton, Florida. Additionally, a December 2004 survey was conducted at the Holly Beach borrow area by ERIS under contract to Baird & Associates.

For Ship Shoal Block 88 proposed dredge pit area, a survey was provided by C & C Technologies, Inc., Lafayette, Louisiana. The survey, referred to as ‘4036a’ is assumed to have been conducted in May 2002 (no metadata was provided with the spot depths data file) covering an area of about 25,000 feet by 16,000 feet, the survey lines run North-South with a spacing of about 500 feet between transects, and a spacing of about 150 feet between points along a transect.

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 via both a DVD (v 4.1.18) and online Internet web interface to provide multiple surveys from many different time periods. For Holly Beach Pit, the two primary datasets used were:

- 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.

For Ship Shoal Block 88, the primary datasets used were:

- Ship Shoal, NGDC# 03071111, surveyed in 1936, at a mapping scale of 1:40,000. Around the proposed dredge area, the survey lines run North-South with a spacing of about 1000 feet between transects, and a spacing of about 500 feet between points along a transect.
- Caillou Bay, NGDC# 03F11480, surveyed in 1934, at a mapping scale of 1:20,000.

For Sandy Point proposed dredge area, one dataset was referenced:

- A dataset identified as 'Barataria_1979_NOAA_MLLW83 - NOAA Offshore Data (MLLW)' was provided by Coastal Planning & Engineering, Inc. (CP&E) Boca Raton, Florida. This survey was extremely coarse, with the survey line spacing about 2000 feet between transects, and a spacing of about 1000 feet between points along a transect.

Bathymetry – Regional

To provide a quick overview and regional context, a 2 m contour interval bathymetry dataset known as the Louisiana Offshore Bathymetry was used from the Louisiana Oil Spill Coordinator's Office, 1999. The contours were derived from point depths depicted on NOAA Navigation charts, typically relative to 'mean low Gulf' levels.

MODIS Satellite Image

NASA operates two satellites (TERRA and AQUA), each with an instrument called MODIS (Moderate Resolution Imaging Spectroradiometer). One of the imagery products from MODIS is a 250-m resolution image that provides a good view of regional suspended sediments. A MODIS image acquired 27 January 2004 (and several other dates) and covering an area of the Gulf from Texas to Alabama was georegistered to the Louisiana State Plane South coordinate system for use with other datasets and to provide a regional overview.

Mobile Bar Channel, Alabama

Multiple surveys of the Mobile Bar navigation channel were provided by Great Lakes Dredge and Dock Company, Oak Brook, Illinois. The surveys provided before and after dredge surveys for 2004 and 2005. The US Army Corps of Engineers Mobile District office provided before and after dredging surveys.

Bathymetry at Delray Beach, Florida

Spot depth data were provided by Coastal Planning & Engineering, Inc. (CP&E) Boca Raton, Florida. It was indicated that this data was collected at the end of 2002. The data was acquired by Laser Airborne Depth Sounder (LADS), and consisted of over 1.4 million individual spot depths.

Nile River, Egypt LNG Channel Surveys

Bathymetry data were provided by Great Lakes Dredge & Dock for a new LNG facility located in Abu Quir Bay just west of the mouth of the Rosetta branch of the Nile River in Egypt. The data consisted of cross-sections along a newly dredged channel. The data included before and after dredge surveys taken in October 2003 and a later survey to document infilling and channel evolution in April 2004.

Bed Sediment Composition

Bed sediment composition was downloaded from NGDC, NOAA
(http://map.ngdc.noaa.gov/website/mgg/deck41/viewer.htm or from:
http://mysticplum.colorado.edu/aims/website/ngom/viewer.htm).
It shows that the nearshore sea bed in the vicinity of the Holly Beach pit is composed of mud, the bed at the proposed Sandy Point pit is composed mostly of mud with some sand, and the bed at the proposed Block 88 and South Pelto pits on Ship Shoal is composed of sand (see Figure 2.3). In general, the sea bed is muddy offshore the Louisiana coast.

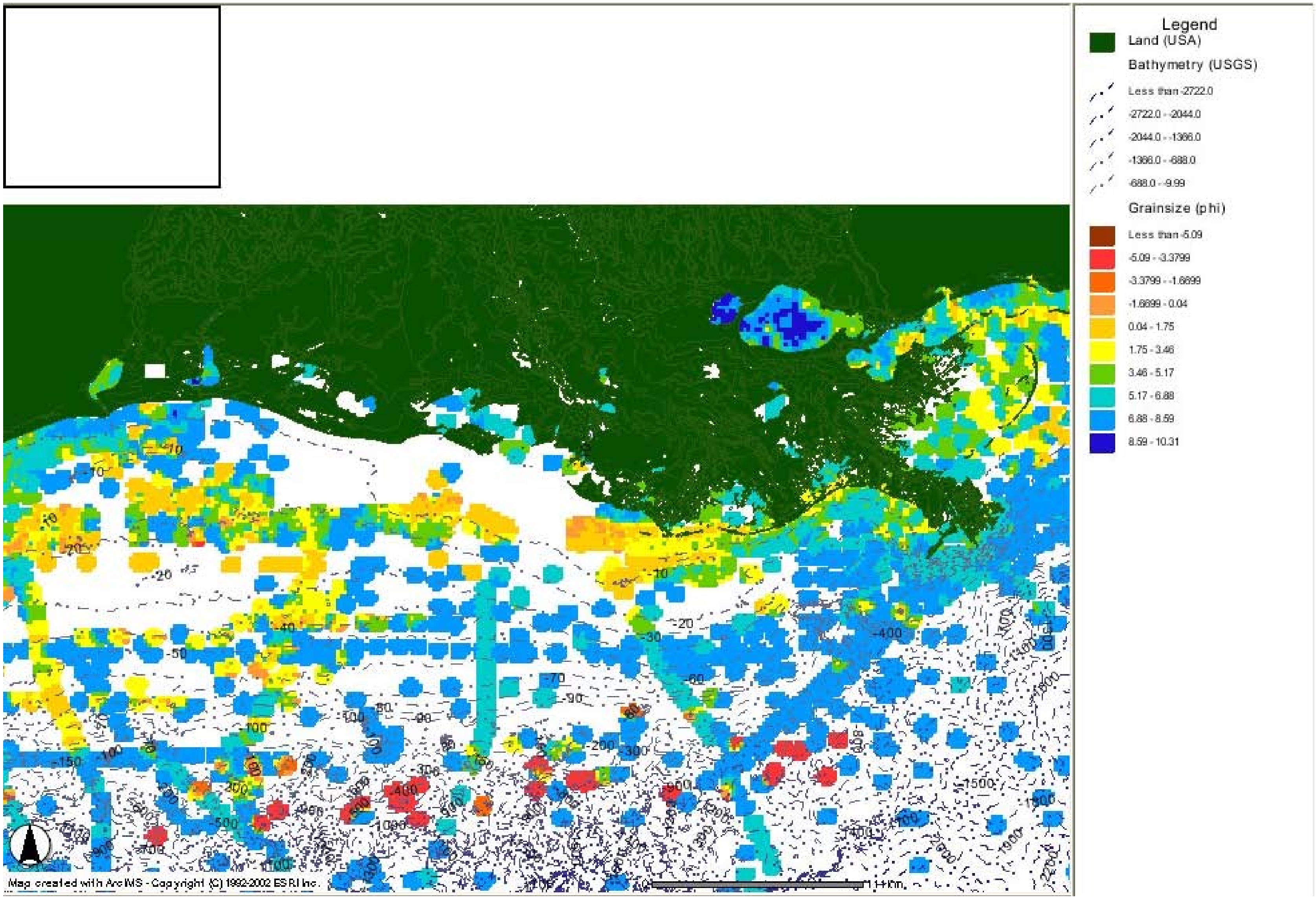


FIGURE 2.3. Sea Bed Sediment Texture (Phi Units) Offshore Louisiana

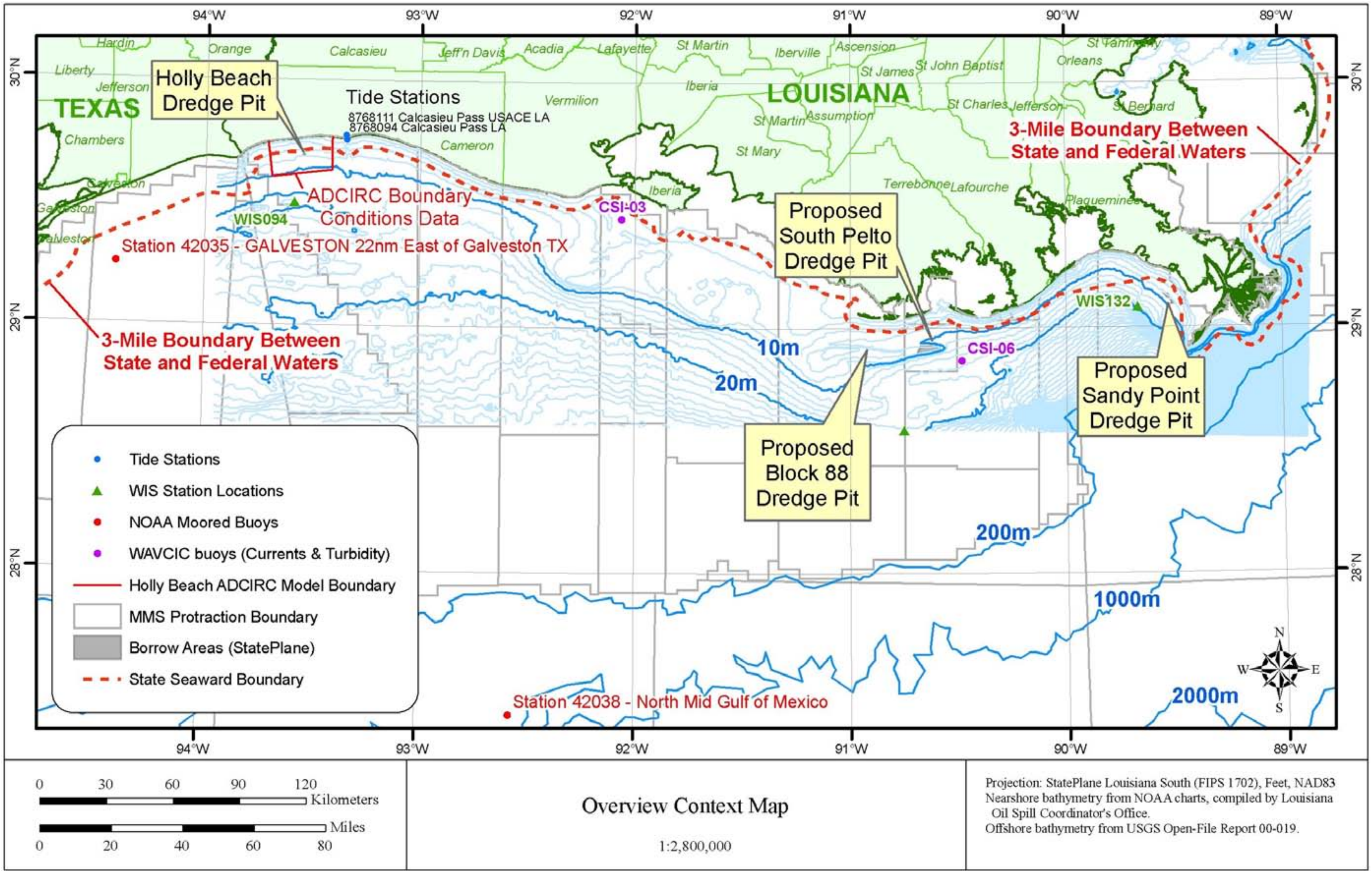
(From: http://mysticplum.colorado.edu/aims/website/ngom/viewer.htm).

2.1.2 Temporal Data

Various temporal datasets were collected from a variety of sources, including:

- River flow and sediment load for the Mississippi River from USGS gages;
- Climatology, waves, tides, and sediment load from two WAVCIS stations;
- Tide level and current information from the US Army Corps of Engineers ADCIRC model;
- Currents and surface temperature from Navy Coastal Ocean Model (NCOM), Naval Research Laboratory;
- Total suspended sediment sampling from NOAA cruise survey reports.

The locations of many of these stations are shown in Figure 2.4.



Locations of Temporal Data Used in the Investigations.

FIGURE 2.4.

Tide Levels and Currents

Tide level and tide current data were derived from:

- Tidal constituents extracted from the ADCIRC model at the Holly Beach pit;
- Hourly tide levels (water depth) measured at WAVCIS CSI-03 station from 2001 to 2004;
- Hourly tidal currents measured at WAVCIS CSI-03 station from 2001 – 2002;
- 36 hour trajectories of surface flows predicted by NOAA NCOM;
- ADCP measurements of currents in the vicinity of the Mississippi River mouth and delta by NOAA.

The tidal constituents at the Holly Beach borrow pit site were extracted from the existing ADCIRC model and provided to Baird (personal communication, Mitch Brown, ERDC-USACE) and indicate that 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 tide levels calculated using the tidal constituents for a selected two-month period are shown in Figure 2.5. The Louisiana coast is microtidal with a mean tide range of about 0.6 m. Figure 2.6 shows the water depths measured at WAVCIS Station 3 over the period of record.

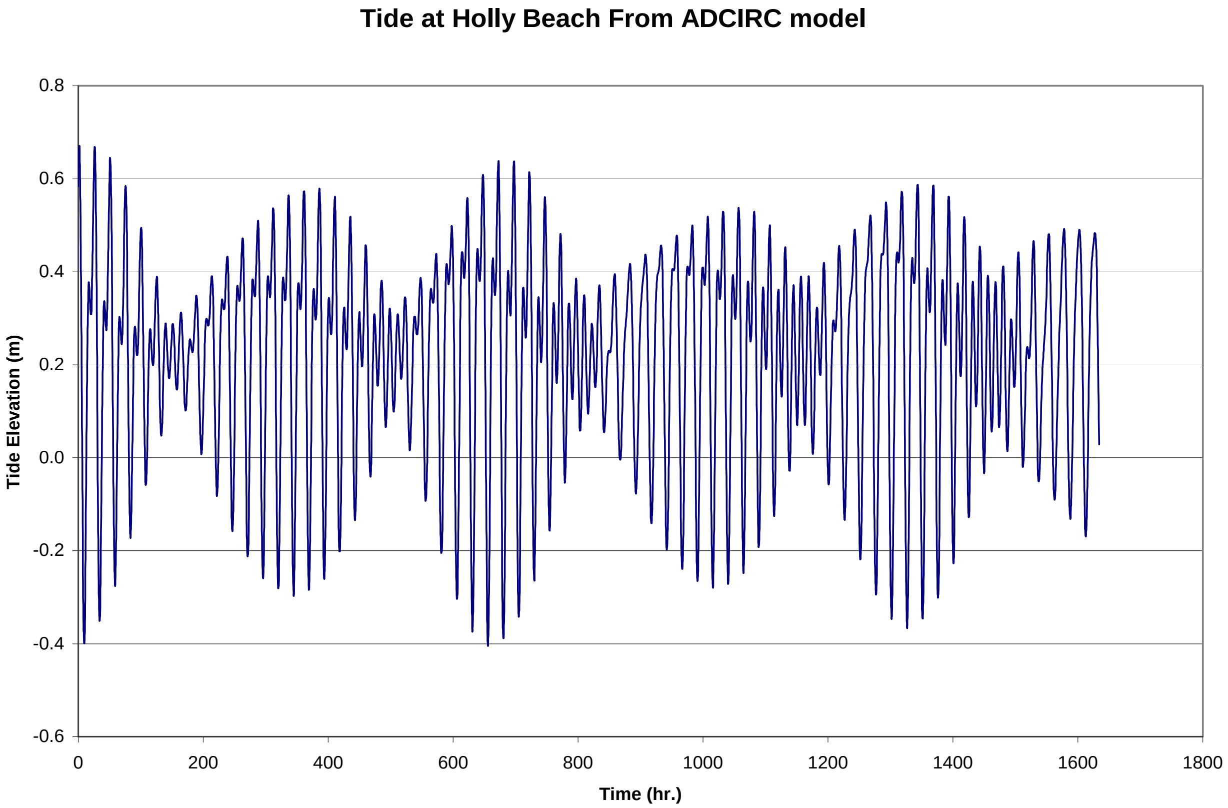


FIGURE 2.5. Tide Levels at Holly Beach from the USACE ADCIRC Model.

Correspondingly, the tidal currents in the Gulf of Mexico are weak. The measurements at WAVCIS Station 3 (average water depth of 5 m) from 2001 to 2002 indicate that the average flow velocity is about 0.3 m/s under normal weather conditions (see Figure 2.7) but that the current speed can peak in the range of 0.6 to 1.4 m/s due to wave and wind-driven contribution to the currents. The NOAA NCOM results indicate that the tidal current trajectory at the surface is mainly towards the west (see Figure 2.8), which implies that the net (or residual) current along the Louisiana coast is towards the west. NCOM results also show that the current speed near the shore is generally similar to that measured at WAVCIS Station 3.

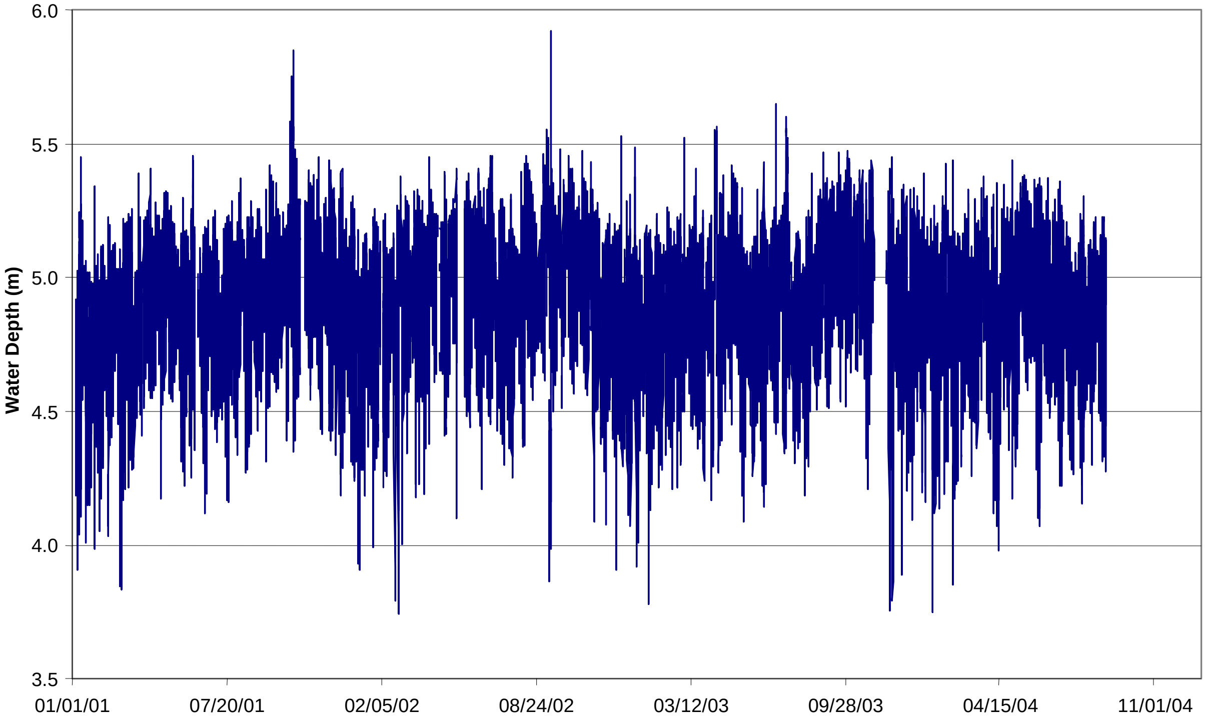


FIGURE 2.6. Water Depths Measured at WAVCIS Station 3.

ADCP current data measured around the mouth and delta of the Mississippi River were found in a NOAA AVHRR image (see Figure 2.9). There is no detailed information about the ADCP measurements (when and at what depth the measurements were made). Nevertheless, the data shows that there is a large eddy in the lee of the west flank of the Mississippi River delta, where the proposed Sandy Point borrow pit is located. The current speed in that area is in the range of 0.1 to 0.5 m/s.

Figure 2.9b shows water temperature from satellite images together with NOAA drifter tracks (from the Coastal Studies Institute of LSU). The drifter tracks show the net westerly residual current that exists along the Gulf coast west of the Mississippi River delta (see also Figure 2.8).

Waves

Several sources are available for wave information offshore Louisiana. The data sets include:

- Wave measurement at WAVCIS Station 3 from 2001 to 2004;
- Wave information along the Louisiana coast from the WIS hindcast data base of the US Army Corps of Engineers (USACE) from 1980 to 1999 (http://frf.usace.army.mil/wis/);
- Wave measurements at NOAA's NBDC buoys;
- Wave distribution images produced from images of several satellites including TOPEX-POSEIDON

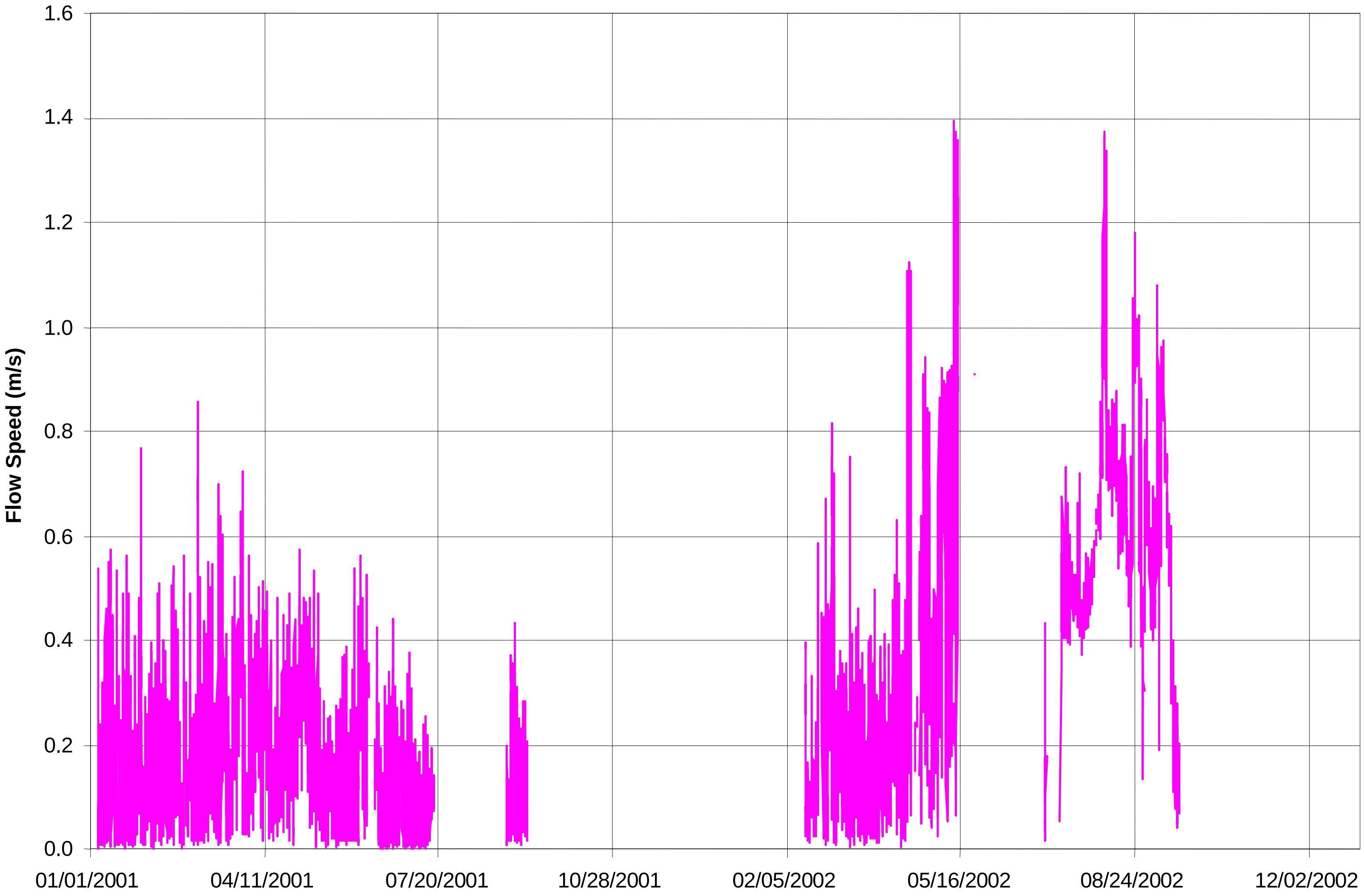


FIGURE 2.7. Current Speed Measured at WAVCIS Station CSI-3.

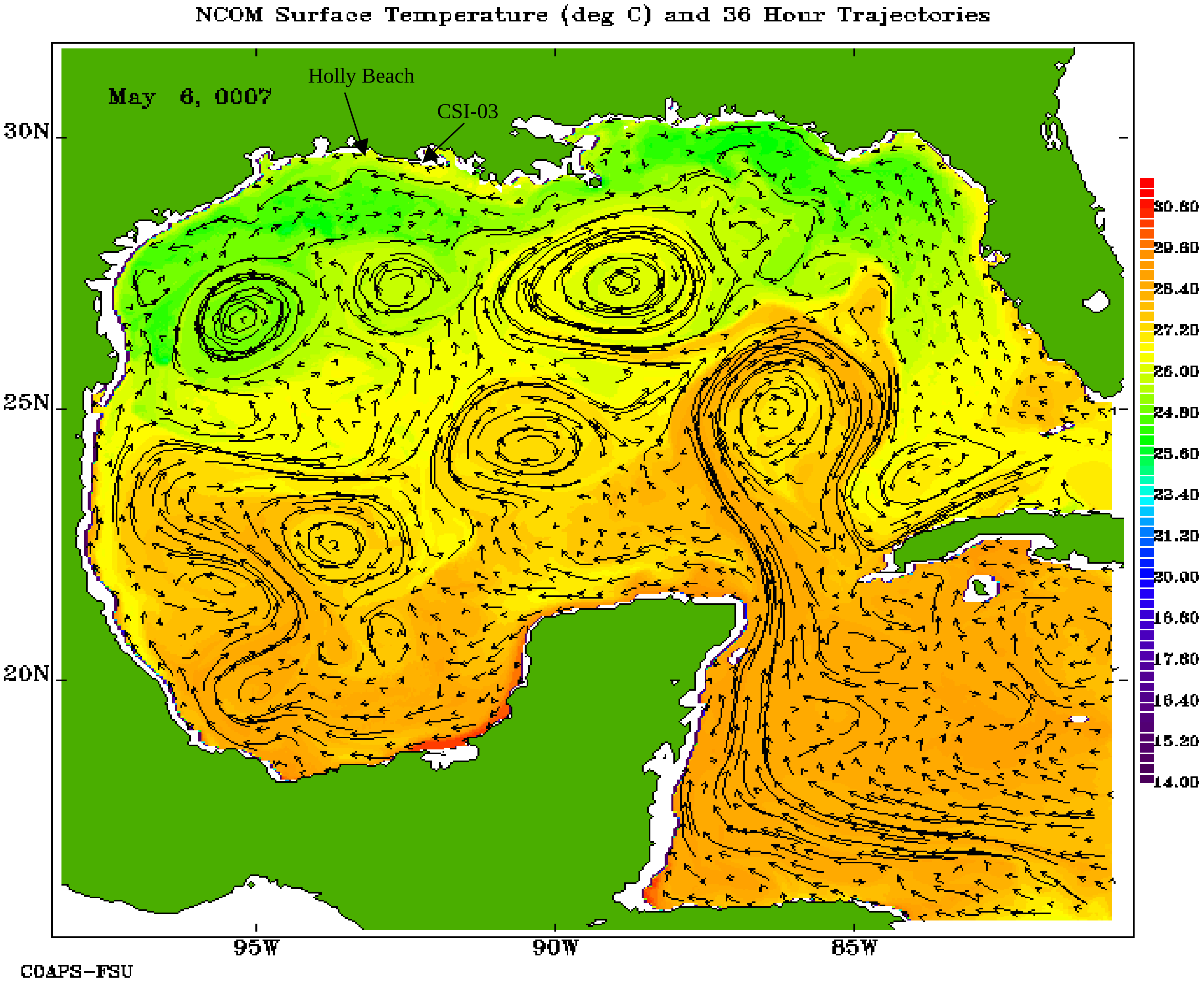


FIGURE 2.8. NCOM Surface Temperature (deg C) and 36 Hour Trajectories.

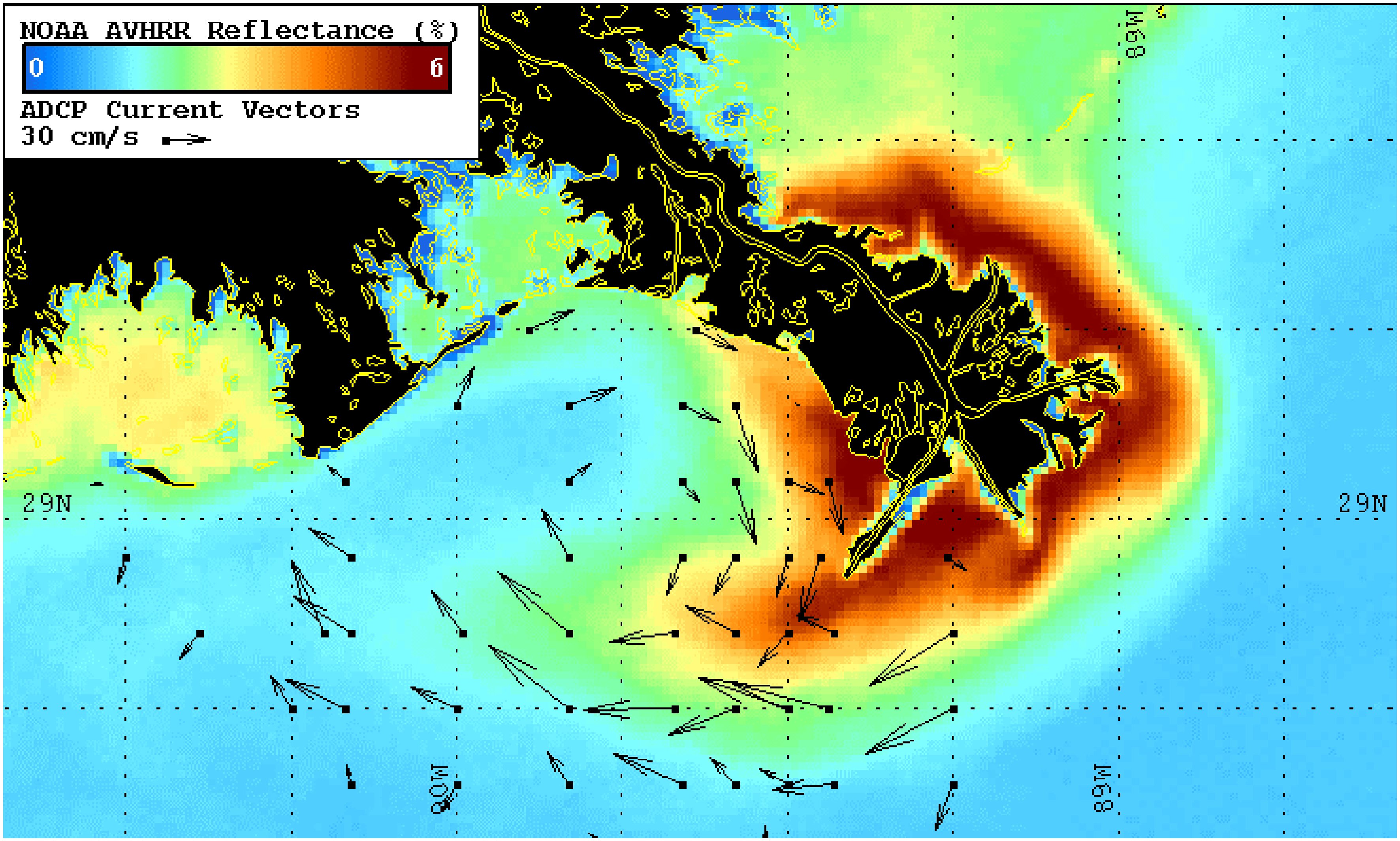


FIGURE 2.9.a. Current Vectors from ADCP Measurements (from NCAA).

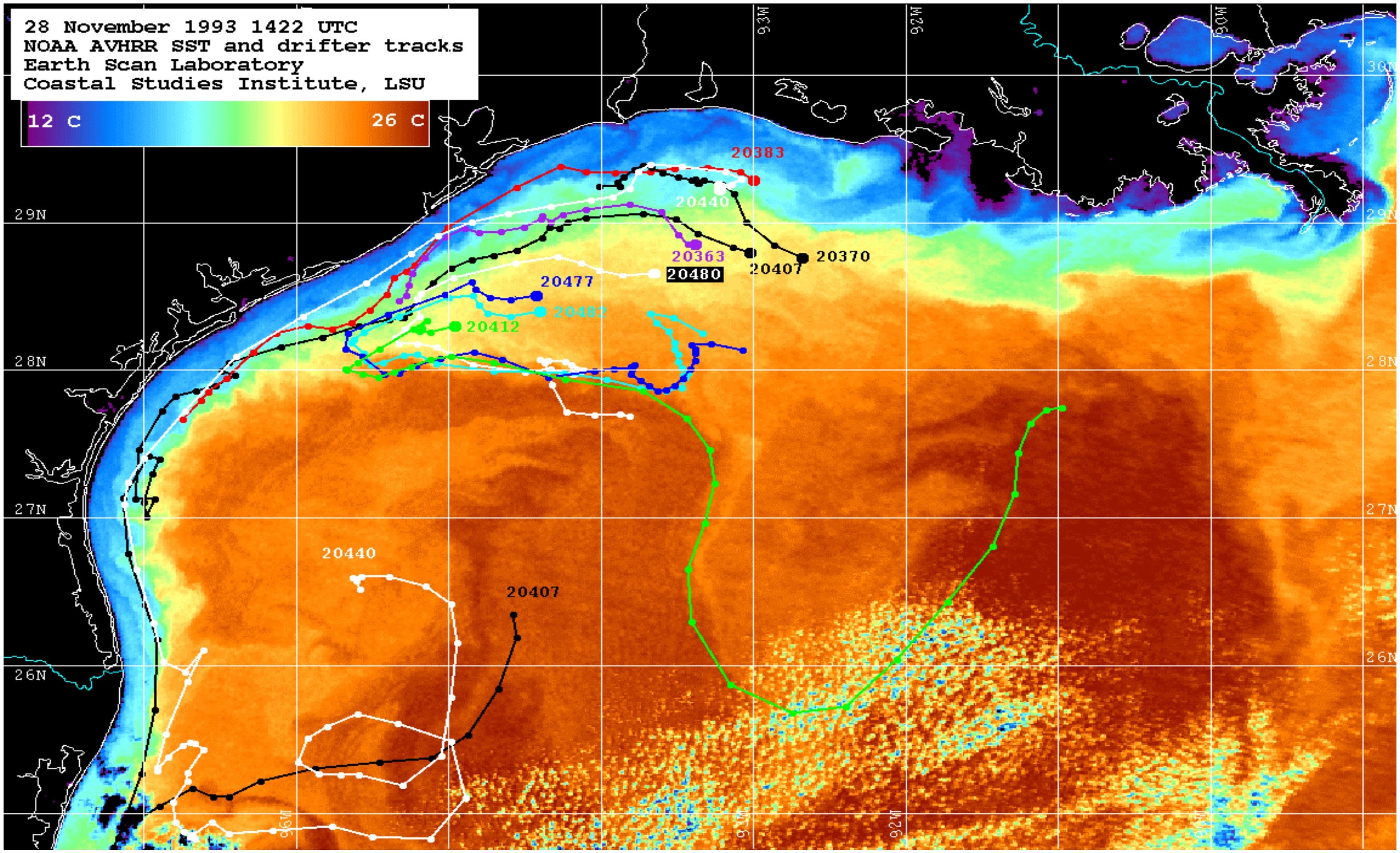


FIGURE 2.9.b. Drifter tracks for the Gulf of Mexico showing a residual westward current (from the Coastal Studies Institute, LSU).

The measurements at WAVCIS Station 3 (see Figure 2.10) show that the mean significant wave height is about 0.3 m and the mean wave period is 4 seconds. The largest significant wave height found in the measurement period is about 2.8 m.

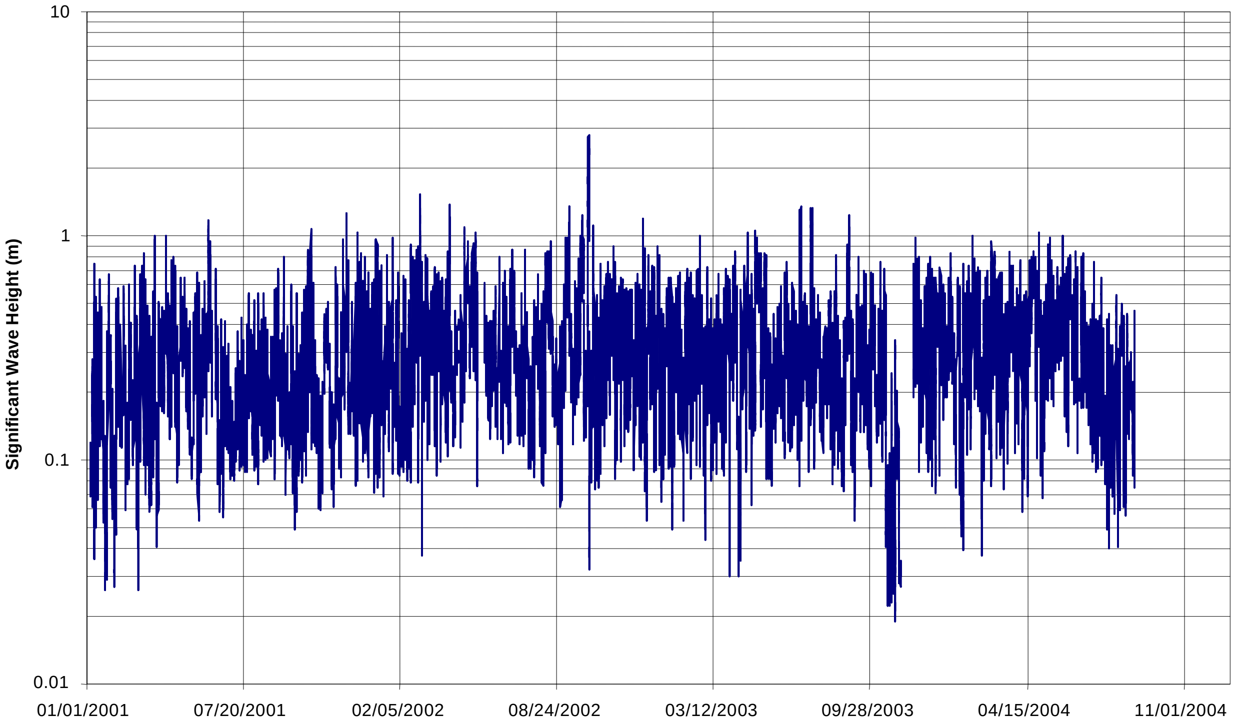


FIGURE 2.10. Significant Wave Height Measured at WAVCIS Station CSI-3

The WIS database provides 20 years of hindcast wave data at stations distributed along the Louisiana coast at a variety of depths from 10 to 15 m. The wave information at the three stations, which are the closest to the three existing and proposed sand borrow pits (Holly Beach, Ship Shoal Block 88, and Sandy Point), were downloaded from the USACE web site. Figure 2.11 shows a comparison of the WIS predictions and the waves measured at NDBC Buoy 42035 (refer to Figure 2.4 for the location of this buoy) which are the nearest long-term wave measurements to the Holly Beach dredge pit. The wave roses for the three sites from the WIS data stations closest and offshore of each site are provided in Figures 2.12(a) to (c). All tabular data for the three stations is provided in Appendix A. The Sandy Point site (Station 132 in 19m of water, see Figure 2.12(a)) features waves mostly from the south with some from the southeast (SE waves are diminished through the sheltering provided by the Mississippi River delta). The Ship Shoal Site (Station 125 in 18m of water – see Figure 2.12(b)) features waves from the NE and SE quadrants with the largest waves from the SE (there is more energy from the NE site at this location due to the distance offshore). The Holly Beach dredge pit site (Station 94 in 11m of water - see Figure 2.12(c)) features mostly southeasterly waves that are the expected conditions for fully exposed nearshore sites along the Louisiana coast. The annual maximum significant wave height and peak period combinations (defined here as occurring approximately 1% of the time), according to the WIS data, are 5.5m/12.5s at Sandy Point, 6.5m/12.5s at Ship Shoal, and 5.5m/12.5s at Holly Beach.

The % of calms and % waves between 0.5 and 1.5 m for each site are: 25%/66% for Sandy Point; 13%/64% for Ship Shoal; and 14%/72% for Holly Beach.

The spatial distribution of significant wave heights in the Gulf of Mexico was found and downloaded from Naval Research Laboratory Stennis Space Center (NRLSSC), US Navy. These altimetry data are gathered and extracted from the Geophysical Data Records (GDRs) of information received from each satellite. Significant wave heights for three selected time periods are shown in Figures 2.13(a) to (c). These figures provide an indication of wave transformation from the WIS stations to the three sand borrow pits. Generally, the wave heights at each of the three pits are not significantly different from the waves at the nearest offshore WIS stations, although the waves in the Ship Shoal area appear to be higher than the waves from the nearest offshore WIS station.

Suspended Sediment Concentration

A key variable for the estimation of pit infilling rate is the background suspended concentration representing the equilibrium concentration corresponding to normal tide and wave conditions at each site. Direct measurements of suspended sediment concentration at the three sand borrow pits are not available. However, there are various sources of information for suspended sediment in the Gulf of Mexico, including:

- Time series suspended sediment concentration and turbidity data measured at WAVCIS Station 3 from 2003 to 2004 and Station 6 from 2003 to 2005;

- Images of suspended sediment concentration distribution in the Gulf of Mexico produced from MODIS satellite images by Louisiana State University;

- Sediment sampling data provided by NOAA cruise surveys.

Turbidity was continuously measured at the WAVCIS stations. The turbidity information was converted into total suspended sediment concentration (SSC) by using relationships developed by LSU from simultaneous suspended load and turbidity data. Figure 2.14 shows the suspended sediment concentration measured at the middle depth from Station 3. The mean measured SSC is about 300 mg/l. Note that the highest SSC of about 1,500 mg/l found in the database may be truncated due to the limitation of turbidity readings. Figures 2.15 and 2.16 show a comparison of significant wave height and SSC measured at Station 3. These figures clearly show that the SSC correlates well with significant wave height at lower concentrations (< 200 mg/l). The SSC increases as the wave height increases. However, the higher measured concentration events (>200 mg/l) may not be linked with wave re-suspension events as evident in Figures 2.15 and 2.16. The high concentration levels in these periods may be the result of sediment plumes from the Atchafalaya River. The satellite image taken on May 28, 2004 (see Figure 2.17) shows that the sediment plume from the Atchafalaya River would have had a significant contribution to the SSC level at Station 3.

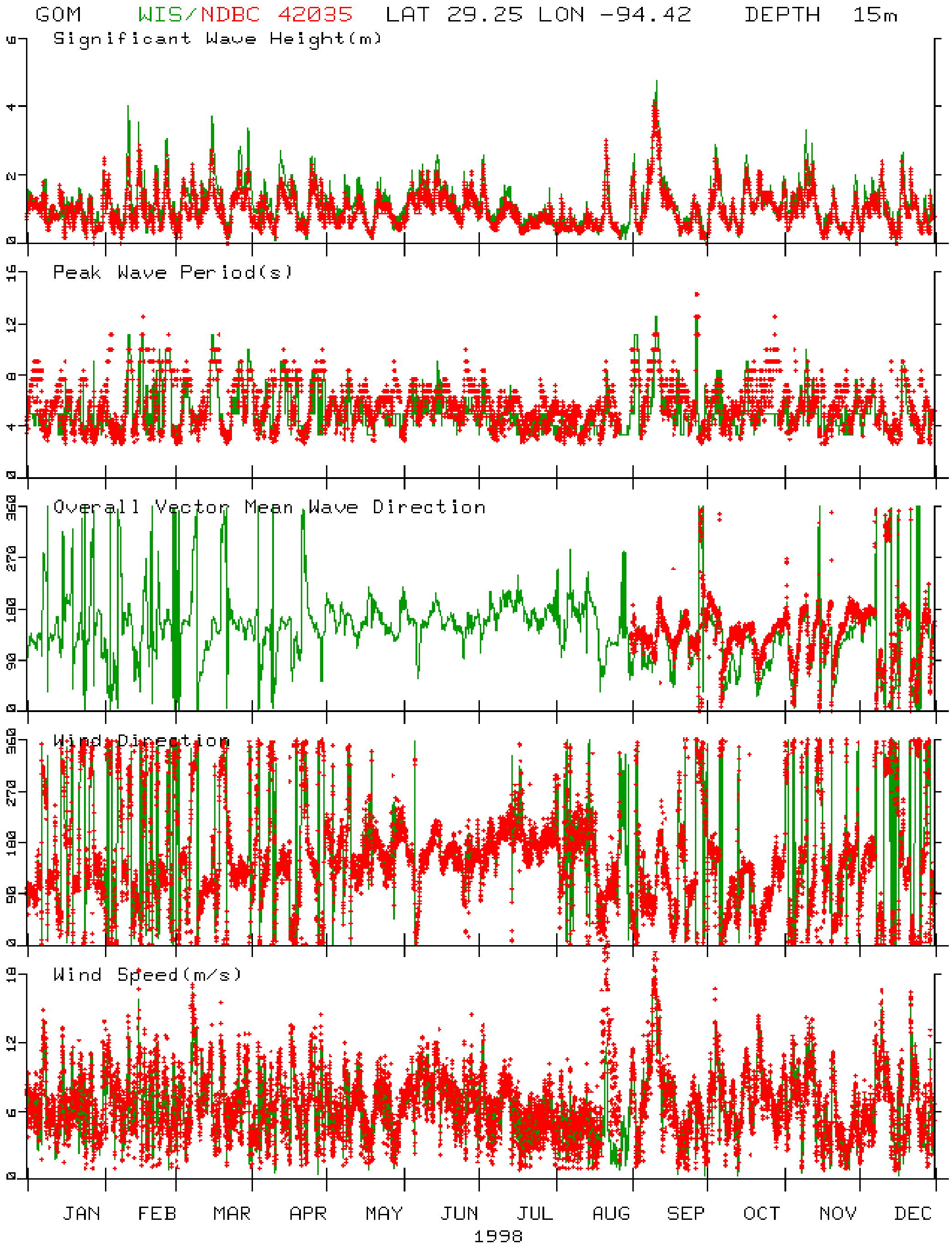
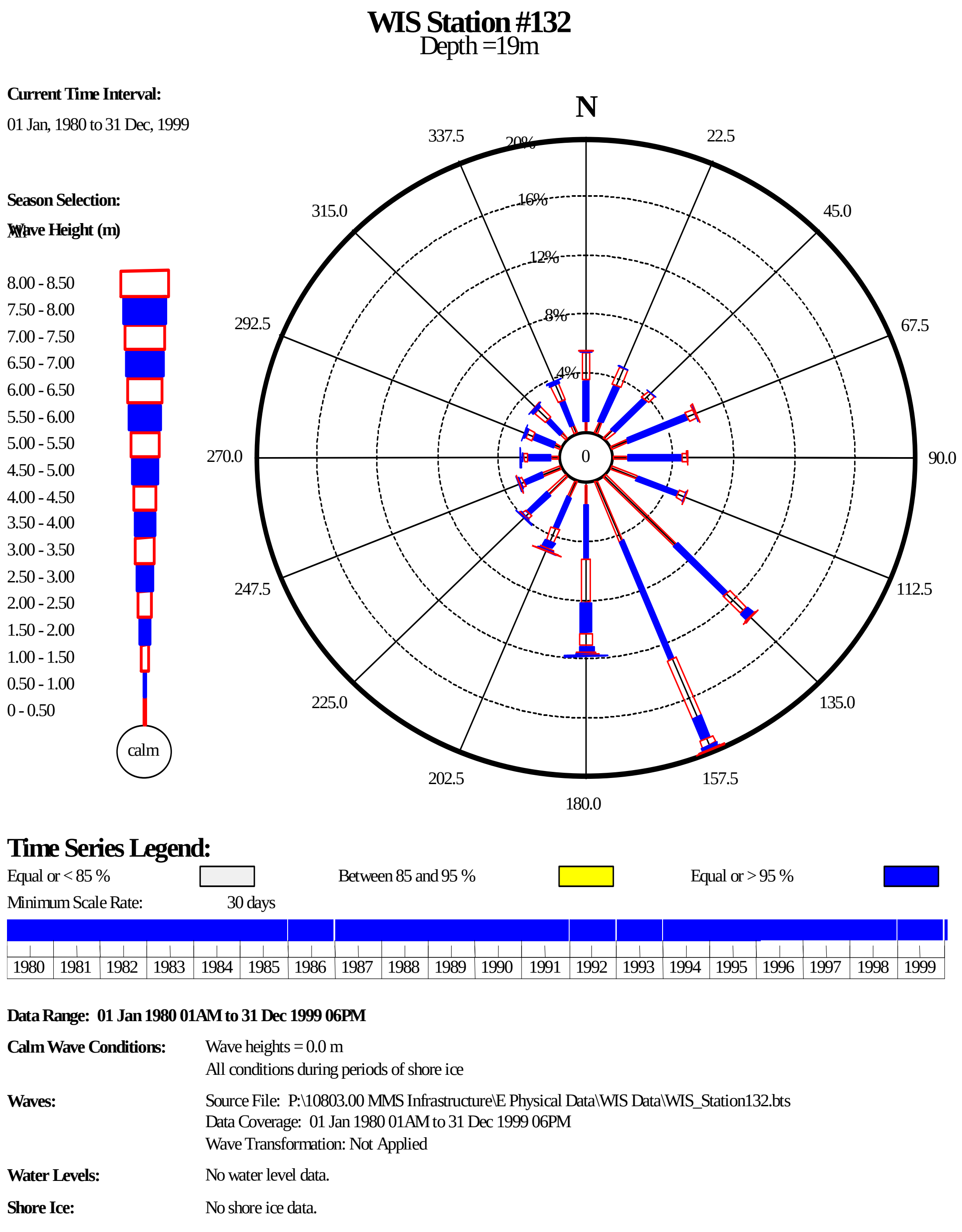


FIGURE 2.11. Comparison of the WIS predictions and measured waves at NDBC Buoy 42035



WIS Station #132
Depth =19m

Current Time Interval:
01 Jan, 1980 to 31 Dec, 1999

Season Selection:
All
Wave Height (m)

Time Series Legend:

Equal or < 85 % ⬜ Between 85 and 95 % 🟨 Equal or > 95 % 🟦

Minimum Scale Rate: 30 days

Data Range: 01 Jan 1980 01AM to 31 Dec 1999 06PM

Calm Wave Conditions:	Wave heights = 0.0 m All conditions during periods of shore ice
Waves:	Source File: P:\10803.00 MMS Infrastructure\E Physical Data\WIS Data\WIS_Station132.bts Data Coverage: 01 Jan 1980 01AM to 31 Dec 1999 06PM Wave Transformation: Not Applied
Water Levels:	No water level data.
Shore Ice:	No shore ice data.

FIGURE 2.12.a. Wave Rose for WIS Station 132 Near Sandy Point.

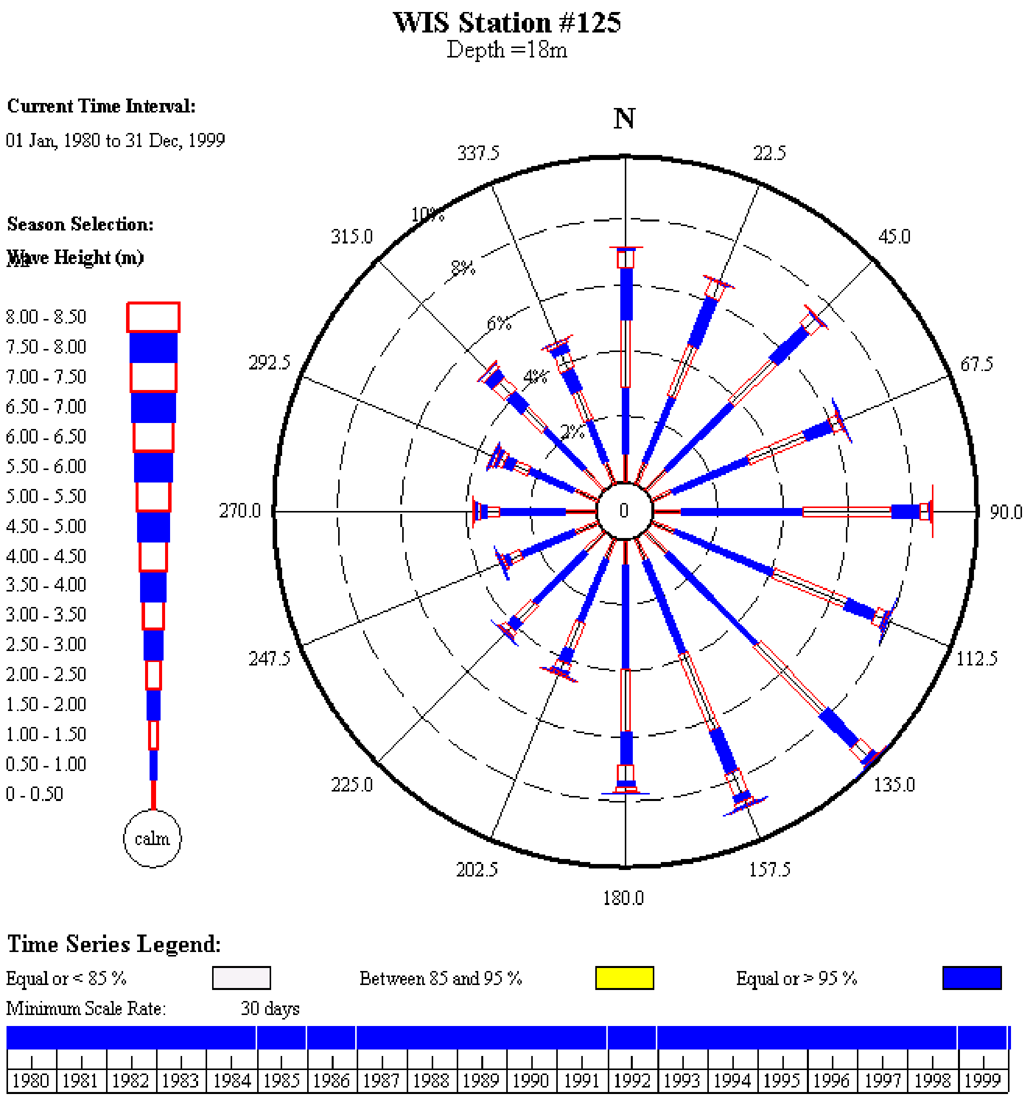


FIGURE 2.12.b. Wave Rose for WIS Station 125 Near Block 88 on Ship Shoal.

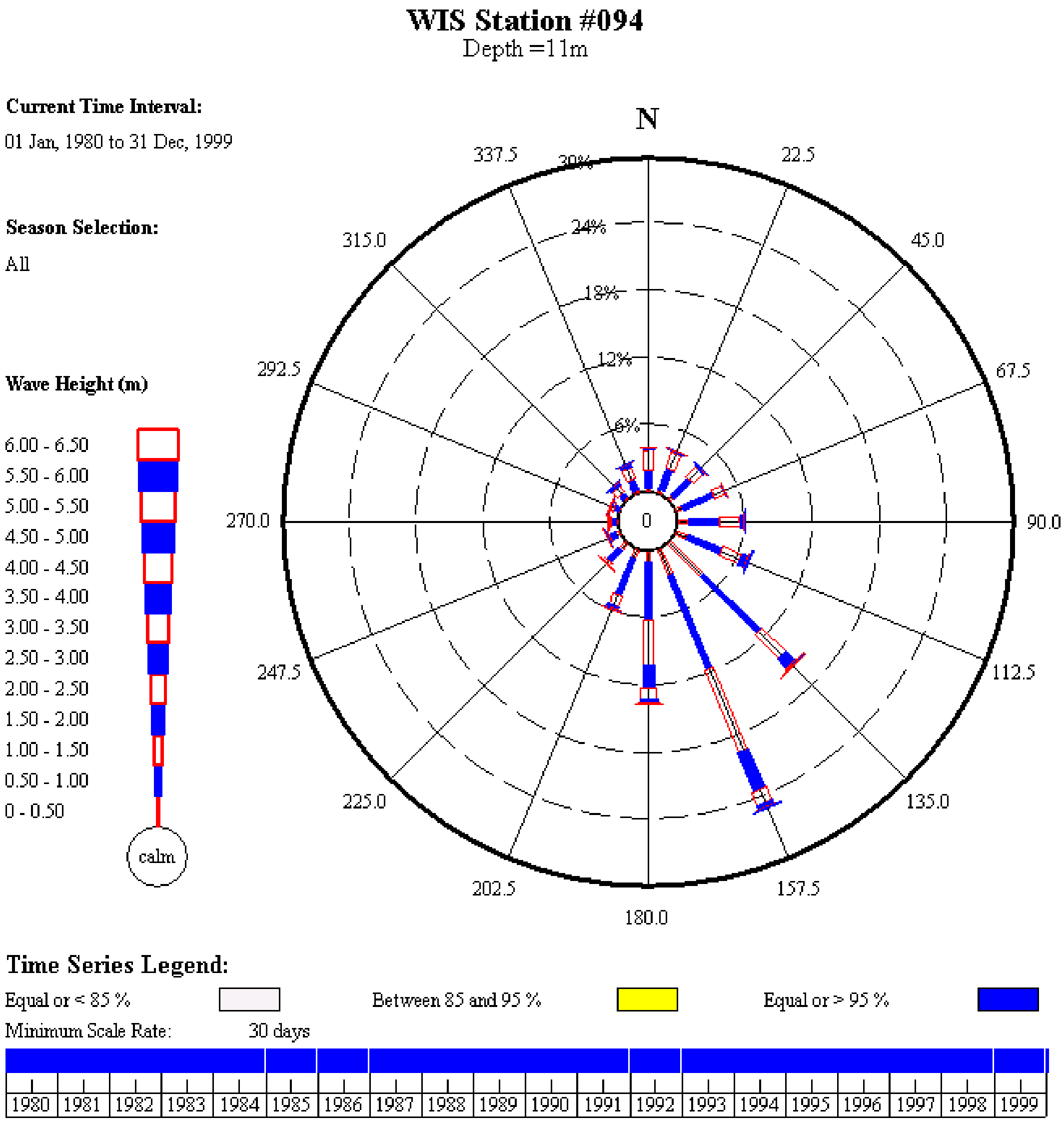


FIGURE 2.12.c. Wave Rose for WIS Station 94 Near the Holly Beach Dredge Pit.

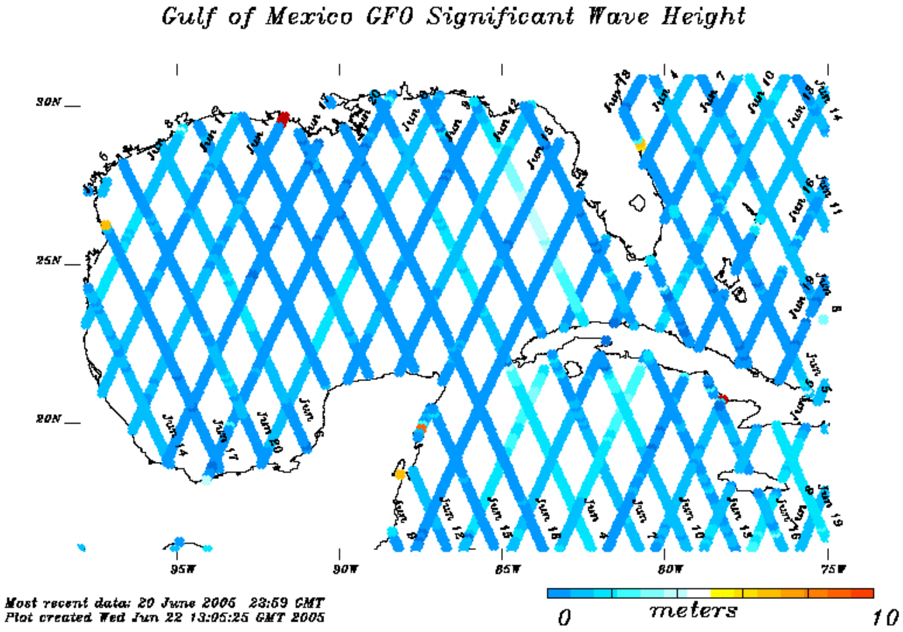


FIGURE 2.13.a. Wave heights from satellite images in June 2005 (from US Navy).

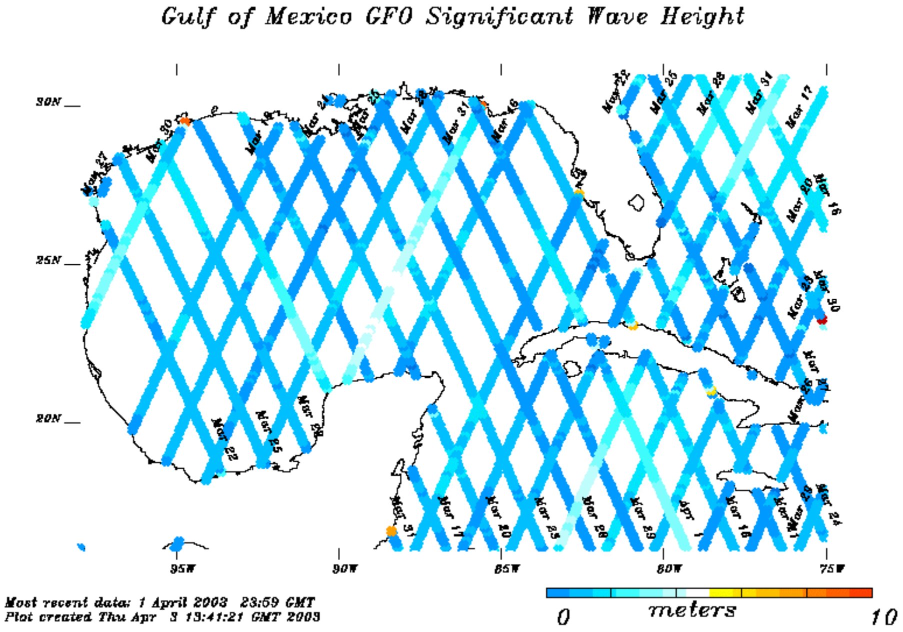


FIGURE.2.13.b. Wave heights from satellite images in March 2005 (from US Navy).

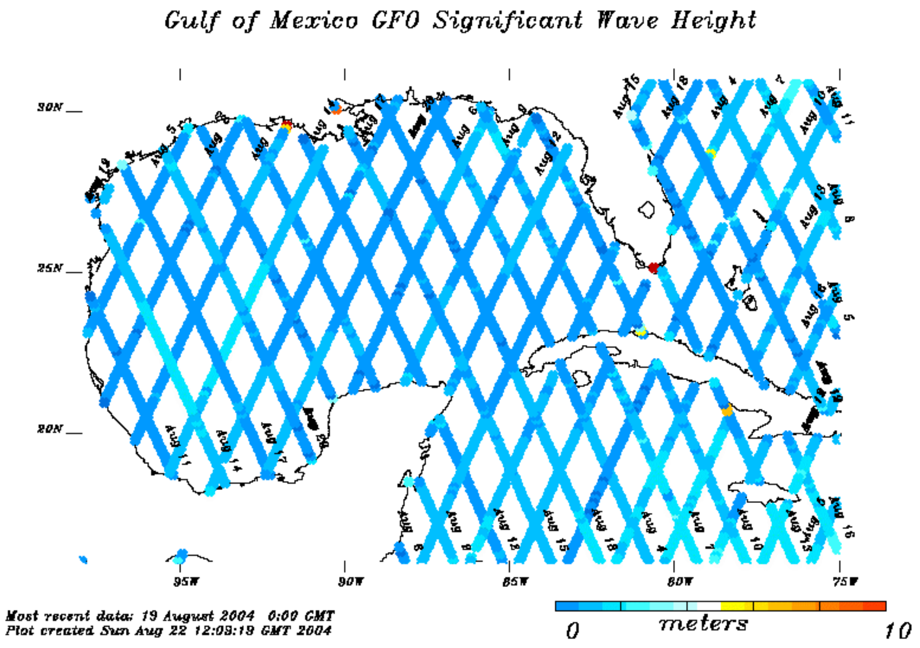


FIGURE 2.13.c. Wave heights from satellite images in August 2004 (from US Navy).

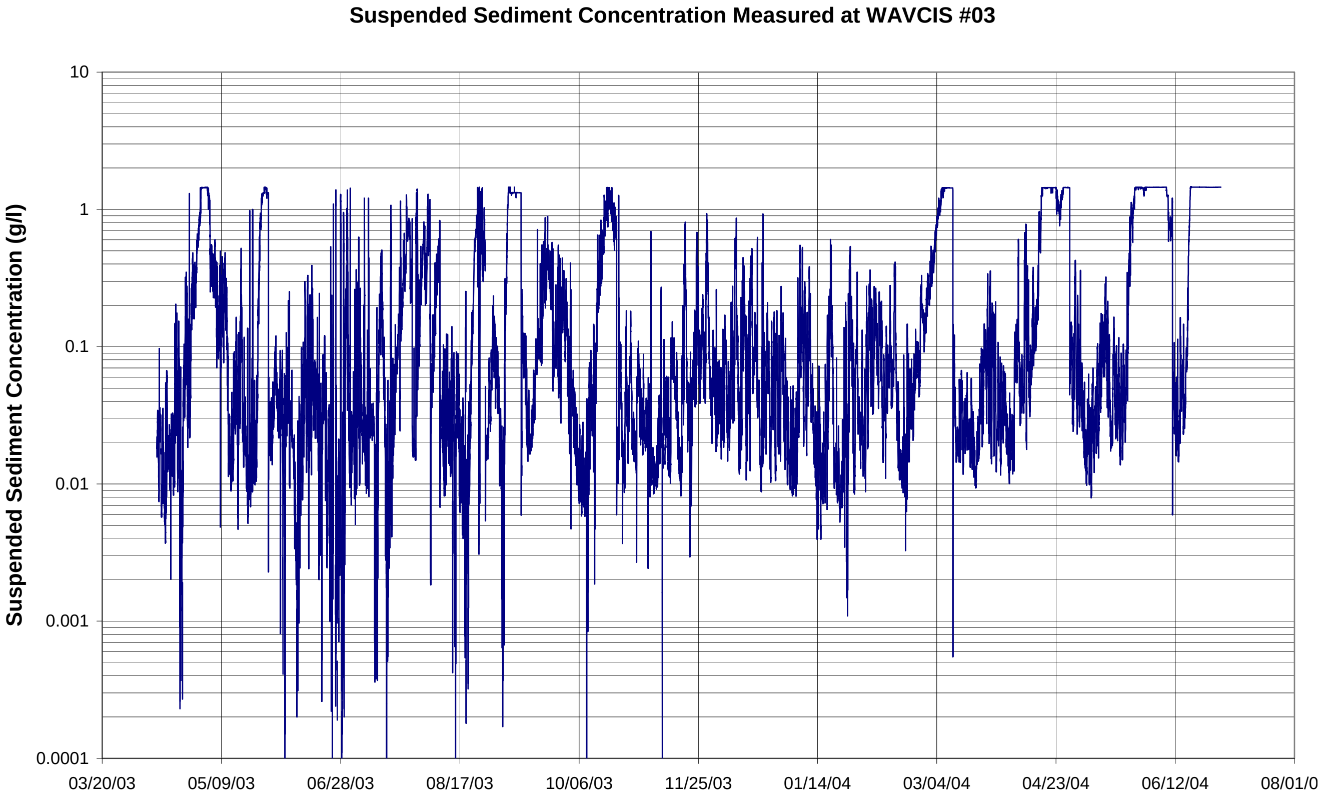


FIGURE 2.14. Suspended Sediment Concentration Measured at WAVCIS Station 3.

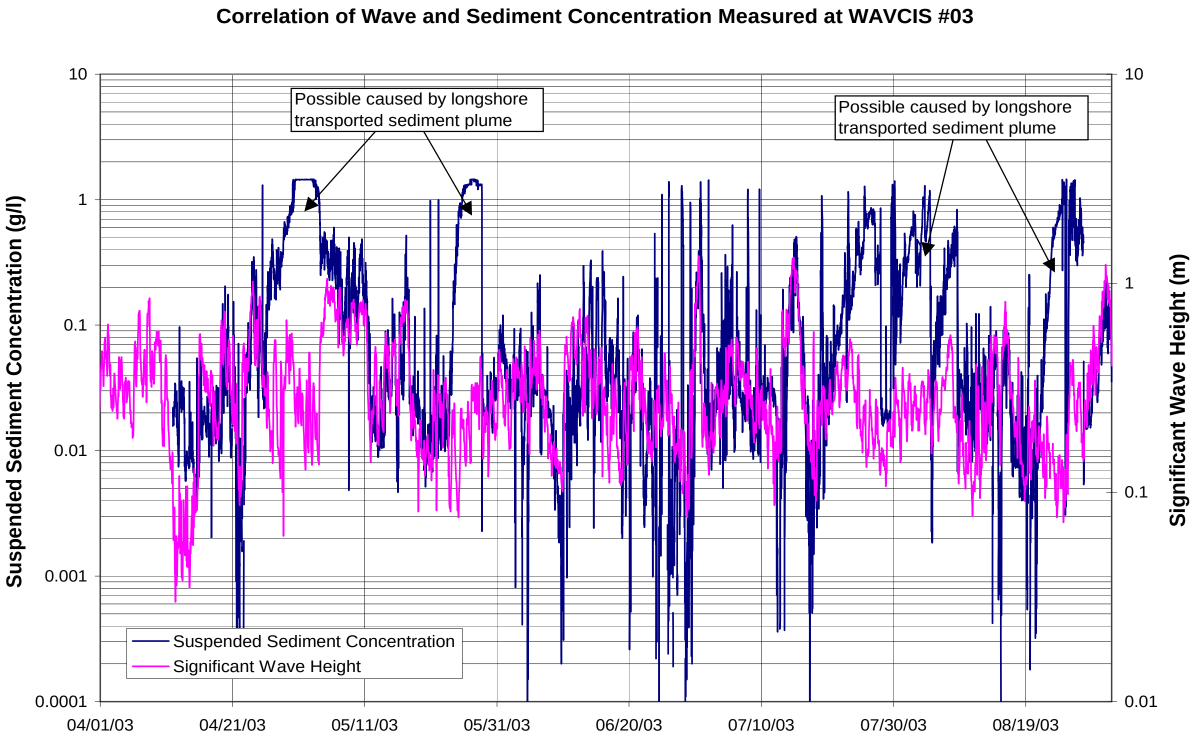


FIGURE 2.15. Correlation of Wave Height and Sediment Concentration Measured at WAVCIS Station 3 (April-August 2003).

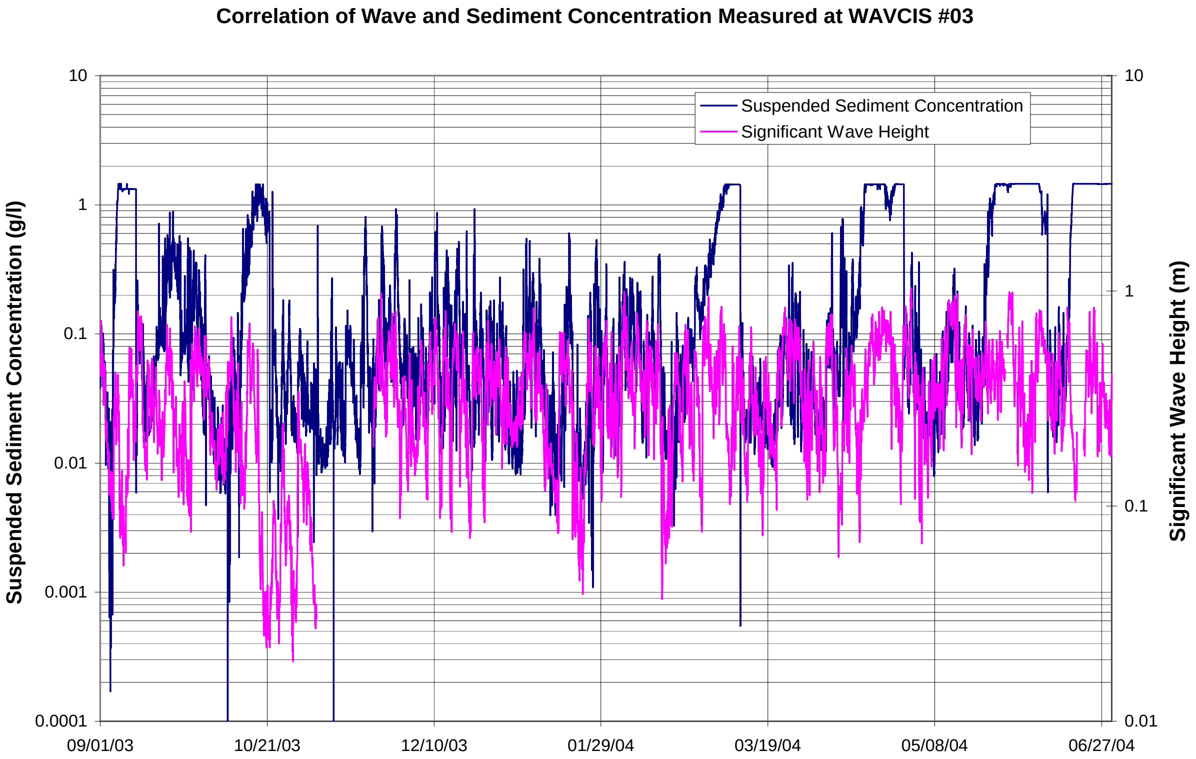


FIGURE 2.16. Correlation of Wave Height and Sediment Concentration Measured at WAVCIS Station 3 (Sept. 2003-June 2004).

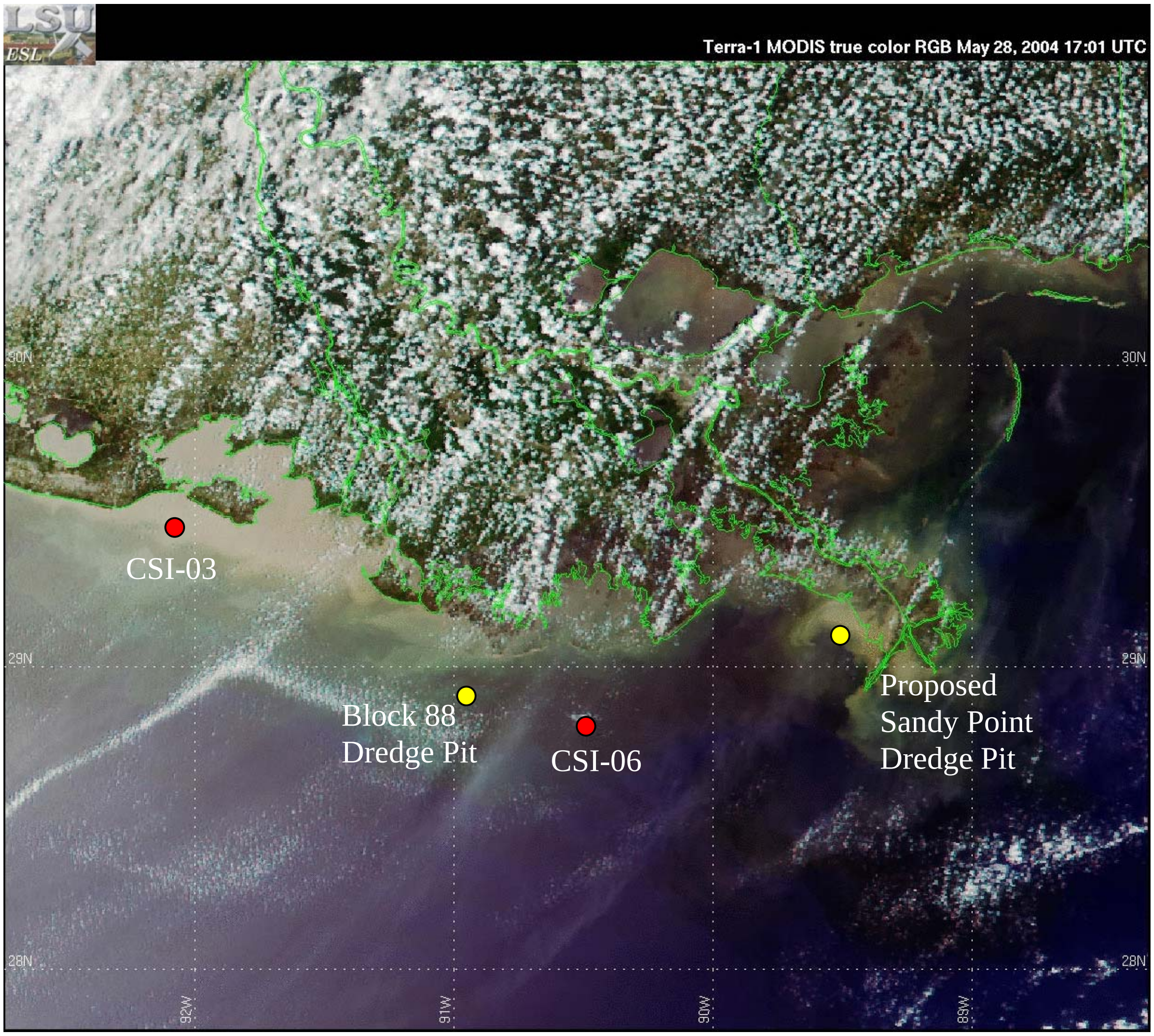


FIGURE 2.17. MODIS Satellite Image Shown, CSI-03, 28 May 2004 (from LSU).

A series of satellite images (MODIS) from 2004 were collected from Louisiana State University. These satellite images provide the valuable information on SSC along the Louisiana coast. Figures 2.18 to 2.22 show various examples of the influence of sediment plumes from the Mississippi and Atchafalaya Rivers, which ultimately are the main sources of suspended sediment along the Louisiana coast. The sediment plume from the Mississippi River will have a significant impact on sedimentation of the proposed Sandy Point borrow pit when the longshore current is towards the west. The plume from the Atchafalaya River may have a significant contribution to the sedimentation of the proposed Block 88 and South Pelto pits on Ship Shoal when the longshore current is toward the east. Ship Shoal consists almost entirely of sandy sediments at and near the seabed. Therefore, the finer sediments associated with river plumes would only deposit in this area if deep pits were dredged. Both plumes contribute to the suspended sediment load along the Louisiana coast and the contribution is significant when longshore currents are strong and toward the west.

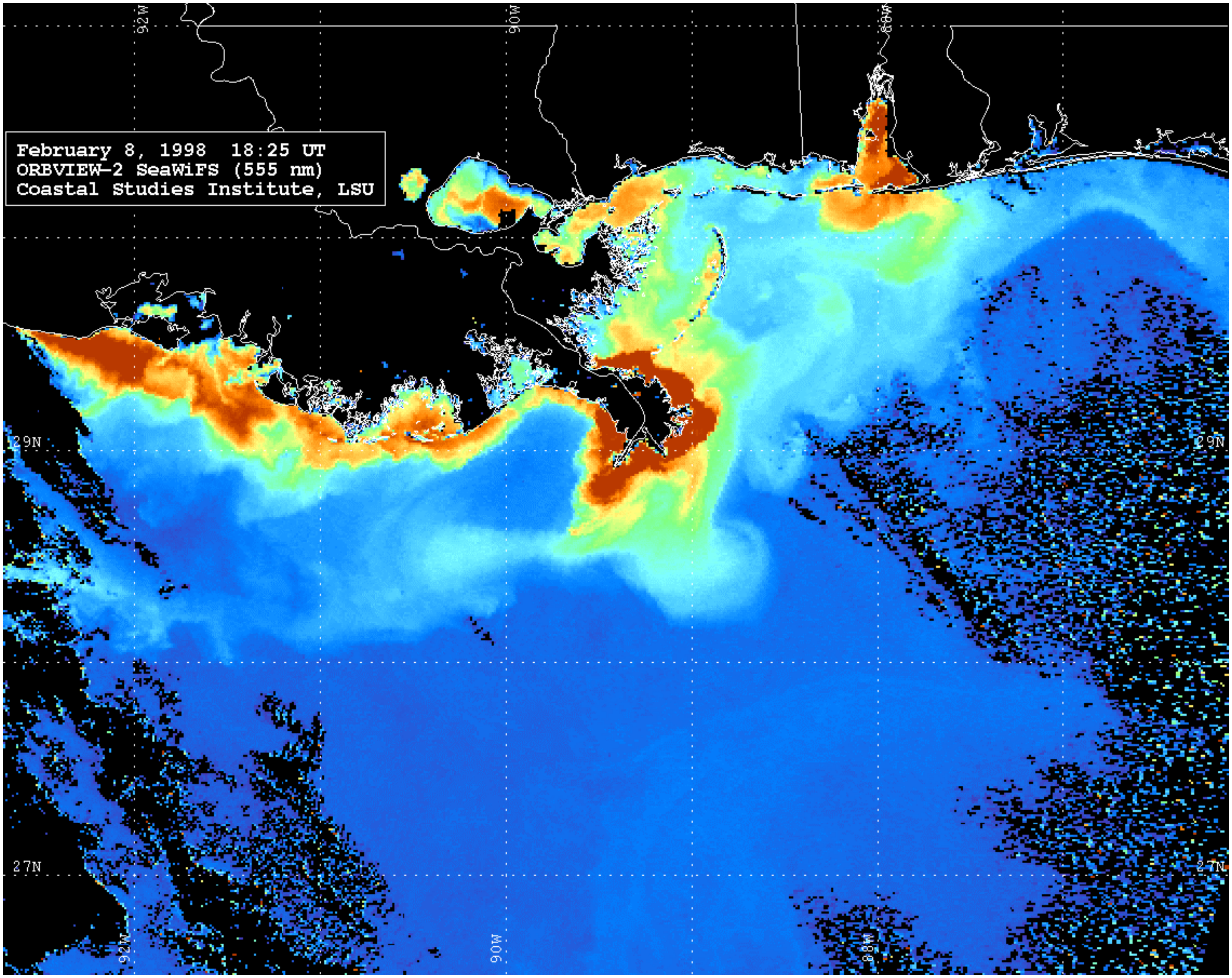


FIGURE 2.18. Satellite Image Showing Suspended Sediment Concentration, 8 February 1998, (from LSU).

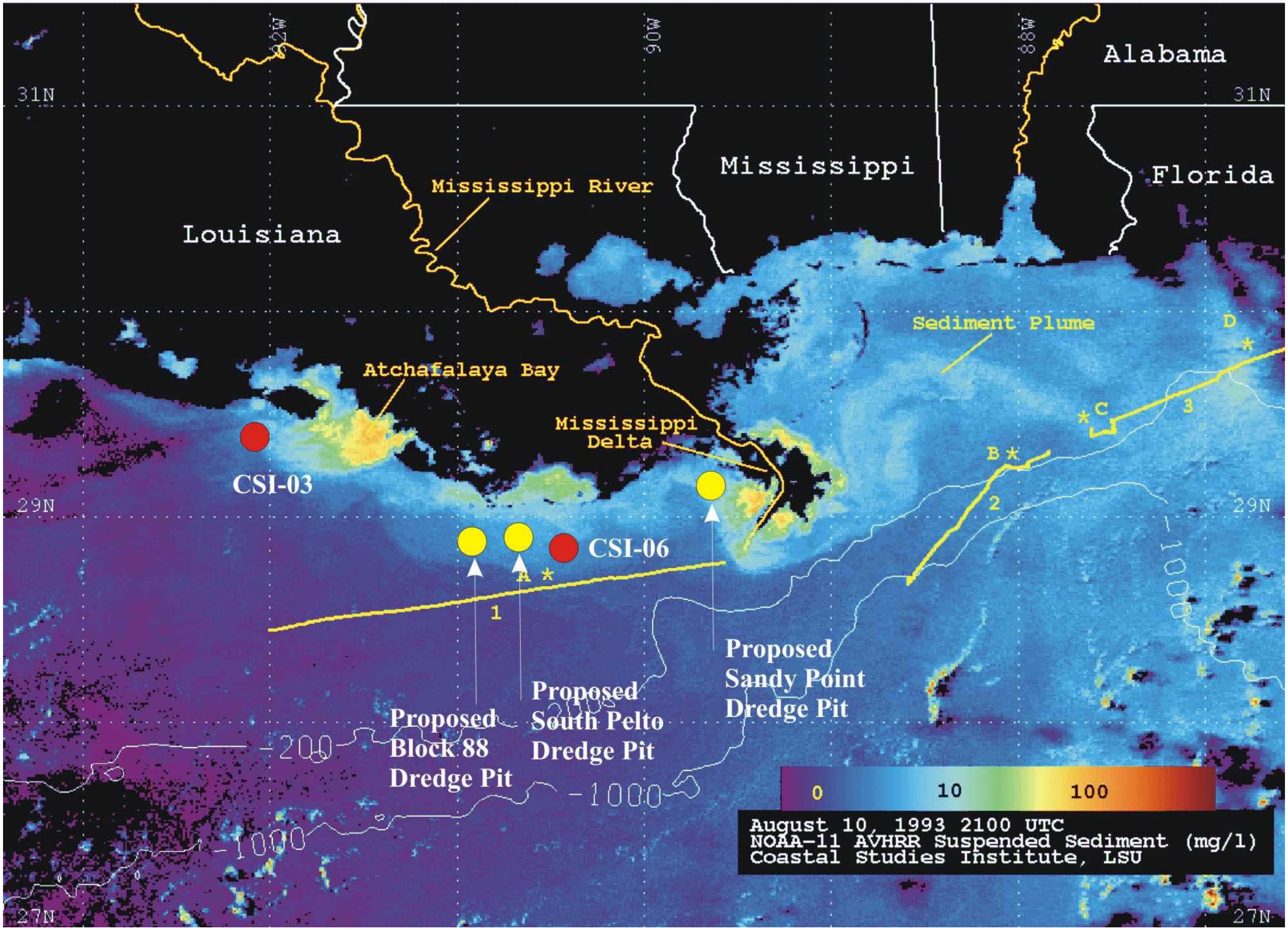


FIGURE 2.19. Satellite Image Showing Suspended Sediment Concentration, 10 August 1993 (from LSU).

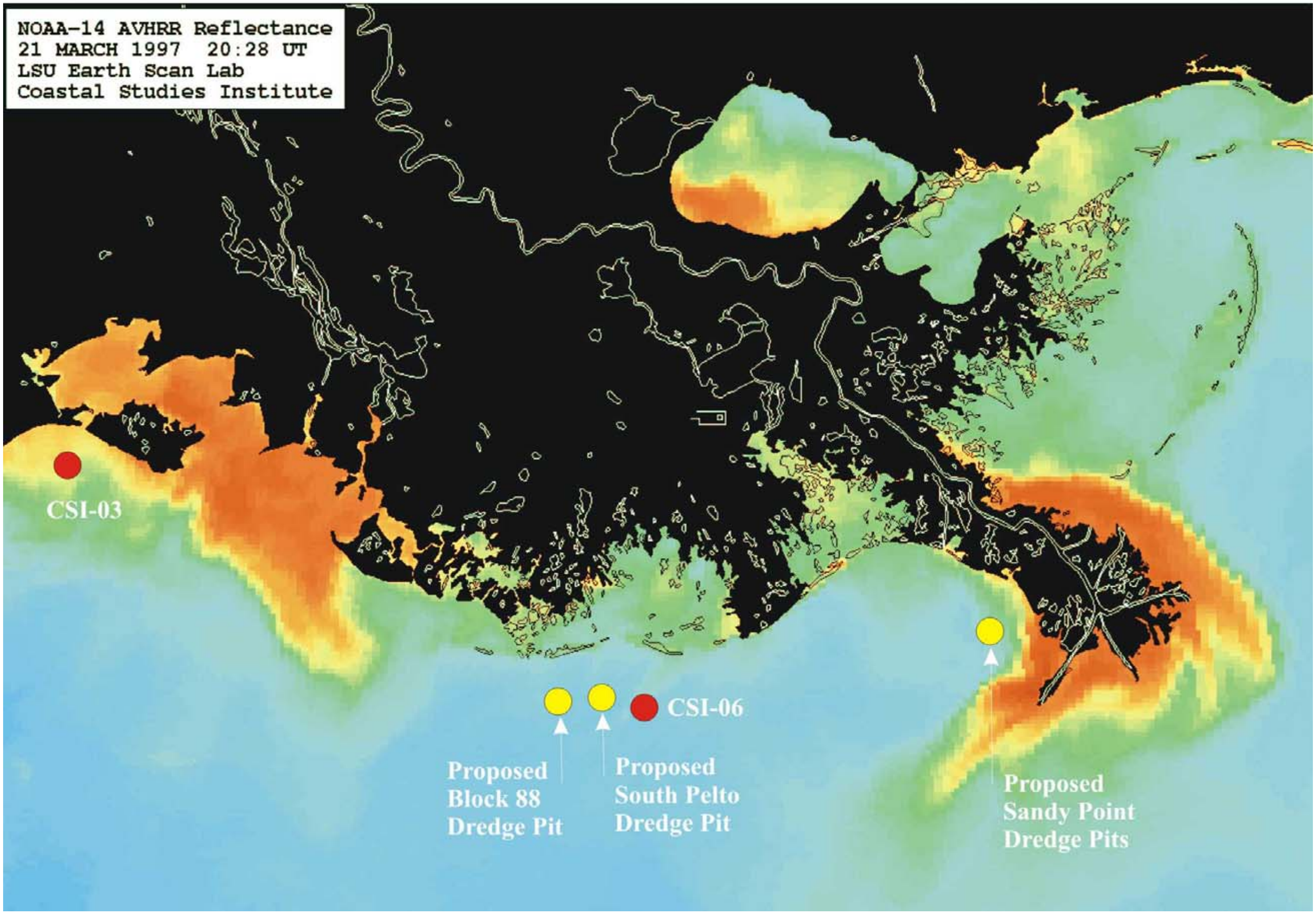


FIGURE 2.20. Satellite Image Showing Suspended Sediment Concentration, 21 March 1997 (from LSU).

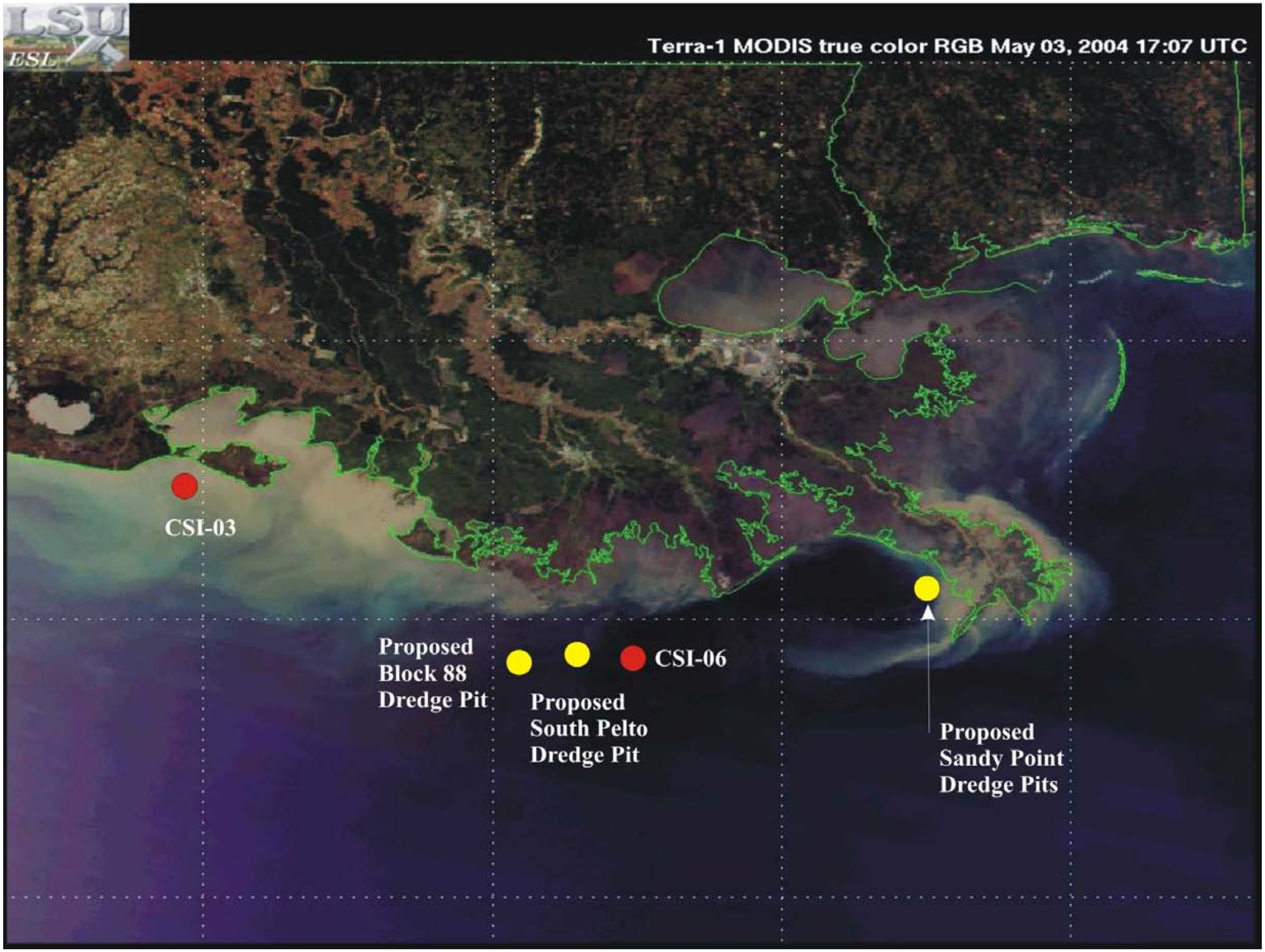


FIGURE 2.21. Satellite Image Showing Suspended Sediment Concentrations, 3 May 2004 (from LSU).

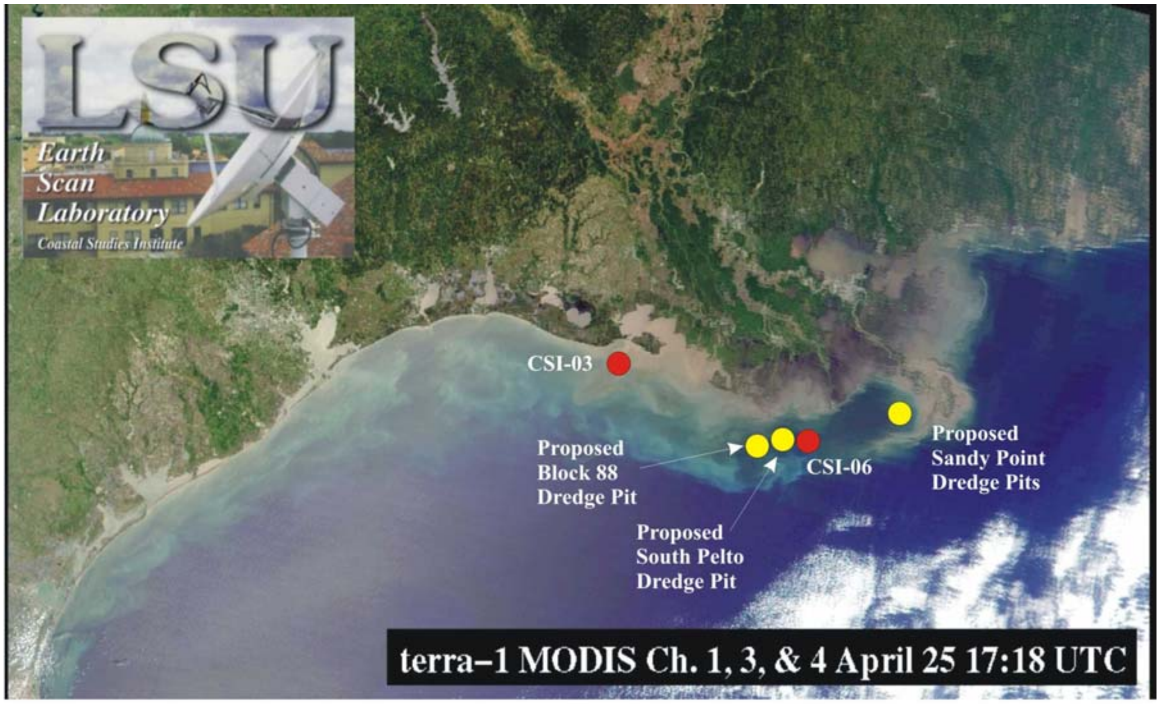


FIGURE 2.22. Satellite Image Showing Suspended Sediment Concentrations, 25 April 2001 (from LSU).

Suspended sediment concentration data around the Mississippi River delta were found in a NOAA data report (Ward, 1984). The report listed all TSS measurements around the delta during four cruise surveys between 1982 and 1984. The sampling locations of the second and third cruise surveys are shown in Figures 2.23 and 2.24. The locations of II-11 and III-14 are close to the proposed Sandy Point borrow pit. The TSS data measured at these two stations significantly improved the suspended sediment concentration estimates for the proposed Sandy Point borrow pit.

Mississippi River Flow and Sediment Load

River flow and sediment load data were downloaded from the USGS gages at the Mississippi River (Station ID: 07373293) and the Atchafalaya River (Station ID: 07381490). These data were used to develop a relationship of sediment concentrations between those measured in the river and at the mouth of each river. The relationships for suspended sediment concentration at the river mouths are necessary to estimate the plume size and the concentration at the existing and proposed sand borrow pits. The average suspended sediment concentration at the gage in the Mississippi River is about 400 mg/l and ranges from 50 to 2,300 mg/l (see Figure 2.25) while the average concentration in the Atchafalaya River is about 360 mg/l and ranges from 30 to 1,500 mg/l (see Figure 2.26).

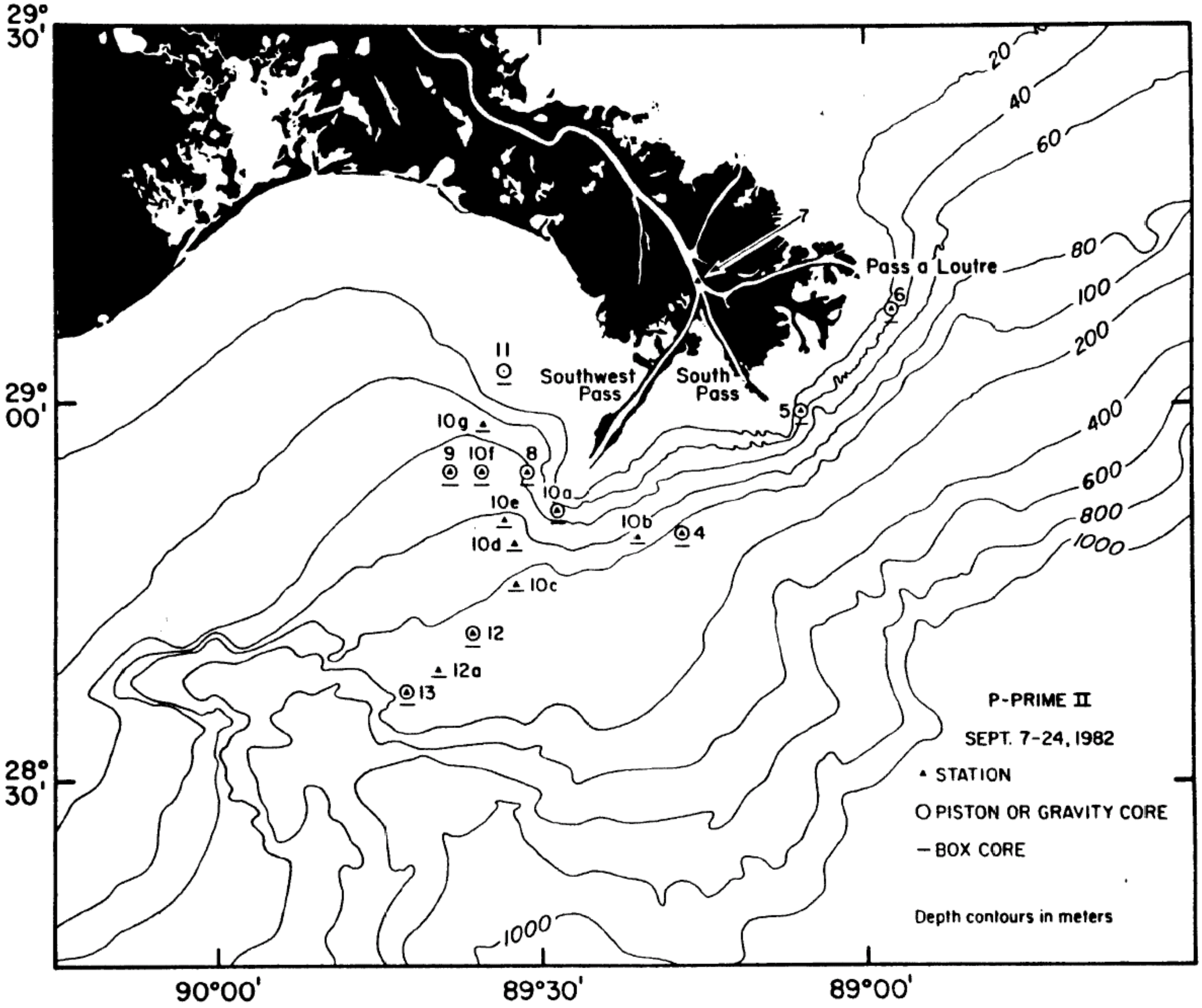


FIGURE 2.23. NCAH Suspended Sediment Sampling Locations (Ward, 1984).

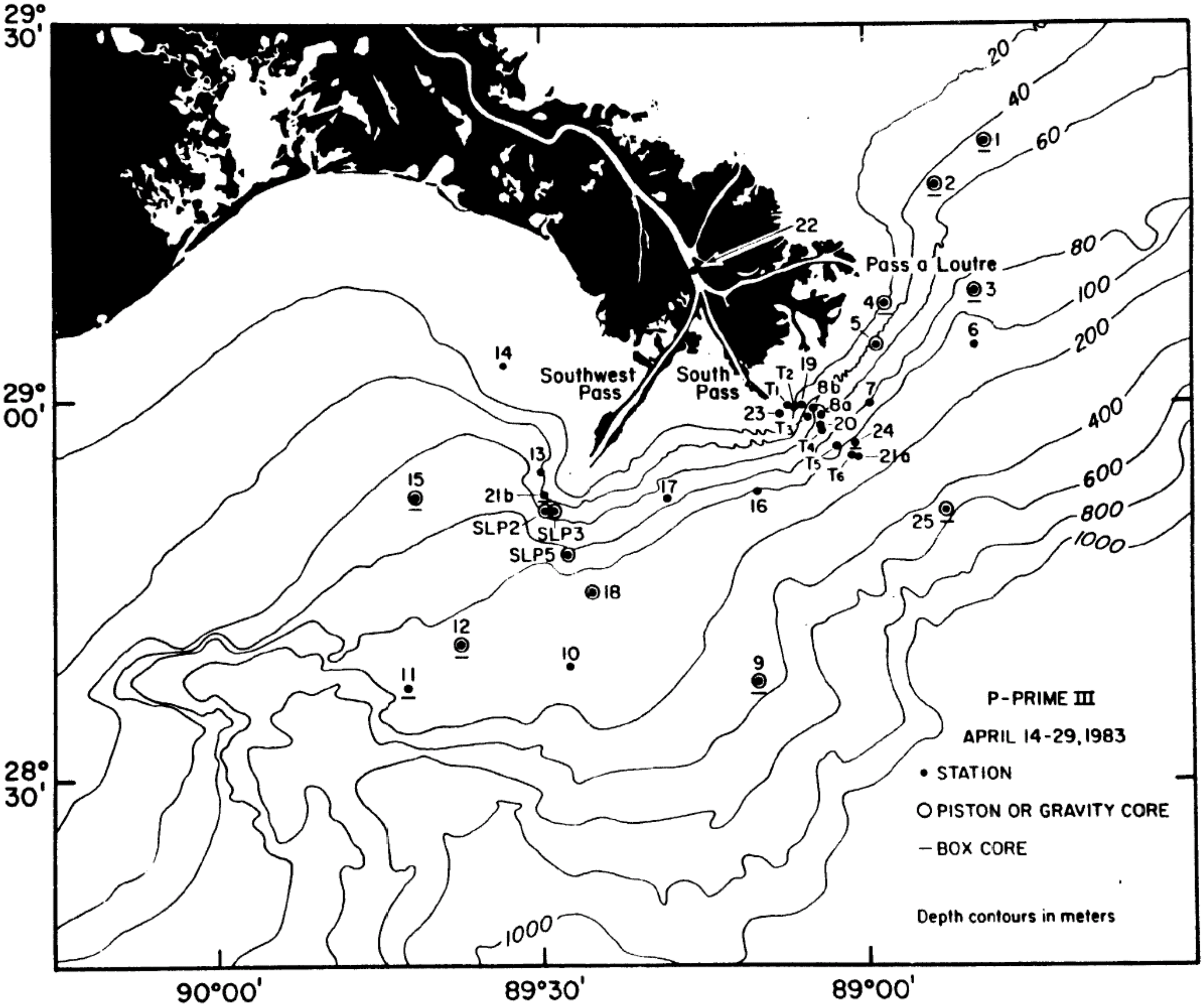


FIGURE 2.24. NCAH Suspended Sediment Sampling Locations (Ward, 1984).

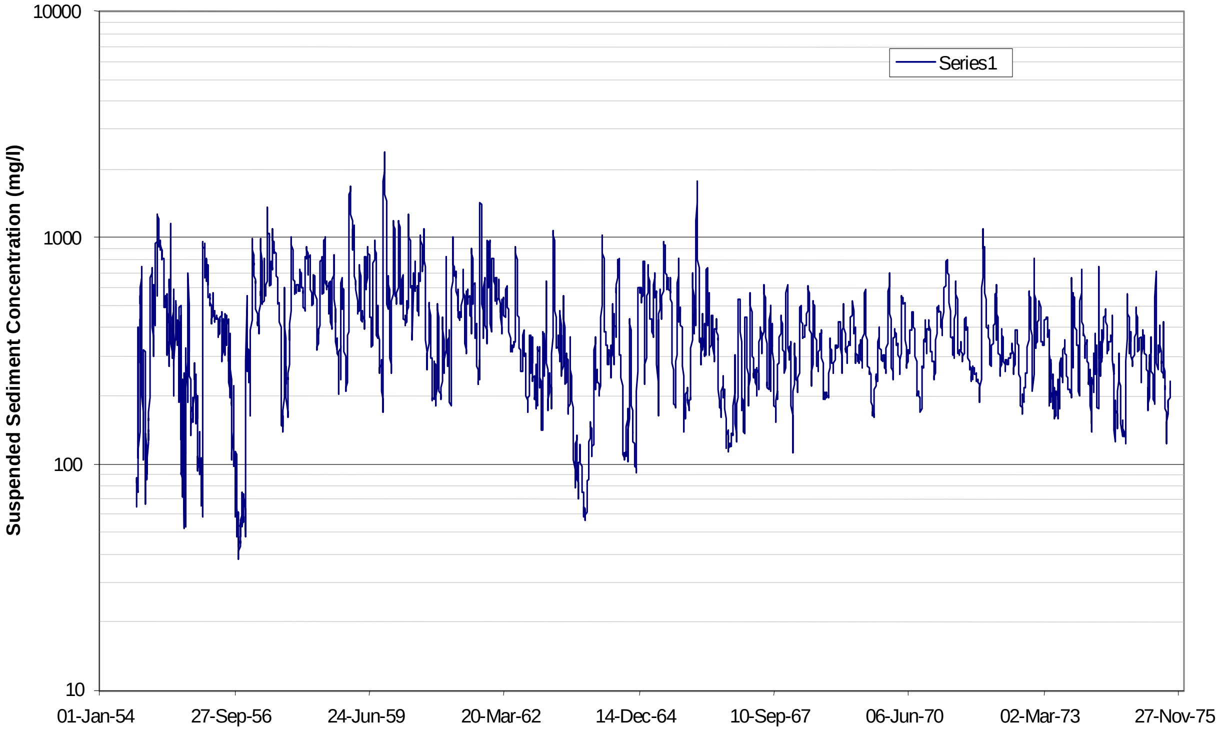


FIGURE 2.25. Suspended Sediment Concentration in the Mississippi River (USGS Gage# 7373293).

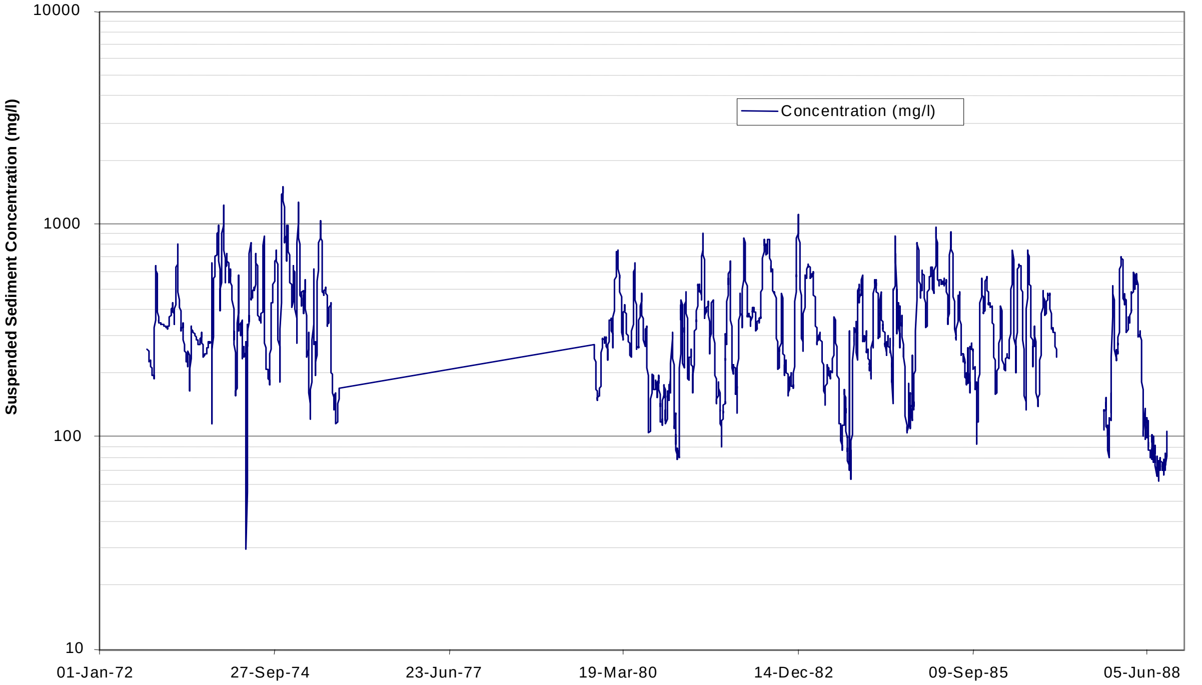


FIGURE 2.26. Suspended Sediment Concentration in the Atchafalaya River (USGS Gage# 07381490).

2.2 The European Community SANDPIT study

2.2.1 Introduction and Background

In April 2002, seventeen institutes from seven countries of the European Community started a three-year $5 million study called SANDPIT. The purpose of the study was to better define near field and far field impacts of dredged pits for the purpose of improved Coastal Zone Management.

Dr. Nairn of Baird & Associates attended and contributed to the final meeting of the SANDPIT study in March 2005. This section provides an overview of the findings of that study based on the presentations during that meeting and based on a Confidential Draft of Part I of the Final Report on this project (Van Rijn, et. al., 2005). A public domain version of this report will be issued in mid-year 2005.

The SANDPIT study focused mostly on sandy settings and primarily physical impacts of dredging; ecological impacts were addressed only through literature surveys. Physical impacts were assessed through large-scale laboratory and field experiments, analysis, and numerical modeling.

The primary focus of the investigation was on five Coastal Zone Management questions addressing near field (1 and 2) and far field (3 to 5) effects as follows (taken directly from Van Rijn et. al., 2005):

1. Will an offshore mining pit modify the local flow and wave fields in such a way that the transport regime and the large-scale bedforms (sand banks) in the direct vicinity are influenced? Can the magnitude of an effect be quantified?
2. Will the mining pit act as a sediment sink and thereby have a particularly marked impact on the seabed immediately adjacent to the pit? Can the magnitude and extent of this impact be quantified? How can this impact be minimized?
3. Will a large-scale mining pit affect the overall tide- and wind-induced flow regime in a coastal sea including nearby tidal inlets? Can the effect be quantified?
4. Will the mining pit allow more wave energy to reach the coastline through mechanisms such as reducing nearshore wave limiting conditions (e.g. by removing sand banks) or by acting as a lens to focus wave energy on the coastline? Can the magnitude and extent of this impact be quantified and to what degree of accuracy?
5. Will an offshore mining pit (removal of sand below bed or removal of sand banks) act as a sediment sink and what impact will it have on nearshore sediment transport regimes and will it lead to increased coastal erosion? Can the magnitude and extent of this impact be quantified and to what degree of accuracy?

Although all of these questions have direct relevance to the evaluation of impacts of dredging for beach nourishment sand or aggregates within the OCS under MMS jurisdiction, for the purposes of this study on potential impacts to oil and gas infrastructure, the primary focus of our summary is on the findings associated with Questions 1 and 2 above: the near field effects.

For each of the Coastal Zone Management questions above, a series of research questions was posed as listed below for the two areas (again, quoted directly from Van Rijn, 2005).

1. Will an offshore mining pit modify the local flow and wave fields…
    a. What is the change in maximum tidal current velocity due to the presence of a dredged pit (or dredged sand bank) of given size?
    b. What is the change in wave height during a storm due to the presence of a pit of given size?
    c. What are the effects of modified flow and wave conditions on the local sand transport capacity?
    d. What is the influence area?
2. Will the mining pit act as a sediment sink and thereby have a marked impact on the seabed immediately adjacent…
    a. What is the sand transport regime in relation to the current and wave regime outside the dredged pit (or dredged sand bank)?
    b. What is the effect of (modified) bed forms and (modified) particle size on the sand transport regime outside the pit?
    c. What is the gross and net annual sand transport outside the pit?
    d. What is the amount of sand trapped in a pit of given size per year and over 50 years?
    e. What is the erosion on the flanks of a pit per year and over 50 years?
    f. What are the net migration rates in longshore and cross-shore direction?
    g. What should be the location and dimensions of the pit to minimize these effects?

2.2.2 The Physical Impacts of Pits and the Pre-SANDPIT Limitations in Knowledge

This section provides a summary of the introduction to the general physical impact of pits drawn from Van Rijn et. al. (2005) and Walstra et. al. (1999), the latter a paper generated out of the SANDPIT project. In addition, this section provides the basis for focusing the SANDPIT investigation on key unknowns associated with the process of pit evolution.

The presence of the deepened water associated with a dredged pit results in a reduction in the current velocity (generated by waves, winds, or tide) directly over the pit. This reduction is significantly less than the pre-pit water depth divided by the depth of the pit plus the pre-pit water depth due to the flow attraction effect (where water is diverted from the surrounding area to fill the volume of the pit as it flows past). Modifications to flows beyond the edge of the pit are generally small and limited to one to two times the length or width of the pit. The reduction in current speed over the pit results in a reduction to the capacity for sand transport and the deposition of some of the sediment (bed load and some fraction of the suspended load) in the pit. The side slopes of the pit are flattened due to gravitational effects – as sediment is stirred by waves or currents (in depths where this is possible), the effect of gravity is always contributing to down-slope movement.

At locations where there is a net direction of sand transport, the upstream slope will be steep and close to the angle of repose if sedimentation is rapid, and flatter where the wave and tide driven stirring are able to interact with gravity to flatten the slope (from laboratory and numerical model results this slope may flatten to 1(V):80(H) when the pit is half full, eventually becoming completely flat once the pit is completely filled). The downstream slope will erode as the capacity for transport increases with shallower water, moving up the downstream slope. The process is only well predicted when the so-called relaxation or adaptation effect is considered. The adaptation time or space effect results in the actual sediment transport rates lagging the potential rate reduction (or increase) in space or time (see Galappatti and Vreugdenhill, 1985). The lag effect is particularly important for conditions where there are abrupt spatial changes in suspended sediment transport capacity and this is definitely the case for dredged pits. Where pits are narrow and/or shallow there can also be morphologic interaction between the upstream and downstream slopes where deposition at the toe of the downstream slope (from upstream sedimentation) can lead to enhanced flattening of the downstream slope. The net result at locations where there is a net sand transport rate is the migration of the pit in the direction of net transport, maintenance of a steep upstream and flattening of the downstream slope.

These pit evolution processes, and particularly the slope evolution, only apply to pits in sandy areas.

The SANDPIT researchers believe that pit migration and evolution is a key factor to understand as it effectively expands the area of influence and associated impacts with time (whether they relate to indirect physical impacts such as shoreline change or direct ecological effects such as the change of depths and substrate conditions). Clearly, pit migration is an important process to understand with respect to the stability of nearby fixed infrastructure.

Besides the need to address the spatial lag effect between actual and potential sediment transport, the other primary limitation in the knowledge base required to understand pit evolution is the definition of sediment transport rates in intermediate water depths outside the surf zone (say 10 to 20 m water depths). In these depths under conditions when most of the sediment moves, the bed is covered by ripples, and often complex 2D-3D ripples. Transport over rippled beds is one of the areas of greatest uncertainty in the field of sediment transport. Often it is not possible to predict the direction, let alone the magnitude of sediment transport. While somewhat reliable models have been developed for specific conditions, they are not reliable when applied beyond those conditions.

The laboratory and field investigations of the SANDPIT study focused on developing a better understanding of sand transport over ripples in intermediate depth water.

2.2.3 Findings of the Laboratory and Field Experiments on Sand Transport Processes

The SANDPIT study included two large-scale physical model tests at the University of Aberdeen and Delft Hydraulics, in addition to one full-scale field experiment specifically designed to develop a better understanding of sand transport processes over rippled beds in intermediate water depths without the presence of pits. The field data site was located in 13 m of water about 2 km offshore Noordwijk aan Zee along the central coast of the Netherlands. During the measurement campaign at the site one storm with a significant wave height of 4 m was experienced together with tide and wind-induced currents in the range of 0.3 to 0.5 m/s.

From the Noordwijk site an unparalleled data set has been collected of hydrodynamics, bedfrom and sediment transport rates under combined waves and currents in 13 m of water for a wide range of wave conditions from storms to calm. The two primary complexities in this range of water depths are: 1) the ever-present bed form; and 2) the often-present asymmetric waves under storm and post-storm conditions. The data include descriptions of both suspended load and bed load rates. Without a measured flow field represented by a probability density function, the transport rates could not be estimated accurately. The correct consideration of the role of bedforms on sediment transport was essential. Bedforms are important for both suspended load and bed load and affect both the reference concentration and the distribution of suspended load through the vertical.

2.2.4 Research Modeling Results

A wide range of models was tested and many were refined through the course of the SANDPIT study. These efforts focused on predicting: bedforms, roughness, sand transport, and morphodynamics. A new diagram was developed for the full range of bedform types for varying wave and current strength. New information was generated on the response of bedforms to changing wave and current conditions. It was found that the equilibrium morphology and the time to attain equilibrium were independent of the starting bed morphology, an encouraging result for modeling the bedform influence on sand transport rates (as the antecedent bedform condition is not that important). Bed roughness plays a pivotal role in sediment transport as it not only influences wave energy dissipation (and thus the height of waves), but it is influenced by sediment transport through the development of bedform. Bed roughness is one of the least understood aspects of sediment transport. New data have been acquired for flow conditions inside the boundary layer under combined wave-current conditions to help improve the understanding of bed roughness. Two new approaches for parameterizing roughness have been developed, one related to hydrodynamics parameters and another related to the bedform conditions.

It was found that, in wave-dominated environments, the direction and the rate of transport by asymmetric waves over ripples are determined by the ratio of bed load to suspended load transport. If bed load is dominant the transport is directed onshore. However, if suspended load is dominant, transport may be offshore if the phase lag between the flow and the concentration induced by lee vortices in combination with wave asymmetry are dominant. Improved sediment transport models have been developed to represent these conditions. A range of models was developed from research level models that considered detailed distributions of flow, turbulence/vorticity, and sediment over ripples to more practical and empirical approaches such as TRANSPOR2004 developed by Van Rijn (2004). All have benefited from the breadth of new information developed from the SANDPIT study. The TRANSPOR2004 approach and two other practical approaches were applied to the various data sets generated in SANDPIT and found to be within a factor of 2 of the measured values 40 to 70% of the time, which was considered good considering the variability in the measured data (given the uncertainties in field data it is difficult to measure within a factor of 2). Most of the models were able to predict sand transport rates within a factor of 4 most of the time. This demonstrates the complexity of sand transport in these depth ranges under combined waves and currents with rippled bed.

The morphologic models were tested in two ways: 1) using calibrated sand transport rates based on the observed change in the bed through time; and 2) through the use of predicted transport rates. This allowed for the morphologic aspect of the models to be tested independent of the transport rate predictor. The key models tested included: Delft3D (Delft); PISCES2DH/TELEMAC (HR Wallingford); TELEMAC with SISYPHE and two others (Sogreah); MIKE21 CAMS (DHI); and four other lesser-known models.

In addition to these complex modeling approaches, a much simpler 1D analytical approach was developed using Bailard's transport equation and a representation of the spatial lag effects in suspended sediment concentration following the approach of Galappatti (see Ribberink et. al., 2005). Pit evolution was parameterized as a moving sand wave with the key unknown variables being migration speed and pit infilling (or damping). This practical and simple approach provided reasonable approximations of pit migration velocity and infilling time when compared to the Havinga (1992) and Van Rijn (1986) laboratory data and the Scheveningen test trench (Svasek, 1964). A harmonic solution of the linearized model provided insight into the behavior of the model and pit infilling and migration. The results showed that there were three types of responses depending on the ratio of the length, L (or width) to the depth, h of the pit: 1) the pit is so narrow (L/h<10) that the suspended sediment does not respond to the pit and there is no pit migration contribution of suspended load (and thus migration rates are low); 2) a transition range (from L/h of 10 to 100 or 1000 depending on the ratio of shear velocity to fall velocity) where longer/larger pits migrate faster due to an increasing contribution of suspended sediment to morphology change; and 3) an upper limit to migration speed (L/h greater than 100 or 1000 depending on the shear to fall velocity ratio) where essentially the two slopes act independently. Pit migration is dependent on a net or residual transport rate, usually either due to asymmetry in the wave or tidal transport components. At sites where surface waves contribute to stirring of the seabed sediment and increased bed and suspended load, the pit migration velocity is increased and therefore is proportional to the wave energy at a given site. For short or narrow pits infilling is the dominant process, whereas long or wide pits (i.e. in the direction of transport) are influenced equally by filling and migration. Longer trenches migrate faster and deep trenches migrate slower.

The tests of the morphologic models significantly improved through the course of the study by the addition of improved component predictors (roughness, bedform, hydrodynamics, sediment transport). However, the models still require much improvement to be blindly reliable. Nevertheless, the model results when inter-compared for different conditions do provide relatively reliable guidance on the role of different factors on pit evolution as presented below.

2.2.5 Practical Results

The estimation of annual sand transport rates is essential to predict pit evolution for sandy settings. The infilling rates are primarily determined by the gross transport rate (total of transport in all directions), whereas the rate and direction of migration are determined by the net transport rate. Pits only migrate where there is a net sediment transport rate due to tidal or wind-driven current asymmetry. The net transport is difficult to calculate, as it is generally the small difference of two large numbers.

Even with current computing power it is not possible to apply 3D hydrodynamic, sediment transport and morphodynamic models for long periods (20 to 60 years) on the morphologic scale of large dredged pits. It is necessary to apply process or input filtering to apply these complex models for such long time periods.

Net and gross sand transport rates were estimated using several predictive approaches and with the available data. The Noordwijk site bears many similarities to some of the deeper sandy areas offshore Louisiana in terms of wave height (average maximum annual wave heights in the range of 5 m with period of 11 s), water depths (13 m with a 2 m tide range), current velocities (most common speed being 0.2 m/s up to a maximum of 0.6 to 0.8 m/s depending on direction), and a D50 of 0.2 mm. The net annual sediment transport rate was estimated by various predictors and considering the measured data to be in the range of 1.5 to 7 m^3/m/year, and the gross transport rate was in the range of 70 m^3/m/year for the central estimate.

The Teignmouth test site on the English Channel in the UK featured a water depth of 5 m (but varying in a range of 2.2 to 8.4 m with tide), D50 =0.17 mm, an annual mean current speed of 0.1 m/s and maximum of 0.85 m/s and a maximum annual significant wave height of 2.7 m (with an annual mean of 0.4 m). The estimated gross transport rate was in the range of 80 to 110 m^3/m/year, and the net transport was 4 to 10 m^3/m/year.

The CNEXO site on the Baie de Seine on the French coast of the English Channel featured an actual dredged pit that was mined in the period 1974 to 1980. The pit is 2500 m long, 400 m wide, and the adjacent depths are 17 m. The tides generate rotary tidal currents with maximum and minimums of 0.7 and 0.2 m/s, respectively, for the large tidal range of 6.5 m. Significant wave heights exceed 1.4 m 22.5% of the time and the peak annual significant wave is 3.3 m with relatively short peak periods in the range of 4.4 to 7.5 s. The sand is relatively coarse with D50 of 0.2 to 0.5 mm. The pit consists of a narrow deep part (10 m deep) and a wide shallow section with a depth of 5 m. The gross transport rates were estimated to be in the range of 1 and 50 m^3/m/year (depending on the direction – cross-shore or alongshore and depending on the predictor approach). The CNEXO pit had filled to only 25% of capacity 20 years after dredging. In other words, morphologic response at this site is slow, and this is consistent with the low gross and net transport rates at this site.

Table 2.1 provides a summary of the net and gross transport rates at each site together with the main influencing factors. It is interesting to note that this range of conditions is roughly similar to the conditions on Ship Shoal offshore Louisiana. The estimated rates for the Ship Shoal area using similar approaches are presented in Section 3.2.

In summary, the gross transport rates increase with wave height and current speed and decrease with grain size and water depth, however, there is no simple rule of thumb to determine transport rates; they must be calculated at each site. The net transport rates are very sensitive to asymmetry of waves and tides and hence are very site dependent.

The ability of the numerical models to predict pit evolution was tested through comparison to the numerical model results to laboratory and field data on pit evolution; the following data sets were used:

- Van Rijn (1986) consisting of a pit in a laboratory flume with waves and currents parallel to coast; velocity profiles, sediment concentration, and bed change were measured;

- The Havinga (1992) tests in a laboratory wave basin with waves normal to the shore and currents parallel to the shore, velocity profile, sediment concentration and bed change were measured (see Walstra et. al., 1999 for examples of model to laboratory data comparison). A comparison of results from the SUTRENCH model to the laboratory results of Havinga (1992) with perpendicular wave and currents is given in Figure 2.27 (from Walstra et. al., 1999);

TABLE 2.1. Summary of Gross and Net Transport Rates from SANDPIT study (modified from Van Rijn et. al., 2005).

Site	Region	Mean Water Depth (m)	D50 (mm)	Annual Max. Current (m/s)	Annual Max. Wave Hs (m)	Gross Transport (m^3/m/yr)	Net Transport (m^3/m/yr)
Noordwijk	East North Sea	13	0.25	0.87	4.6	15 to 75	1.5 to 7
Teignmouth	North English Channel	5	0.17	0.85	2.7	80 to 110	4 to 10
CNEXO Pit	South English Channel	21	0.2-0.5	0.76	3.3	1 to 50	0.3 to 3

- The PUTMOR pit offshore the Netherlands where only velocity profiles were measured (Svasek, 2001; see Walstra et. al., 2003 for comparisons of model to field data);

- The Scheveningen Test Trench dredged excavated normal to shore in depths of 7 to 10 m filled in six months in 1964, only morphology measurements were made (Svasek, 1964);

- CNEXO pit on the French coast of the English Channel near the mouth of the Seine River where only morphology change measurements were made (Gomi and Sergent, 2004).

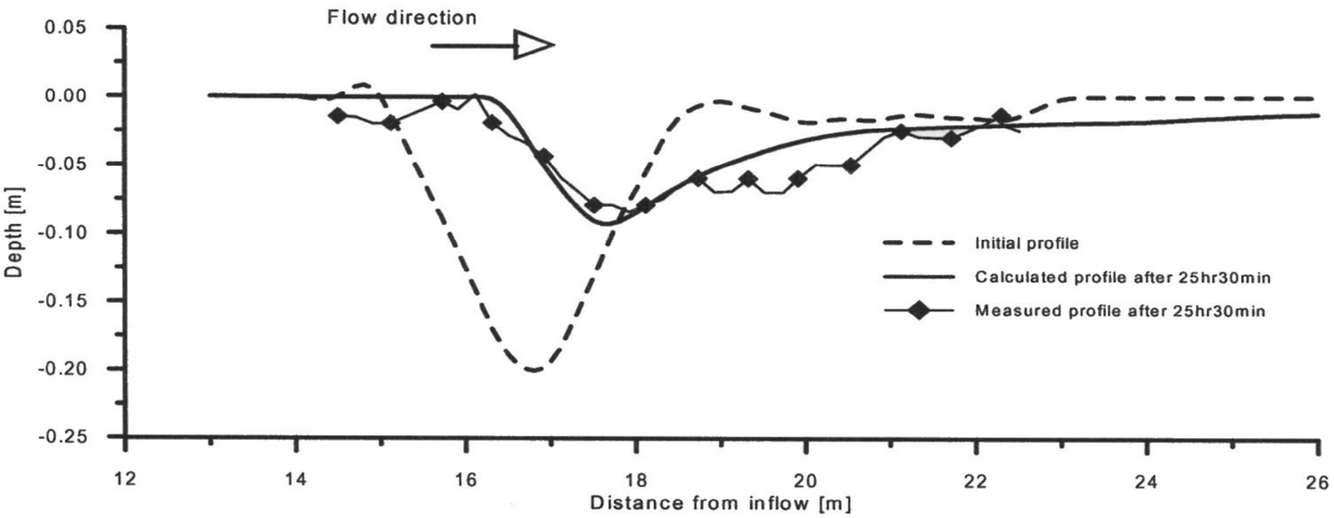


FIGURE 2.27. Comparison of Measured and Calculated Pit Evolution for the Havinga (1992) Laboratory (with the Delft model SUTRENCH) Test with Wave and Currents (from Walstra et. al., 1999).

Clearly, in all cases the field data sets are not ideal due to limited observations. Nevertheless, these data sets provided a valuable tool to test the various morphologic models. The greatest weakness of these models remains the ability to accurately predict the gross and net transport rates in the absence of the pit. Once these rates were calibrated for a given pit (laboratory or field data), the models did reasonably well at predicting pit evolution, but there remained discrepancies between models.

The second approach taken for the morphologic model testing, after completion of comparisons to the laboratory and field data sets, was to complete benchmark testing for a hypothetical test pit using the different morphologic models. The hypothetical test pit conditions were developed to be roughly representative of conditions offshore Noordwijk on the Dutch coast. The following is a description of the conditions considered:

- Water depth of 10 m for the baseline case (but depths from 5 to 20 m were tested);

- Pit shape, varying length, breadth, depth and aspect ratio for a fixed volume of 3.5 million m^3 (base dimensions: 1000 m alongshore, 300 m wide and 10 m deep);

- Pit volume was varied from 0.4 to 28 million m^3;

- Distance from shore was tested by varying the profile steepness (with the pit always at a depth of 10 m);

- Sediment characteristics – finer and coarser than the base 0.25 mm;
- Tides larger (e.g. UK, France) and smaller (e.g. Mediterranean, Baltic);
- Waves larger (e.g. Atlantic coasts) and smaller (e.g. Mediterranean).

The detailed results for all tests are provided in Part 2 of the End Document for the SANDPIT study. A summary of those results relevant to the initial management questions is provided in Section 2.3.6 below.

2.2.6 Answers to Management Questions

This section provides a summary of the answers *(in italics)* to the management questions taken directly from the SANDPIT Part 1 report (Van Rijn et. al., 2005). Our comments are included in square brackets without italics. It is noted that while the SANDPIT studies focused on sandy environments (versus muddy settings where mud must be stripped to access buried deposits – such as Sandy Point offshore the west flank of the Mississippi River delta) the answers to questions 1a, 1b and 1d below would apply to either setting. The answers to the remaining questions below are mostly only relevant for sandy settings.

1. Will an offshore mining pit modify the local flow and wave fields in such a way that the transport regime and the large-scale bedforms (sand banks) in the direct vicinity are influenced? Can the magnitude of an effect be quantified?

   a. What is the change in maximum tidal current velocity due to the presence of a dredged pit (or dredged sand bank) of given size?

      Over the pit the depth-averaged velocity for a 10 m pit in 10 m of water decreased by 10% in the pit and to both sides of the pit. *There is a 10 to 20% increase in velocities outside the pit in the direction of the flow caused by the reduced resistance to flow in slightly deeper areas, and a slight reduction of the edges perpendicular to flow* [the flowing water needs to fill the volume of the pit and is therefore attracted to the pit – this decreases the flow at the sides and increases the flow beyond the ends]. *The flow is decreased by 10 to 15% in the center of the pit and 20-25% at the toe of the side slopes* [without consideration of the flow attraction effect the reduction would be 50% due to an increase in water depth from 10 to 20 m over the pit]. *The influence areas are of the order of 50% of the length of the pit* [i.e. about 500 m upstream and downstream].

   b. What is the change in wave height during a storm due to the presence of a pit of given size?

For the baseline case, the model results show small changes (<5%) except for two lobes pointing towards the shore off each end of the pit where the wave heights are increased by 10 to 15%.

c. What are the effects of modified flow and wave conditions on the local sand transport capacity?

In the center of the pit the sand transport rates were reduced by 40 to 90% and outside the pit the rates were increased by 70 to 200%. However, large differences were found between the absolute values predicted by different models. Outside the pit, shallower pits have a smaller impact (although over a greater area) than deeper pits of the same volume.

d. What is the influence area?

For the baseline case (a 1 km long pit), currents and waves were modified by 5% or less beyond a 1 km boundary around the pit and sediment transport are affected by 5% or less beyond a 1.5 km boundary around the pit.

2. Will the mining pit act as a sediment sink and thereby have a particularly marked impact on the seabed immediately adjacent to the pit? Can the magnitude and extent of this impact be quantified? How can this impact be minimized?

A follow-on question was added by end-users through the course of the SANDPIT study: Over what time-scales will the effects be felt? *The characteristic time scale is based on the assumption that pit infilling follows an exponential decrease (V_0: initial volume, V_t: backfilled volume at time t, T_k characteristics time scale):*

$$V_t=V_0(1-e^{**}[-t/T_k]).$$

a. What is the sand transport regime in relation to the current and wave regime outside the dredged pit?

The stirring effect of the waves plays a dominant role in sediment transport [this role is significantly reduced or completely eliminated for deep pits]. *The tidal currents are strong enough to transport the sediment on their own, but the transport magnitude is greatly enhanced by wave action. At the test site the asymmetry in the tidal currents (stronger flood than ebb current) results in a net sediment transport to the north, which in turns causes the pit to migrate to the north* [due to a reduction in transport down the upstream slope and an increase in sand transport up the downstream slope].

b. What is the effect of (modified) bed forms and (modified) particle size on the sand transport regime outside the pit?

[The first part of the question was not directly answered, other than to say the influence of bedform was considered implicitly in the sediment transport formulae used in the models]. *The effect of a 50% increase in particle size is to increase the northward migration rate of the pit by about 40%, and the vertical migration (infill rate) by about 100%* [this is because the coarser sediment would feature more bed load that reacts more quickly to the change in depth]. *A decrease in particle size by 50% reduces horizontal migration by 30% and vertical migration by 20%.*

c. What is the gross and net annual sand transport outside the pit?

For the baseline case, there was a wide range of predicted annual transport rates between the various models, with the net rates varying between about 20 and 600 m^3*/m/year and the gross rates between 180 and 2,500* m^3*/m/year* [the higher end rates were for a much more exposed Atlantic Ocean coast which we have not summarized here due to the fact it represented much more energetic conditions than those that exist offshore Louisiana]. *The net values are relatively inaccurate as they depend critically on a small difference between large numbers. A small disagreement in current velocity of the various models (ebb and flood) may result in a relatively large difference in net transport rate. The relatively wide range of transport values predicted by the different models reflects our limited knowledge of sand transport in coastal conditions. It is noted that the field data set obtained during the SANDPIT project actually is the only reliable data set with measured depth-integrated transport rates for deep water (>10 m) in coastal seas.*

d. What is the amount of sand trapped in a pit of given size per year and over 50 years?

Some of the key results are:

- *The exponential time-scale of infill for a pit of 3.5 million* m^3 *volume in the North Sea Conditions with a 0.2 mm sand bed is: in the range of 5 to 30 years, if the pit is located at the 10 m contour; and in the range of 30 to 150 years if the pit is located at the 20 m contour.*

- *The longshore migration rate of the pit is in the range of 10 to 100 m/year.*

- *The pit shape has only a minor effect on the infill time and migration rate.*

- *The time-scale of infill increases by a factor of 5 if the pit volume increases from 3.5 to 28 million* m^3*.*

e. What is the erosion on the flanks of a pit per year and over 50 years?

f. What are the net migration rates in longshore and cross-shore direction?

[One answer was provided for (e) and (f) together]. *For the baseline case, all partners predicted a northward migration of the pit, with rates varying between 10 and 100 m/year. The migration rate increases with pit volume and grain size, with no conclusive trend identified for distance from shore. The effect of an increase/decrease of 50% in particle size is to increase/decrease the northward migration rate of the pit b 30 to 40%. An increase/decrease in pit volume by a factor of 8 caused an increase/decrease in migration rate by a factor of 2. At the baseline site, no significant cross-shore migration was observed.*

g. What should be the location and dimensions of the pit to minimize these effects?

This question was answered by indicating it was really a site-specific consideration due to the trade-offs between different possibilities. For example, a pit could be moved offshore to limit the potential for migration, but at the same time it would cost more to extract the sand. Also, the infill process would take longer and it would be more likely to fill with fine sediment which is a negative ecological influence (if the surrounding area is sandy). Some specific recommendations are presented below:

- If it is desirable for the pit to fill faster, its longest dimension should be aligned perpendicular to the main flow direction. However, this would have economic impacts on the dredging operation, as dredgers prefer to operate into and with the tide instead of across the currents.

- With respect to time-scale for infill (T_k) the model predictions were compared to the actual infill (or dispersal for mounds) of man-made features on the sea floor (6 pits, 2 trenches, and 2 spoil dump sites). T_k increased from 1 year to over 100 years for features in depths ranging from 10 m to 23 m in depth. These may be compared to model estimates of 5 to 30 years and 30 to 100 years for depths of 10 m and 20 m, respectively. The observations displayed a scatter of a factor of 30 at any one depth, which is similar to the greatest scatter among model results. With respect to the influence of the volume of the feature, T_k increased from less than 1 year for volumes less than 0.5 million m^3 to over 100 years for a pit of volume 4.5 million m^3. In comparison, the models predicted 2 years to infill a pit of 0.4 million m^3 and 50 years for a pit of volume 28 million m^3.

In general the modeling, even when sophisticated (with 3D hydrodynamics and complex sediment transport), was inaccurate in the predictions of morphologic change, primarily due to the inability to predict sediment transport rates in these depths of water.

Nevertheless, the models are able to explain trends in change for the factors influencing pit evolution and why these trends occur.

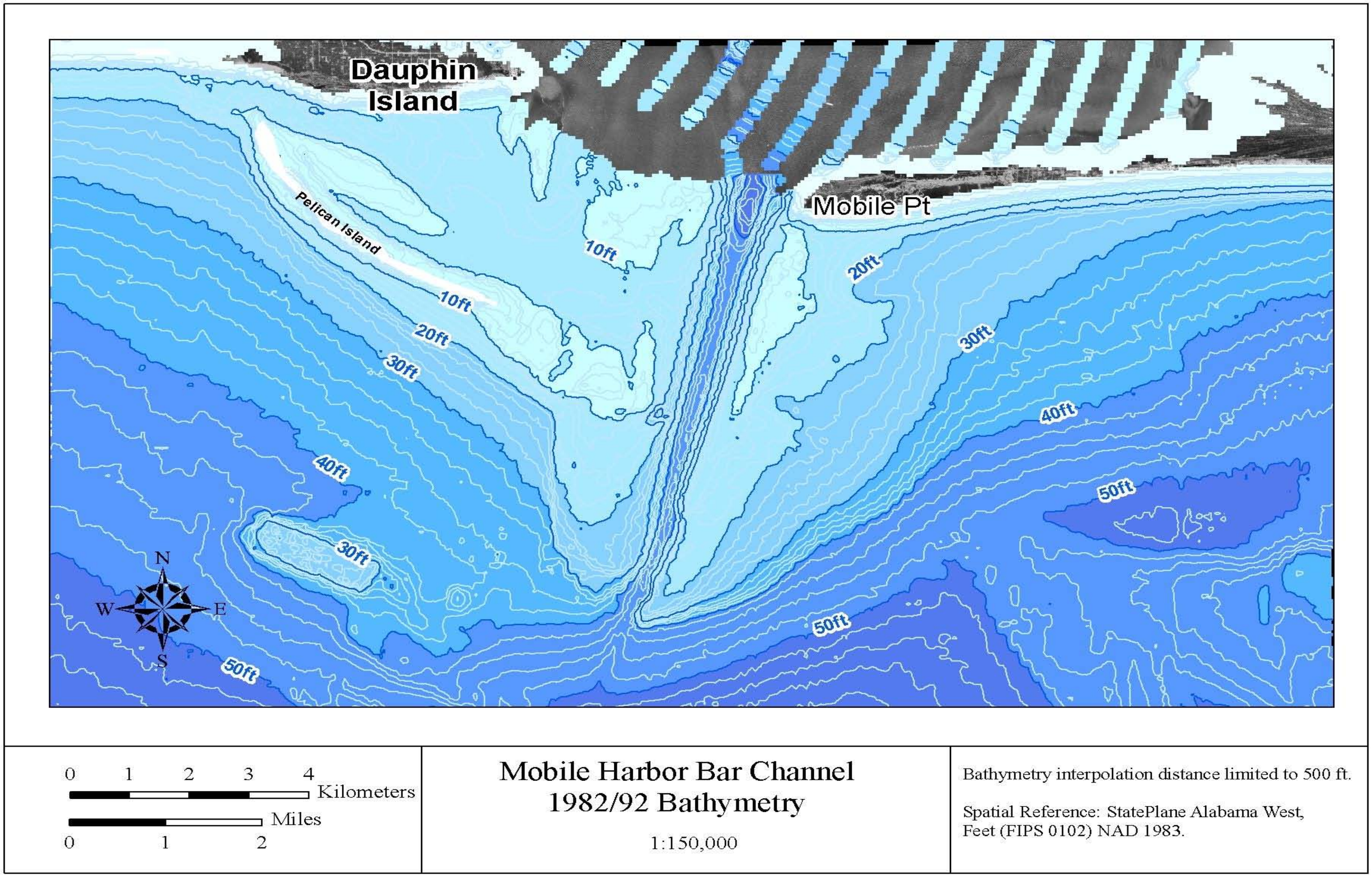
2.3 Evolution of Other Channels and Pits

A review of existing information on some relevant channels and pits was completed based on the in-house experience of Baird & Associates and the LDNR (2004) reference to the Delray Beach nourishment dredged pits offshore the southeast Florida coast.

2.3.1 Mobile Harbor Bar Channel

The Mobile Harbor Bar Channel in Alabama has existed for many years dating back to at least the early 1900s. The most recent regional bathymetry from 1982/1992 is shown in Figure 2.28(a). The channel extends for several kilometers beyond the coastline in water depths of 5 to 10 m. The erosion and deposition history, both long-term regionally and short-term locally, is shown in Figure 2.28(b). The long-term change is based on a comparison of most recent depths (as noted above) to depths from the 1917/1920 charts. The local and more short-term change in the vicinity of the Bar Channel is demonstrated through the before and after dredge profiles shown in Figure 2.28 (based on data provided by Great Lakes Dredge & Dock Co.). The 1917/1920 depth soundings are also shown where available along these selected profiles. The after-dredge profiles provide an indication of the likely condition immediately following the last dredging effort three or four year before (this information was not available due to an ongoing legal action associated with this navigation channel).

The Bar Channel fills in at a rate of about 200,000 m^3/year (personal communication, C. Dyess, Chief of Navigation, Mobile District Office of the U.S. Army Corps of Engineers). Applied Coastal Research and Engineering et. al. (1999) indicate that the net longshore sand transport direction along this coast is from east to west. Therefore, the shape of the navigation channel (and the inferred change from the before- and after-dredge profiles) is consistent with a net migration of the channel from the east to the west. The channel is only held in position by the ongoing dredging efforts. The west slope of the channel provides an indication of the long-term slope change that occurs to a dredged channel (or pit) when there is a net longshore sand transport rate. There has been significant flattening of the slope to approximately 1V:30H. Without the more recent dredged survey data it is not possible to determine whether this slope is continuing to migrate or flatten. In contrast, the updrift slope is about 1V:5H. Therefore, this provides a relatively local example for Gulf of Mexico wave conditions on the evolution of pit slopes exposed to a net longshore sand transport rate. It must be recognized that due to the unavailability of more recent dredging records and surveys, it can only be inferred that the asymmetry in slopes is due to natural influences and not dredging practices. Nonetheless, this pit response evolution is what would be expected theoretically, as noted in Section 2.3.2 on the SANDPIT study review.



Mobile Harbor Bar Channel
1982/92 Bathymetry

1:150,000

Bathymetry interpolation distance limited to 500 ft.

Spatial Reference: StatePlane Alabama West,
Feet (FIPS 0102) NAD 1983.

FIGURE 2.28.a. Mobile Harbor Bart Channel, Alabama

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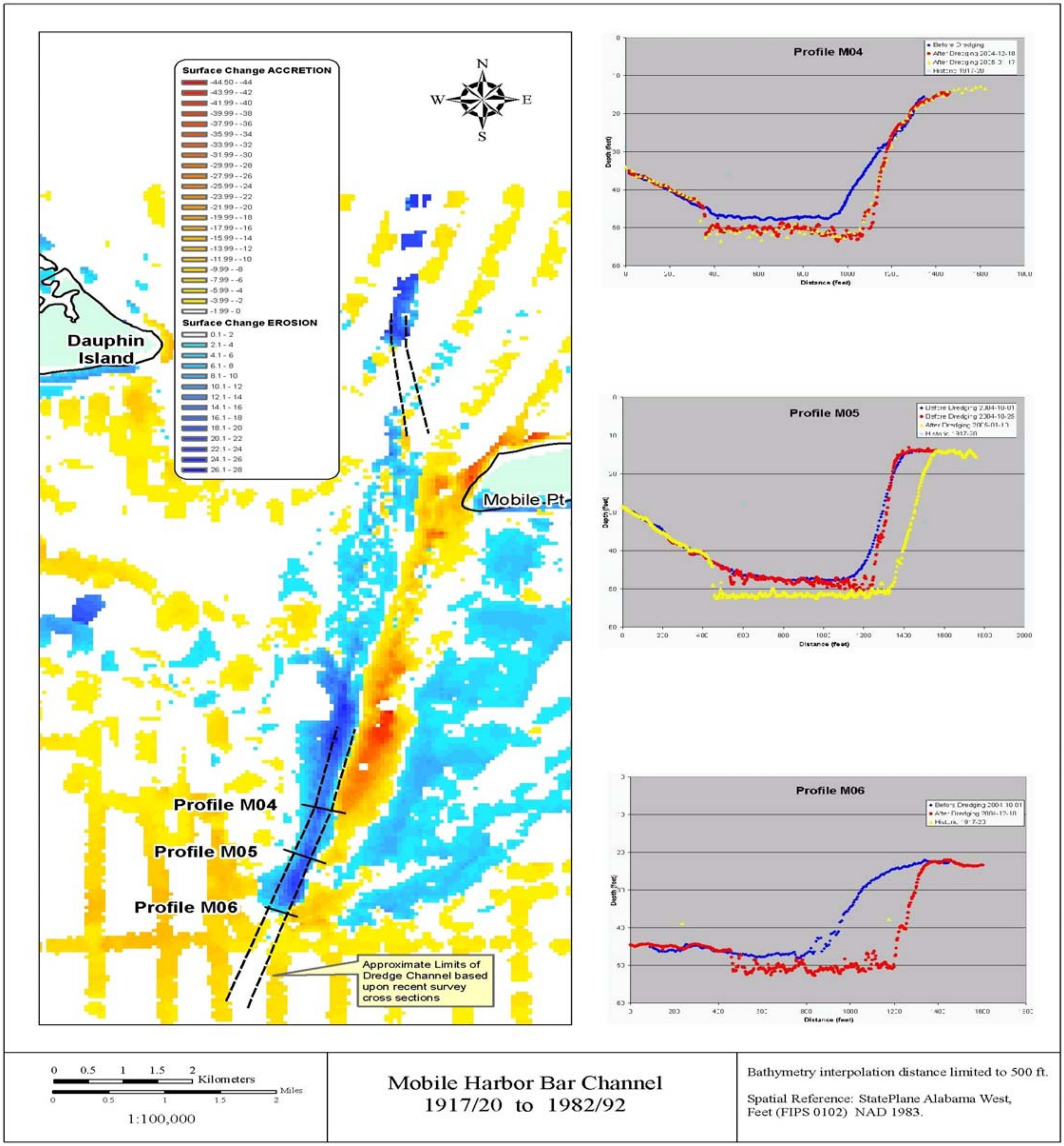


Mobile Harbor Bar Channel
1917/20 to 1982/92

Bathymetry interpolation distance limited to 500 ft.

Spatial Reference: StatePlane Alabama West,
Feet (FIPS 0102) NAD 1983.

FIGURE 2.28.b. Mobile Harbor Bar Channel Evolution.

2.3.2 Tampa Bay Dredge Pits

In an MMS report, Blake et. al. (1996) report on the effects of dredging on the geology and benthic organisms for two dredged pits offshore Tampa Bay (and specifically offshore Egmont Key and Longboat). The borrow sites are located approximately 5 to 10 km from shore with average water depths of 10 to 15 m at Egmont Key and 5 to 6 m at Longboat. Blake et. al. (1996) indicated that the background suspended load is very low generally and the water is clear. The Egmont Key borrow pit was excavated with a clamshell dredge whereas the Longboat pit was dredged with a dustpan dredge.

Unfortunately, the information on pit response at both these sites was incomplete. At the Egmont site there was a pre-dredge survey but no post-dredge survey immediately after dredging. The first post-dredge survey was completed approximately two years after dredging in October 1994. It would appear that the dredged area consists of the removal of 2 to 4 m of sediment in an irregular manner (i.e. there are many peaks and troughs in the dredge area generally with vertical relief of about 2 m). The steepest side slopes of the various cuts in the dredge area are in the range of 1V:50H to 1V:67H. However, it is uncertain whether they were dredged at this angle or evolved to this slope. Interestingly, the bathymetry survey also captured two shipping channels on either side of the borrow area for beach nourishment sand. The side slopes of these channels ranged from 1V:25H to 1V:50H. Although it is possible they were dredged to this angle, it is more likely that they evolved to this angle over time, as there would be no reason to dredge side slopes to a relatively flat slope.

The Longboat borrow site was not surveyed prior to dredging, and the only post-dredge survey was completed approximately 6 months after dredging in September 1993 (Blake et. al., 1996). The survey results show a relatively irregular seabed (at least when plotted with a vertical exaggeration of 100x). The range of slopes between the peaks and troughs in the dredge area range from 1V:5H at the steepest to 1V:32H at the flattest with an average in the range of 1V:25H. Again, it is not certain whether the slopes were dredged to this angle or evolved to this angle.

2.3.3 Delray Beach Dredge Pits

LDNR (2004) provided information on a series of dredge pits located offshore Delray Beach, Florida. Coastal Planning and Engineering (Benedet, personal communication) provided additional information on the bathymetry and geology in the area of these surveys and the history of dredging. The pits are located between 1,600 and 3,000 ft (500 and 1,000 m) offshore in depths of 35 to 65 ft (10 to 20 m). The dredge pits are 10 to 20 ft deep and were dredged in 1973, 1978, 1984, 1992 and 2002 (see Figure 2.29).

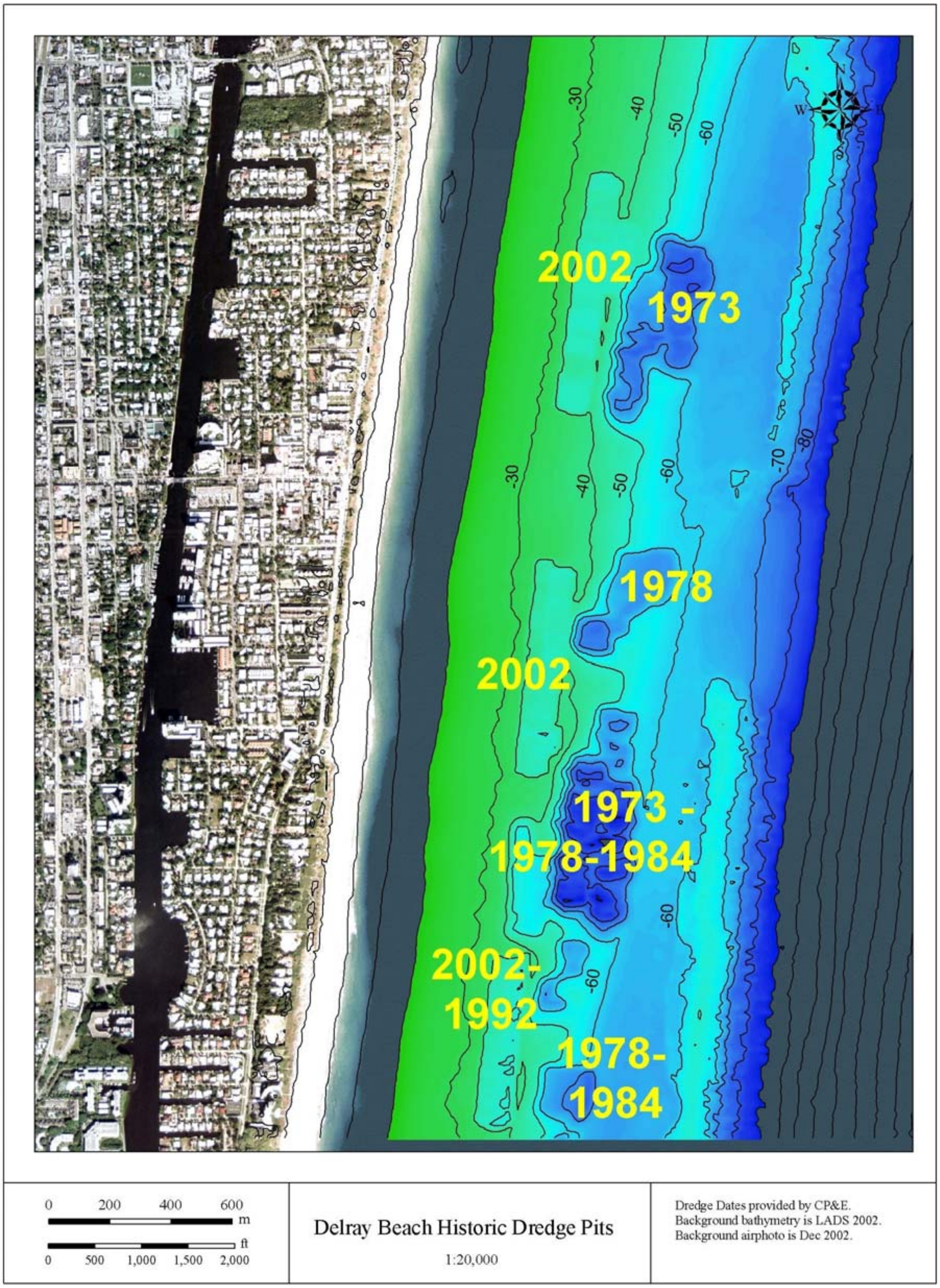
In the LDNR (2004) review contribution by Finkl of Coastal Planning and Engineering, it is noted that "…the measurements indicated the side slopes on these sandy borrow areas ranged from 1V:3H to 1V:7H". Furthermore the dredge pits do not appear to have filled in significantly, if at all. The morphologic time-scale for these pits must be very long.

To evaluate the morphologic time scale, estimates of the annual average gross transport rate were made using the Van Rijn (2004) formulation (this approach was used in the estimate of gross and net rates summarized in Table 2.1 for the SANDPIT study). Wave data were derived from WIS Stations 462 and 463. Representative current data were derived from Soloviev et. al. (2003) based on ADCP measurements offshore Dania Beach (about 60 km south of Delray Beach) in water depths of 11, 20 and 50 m. The gross transport rate was estimated to be 5 m^3/m/year at the 12.5 m contour and 5 m^3/m/year at the 17.5 m depth contour. Even the higher value is less than the lowest estimates at most SANDPIT test sites with the exception of the CNEXO site on the French coast of the English Channel where morphologic response was also slow (the pit was only 25% full 20 years after dredging). The three older pits dredged between 1973 and 1984 are located between the 15 and 20 m depth contour and little response if any is expected due to the very low gross annual transport rate. Therefore, the slow morphologic response at the Delray borrow sites is due to a combination of factors: moderate wave energy, generally low tidal currents, and relatively deepwater (10 to 20 m) resulting in low gross annual sand transport rates.

2.3.4 South Carolina Dredge Pits

Van Dolah et. al. (1998) describe the evolution of a series of five pits dredged between 1990 and 1995 offshore South Carolina for beach nourishment projects. All but two of these sites were located very close to shore or even within tidal inlets. These two were the Hunting Island borrow site located 2.8 km offshore in 5 m of water and the Gaskin Banks borrow site located 3.7 km offshore Hilton Head in 3 m of water. Details on these two borrow deposits and their infilling rates are summarized in Table 2.2.

The post-dredge information reported for these pits is again limited in nature with simply a written description or it was not available at all. Therefore, it is not possible to determine the slopes of the dredge pit immediately following dredging. However, it is likely that these slopes were dredged to a relatively steep angle, particularly given the shallow nature of the pits. At Gaskin Banks the side slope angles are now in the range of 1V:20H to 1V:50H and at the Hunting Island borrow site they are even flatter at 1V:30H to 1V:90H. Due to the shallow water depths at these sites and the moderate tide range, the wave and current conditions are relatively energetic and the morphologic time scale is relatively short. Where filling is rapid, slope change also appears to be significant, at least for sandy settings.



Delray Beach Historic Dredge Pits

1:20,000

Dredge Dates provided by CP&E.
Background bathymetry is LADS 2002.
Background airphoto is Dec 2002.

FIGURE 2.29. Dredged Pits Offshore Delray Beach, Florida (from Coastal Planning and Engineering).

TABLE 2.2. Summary of Hunting Island and Hilton Head Dredge Pit Evolution (modified from Van Dolah et. al., 1998).

	Gaskin Banks, Hilton Head	**Hunting Island**
Month/Year Dredged	March 1990	February 1991
Water Depth	3 m	5 m
Pit Depth	3 m	1 to 1.5 m
Pit Volume	1,400,000 m^3	625,000 m^3
% Infilled by 1996	51%	68%
Estimated total years to fill completely	11.8	7.7
Grain size (D50, mm)	0.18	0.12
Side Slopes in 1996 (V:H)	Mostly 1:20 to 1:50	Mostly 1:30 to 1:90

2.3.5 Nile River Delta LNG Facility Dredged Channel Evolution

A new LNG facility was recently constructed just west of the mouth of the Rosetta Branch of the Nile River in Egypt at Idku on Abu Quir Bay. The annual maximum significant wave height at the site is about 5 m. The bay has a small tidal range (about 0.2 m) but currents are generated frequently by wind and waves and feature a yearly maximum current of 0.6 to 0.9 m/s with average currents in the range of 0.1 to 0.3 m/s (HR Wallingford, 2002). The grain size between the 10 and 14 m depth contour is very fine sand (D50 of 0.07 to 0.1 mm).

A trestle way services a mooring area protected by a breakwater at the 11 m depth contour approximately 2.5 km offshore. A 4 km long navigation channel extends from this mooring basin outside the breakwater in open water to the 14 m depth contour to provide navigation depths in the range of 14 to 14.5 m. Therefore the channel dredge depth ranged from 3.5 m to 0 m along the length of the navigation channel beyond the breakwater. The navigation channel was dredged in October 2003. Bathymetric surveys are available immediately before and after dredging in addition to a survey completed in April 2004 to document significant infilling of the channel. Eighteen examples of the survey cross-sections extending from Station 3+300 (3.3 km from the breakwater) into Station 1+300 (1.3 km offshore of the breakwater) are presented in Figures 2.31(a) to 2.31(r). The location of the cross-sections is shown in Figure 2.30. The cross-sections show the typical mounding of sediment along the edge of the channel immediately following dredging due to the overspill from the hopper dredging operations. The section surveys document considerable channel infilling over the six-month period since the initial capital dredging. If the infilling during the six month period is extrapolated to a full year (i.e. assuming the infilling would be at the same rate for the period April to October) the infilling rates suggest gross sand transport rates in the range of 600 m^3/m/year at a depth of 12.5 m to 150 m^3/m/year at a depth of 13.5 m (these assume that the channel captures all of the sediment transported over it – i.e. a 100% trapping efficiency).

Immediately following dredging, the side slopes were in the range of 1V:7H to 1V: 10H. Six months later the side slopes were in the range of 1V:5H to 1V:240H. In many cases the side slopes were in the 1V:100H to 1V:200H range. In addition, at several of the cross-sections the slope had migrated either with or without flattening. Where significant erosion did occur, the retreat of the edge of the slope was 17 to 170 m with an average of 88 m in six months or 175 m/year if linearly extrapolated. The cross-sections selected featured some of the greatest migration rates, so an average rate may be closer to 100 m/year. These high migration rates resulted from the presence of a strong residual current.

This is another example of a site with a short morphologic time-scale and rapid and dramatic changes in slope angle and location.

2.3.6 Summary of Pit and Channel Evolution Review

There are limited data available in U.S. waters tracking dredged pit slope evolution with time. While there are abundant data related to navigation channels, in these cases it is difficult to interpret the change owing to the ongoing maintenance dredging. For those borrow pits that were reviewed there was a wide range of slopes from 1(V):5(H) to 1(V):50(H), but sometimes even flatter. There were insufficient repetitive survey data at the U.S. sties investigated to determine whether slope migration accompanied slope flattening. For the data from the new navigation channel serving the LNG facility on the Nile River delta, the slope edge erosion (or migration) rates in some areas were in the range of 100 m/year with gross annual sand transport rates of about 300 m^3/m/year. The Delray Beach borrow pits offshore the southeast coast of Florida in 15 to 20 m of water have been very stable for many years and this slow morphologic response is due to very low annual gross sand transport rates at this site (approximately 3.5 m^3/m/year for a depth of 17.5 m). Even for the more recent pits dredged in 10 to 15 m of water, the morphologic response is expected to be slow due to relatively low gross annual transport rates (5 m^3/m/year).

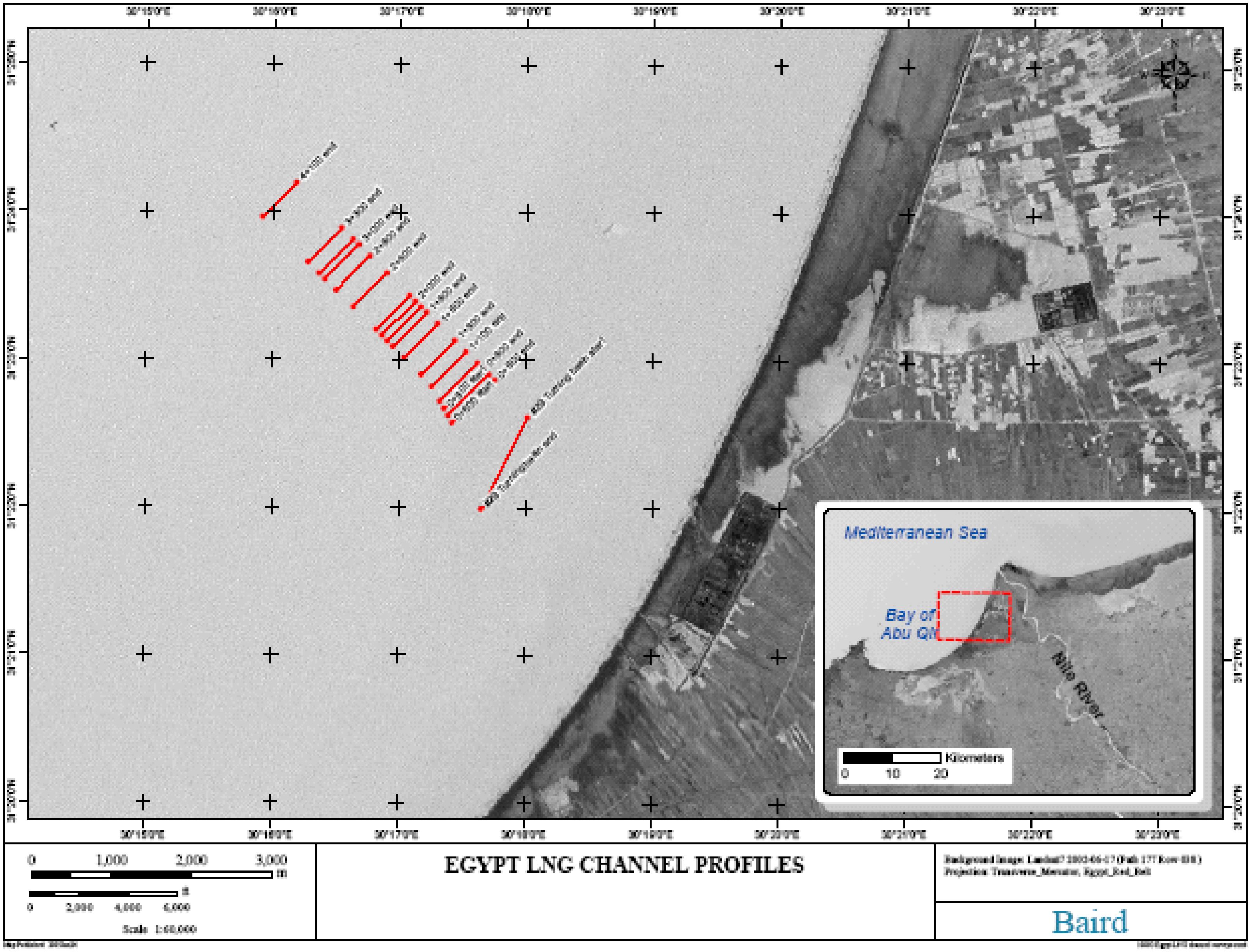


FIGURE 2.30. Nile River Delta LNG Plant Navigation Channel

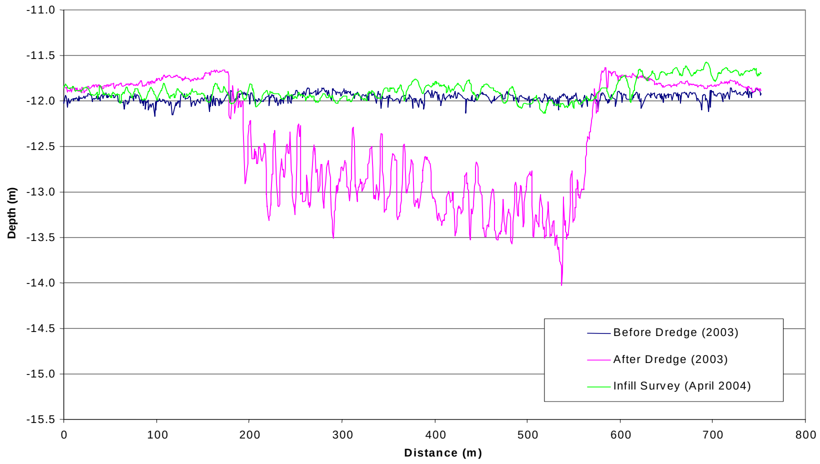


FIGURE 2.31.a. Section 0 + 600, Nile River Delta LNG Plant Channel.

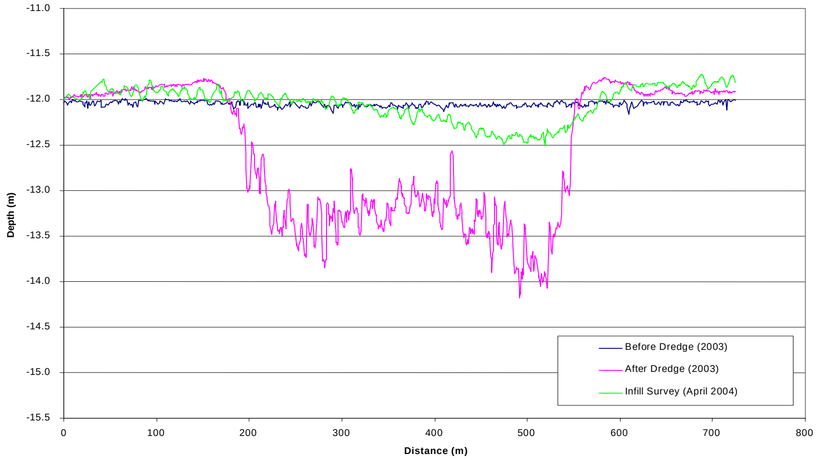


FIGURE 2.31.b. Section 0 + 700, Nile River Delta LNG Plant Channel.

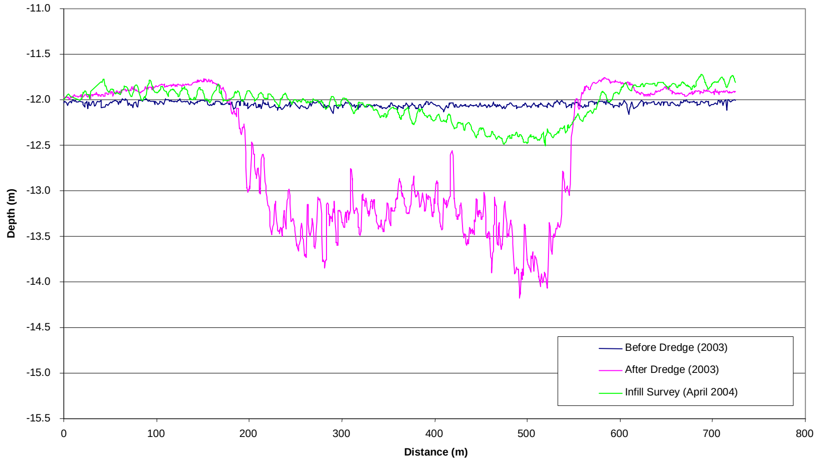


FIGURE 2.31.c. Section 0 + 800, Nile River Delta LNG Plant Channel.

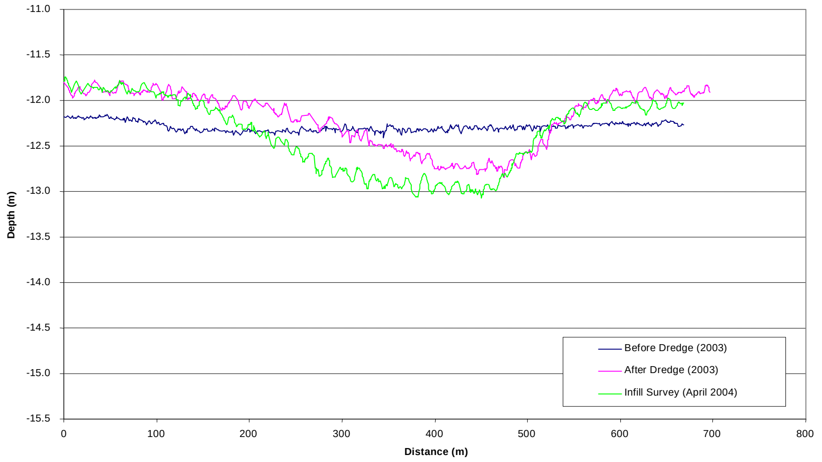


FIGURE 2.31.d. Section 0 + 900, Nile River Delta LNG Plant Channel.

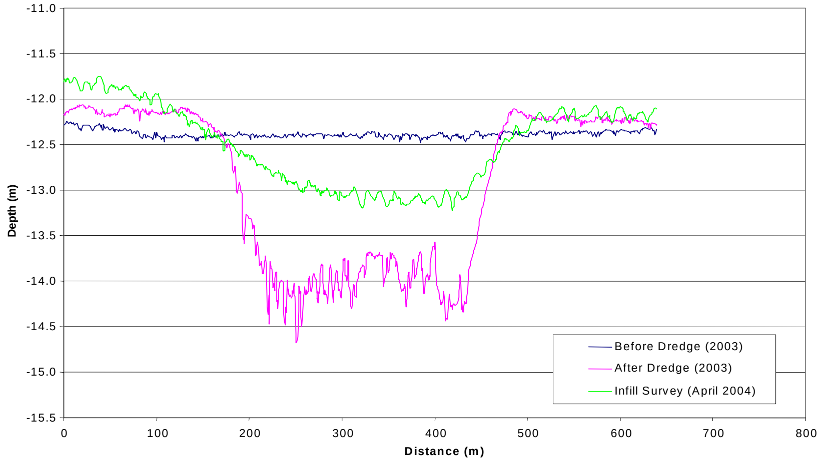


FIGURE 2.31.e. Section 1 + 000, Nile River Delta LNG Plant Channel.

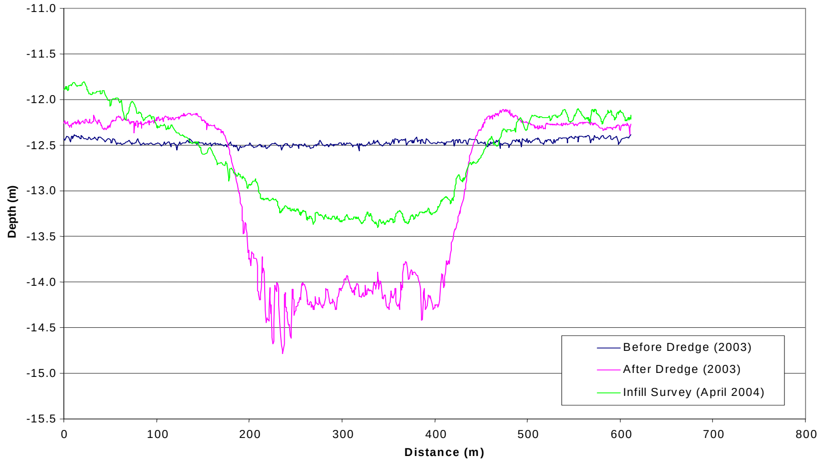


FIGURE 2.31.f. Section 1 + 100, Nile River Delta LNG Plant Channel.

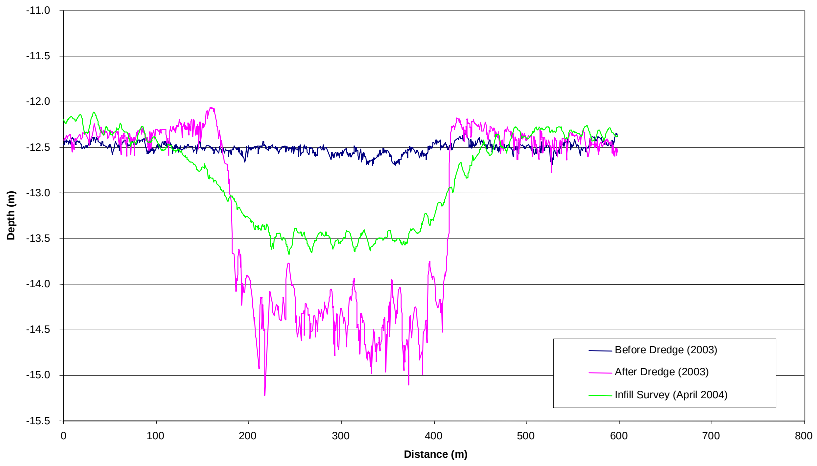


FIGURE 2.31.g. Section 1 + 300, Nile River Delta LNG Plant Channel.

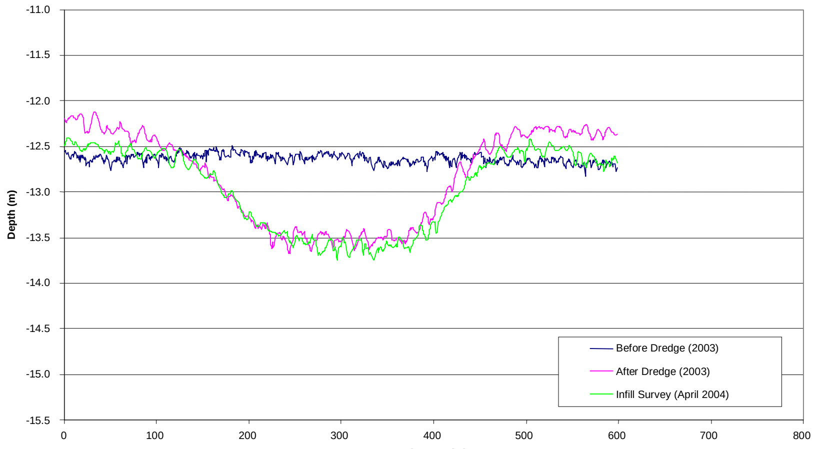


FIGURE 2.31.h. Section 1 + 600, Nile River Delta LNG Plant Channel.

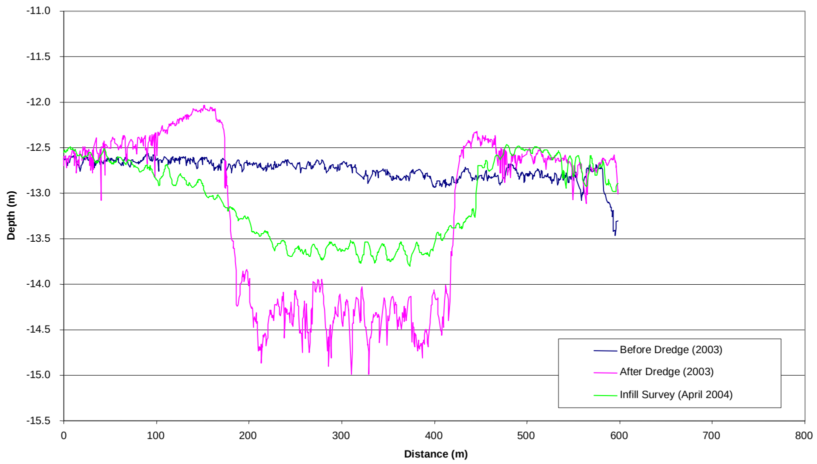


FIGURE 2.31.i. Section 1 + 800, Nile River Delta LNG Plant Channel.

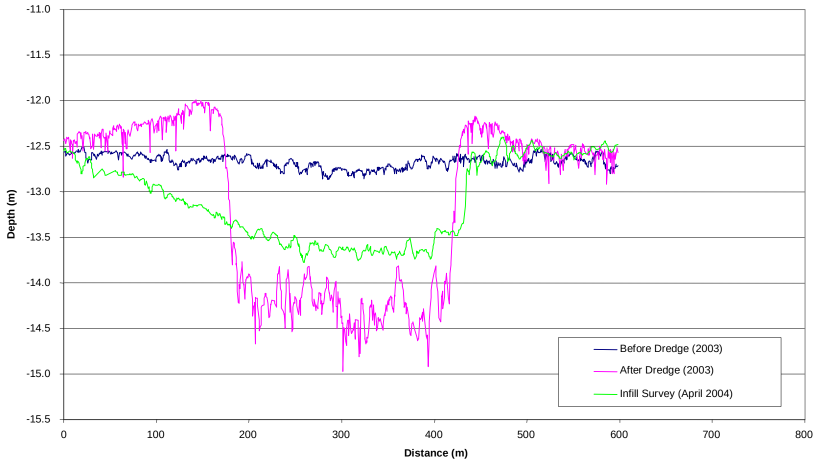


FIGURE 2.31.j. Section 1 + 900, Nile River Delta LNG Plant Channel.

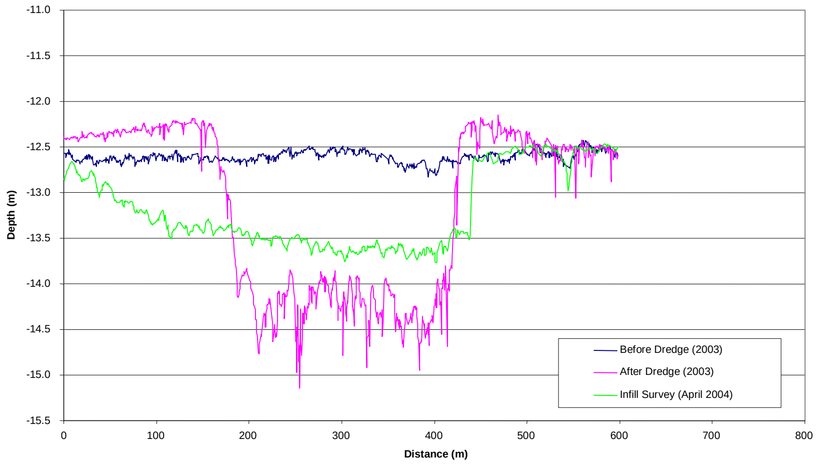


FIGURE 2.31.k. Section 2 + 000, Nile River Delta LNG Plant Channel.

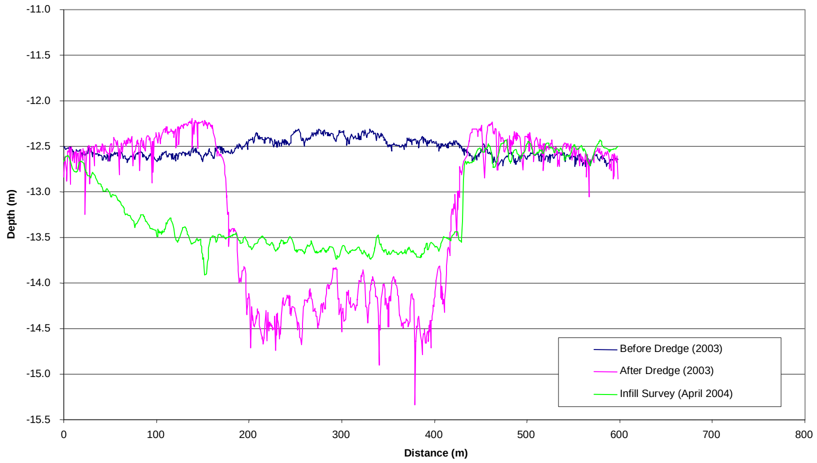


FIGURE 2.31.l. Section 2 + 100, Nile River Delta LNG Plant Channel.

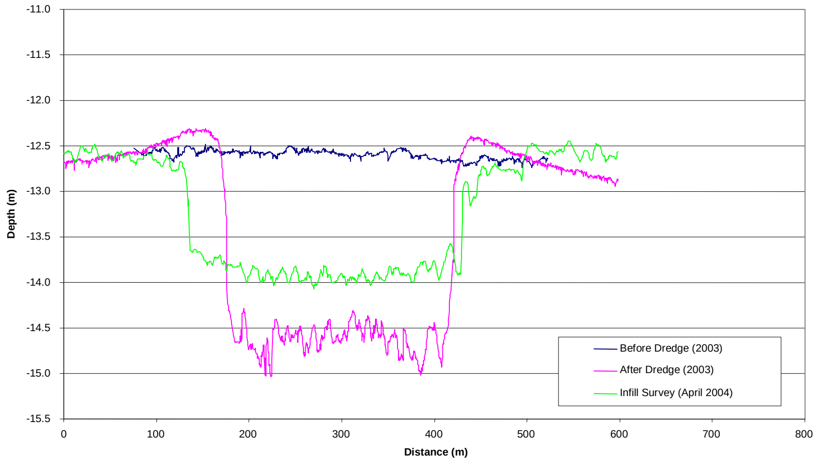


FIGURE 2.31.m. Section 2 + 500, Nile River Delta LNG Plant Channel.

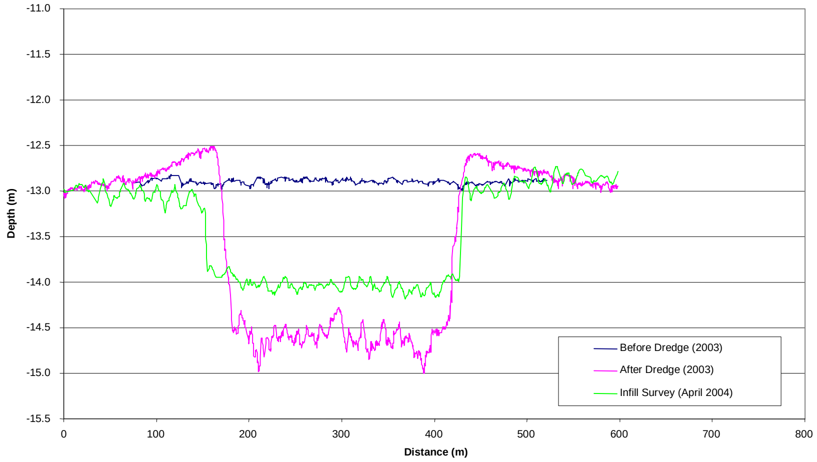


FIGURE 2.31.n. Section 2 + 800, Nile River Delta LNG Plant Channel.

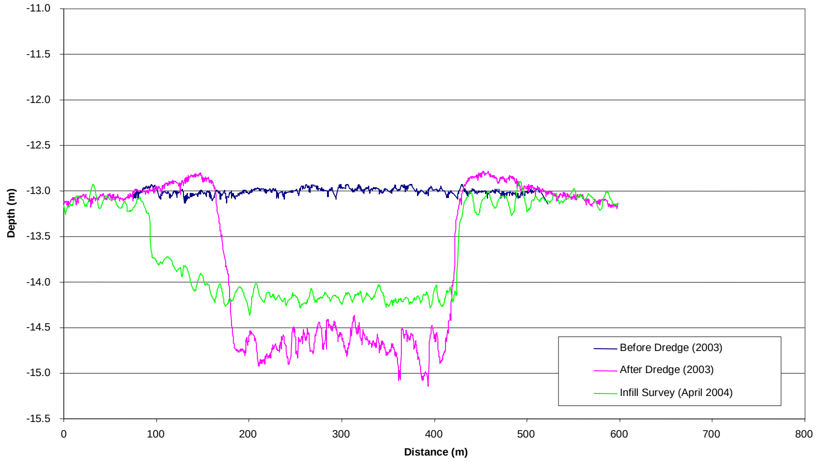


FIGURE 2.31.o. Section 3 + 000, Nile River Delta LNG Plant Channel.

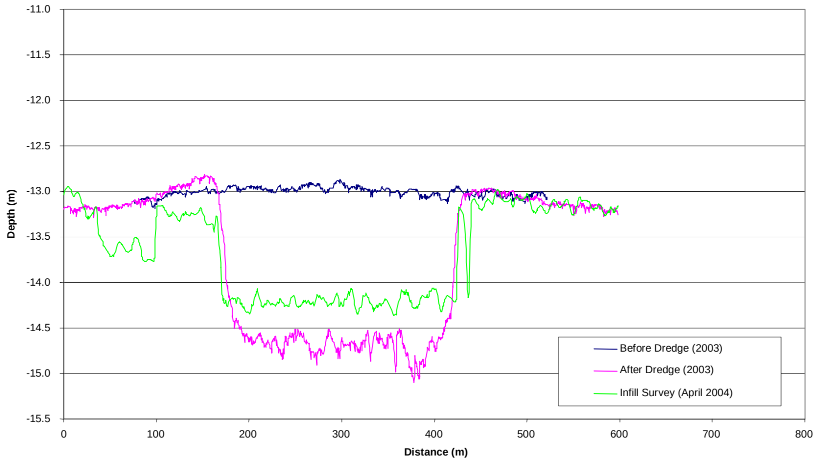


FIGURE 2.31.p. Section 3 + 100, Nile River Delta LNG Plant Channel.

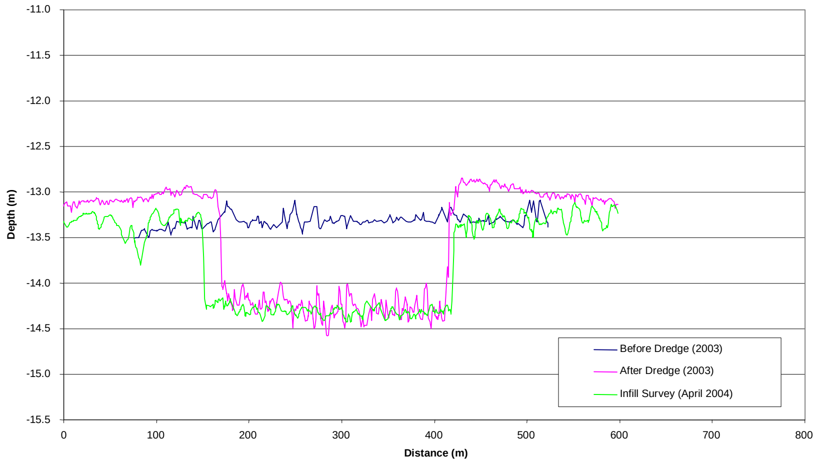


FIGURE 2.31.q. Section 3 + 300, Nile River Delta LNG Plant Channel.

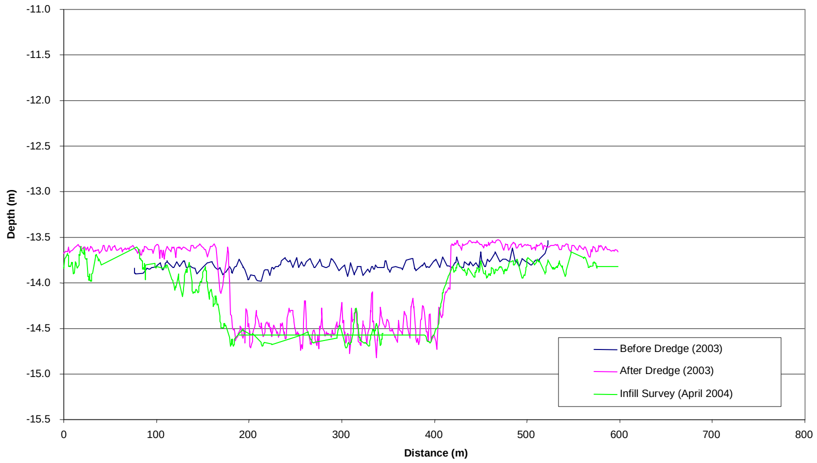


FIGURE 2.31.r. Section 4 + 100, Nile River Delta LNG Plant Channel.

2.4 Underwater Slope Stability

A limited literature review of underwater slope stability was completed and this was complemented by an unpublished review completed by Coastal Planning and Engineering for Louisiana DNR (LDNR, 2004) in response to the preliminary report on possible impacts to infrastructure completed by Baird & Associates and RPI (2004).

The literature review completed by Baird & Associates found that underwater slope stability is generally poorly understood (OCTR 2001-2003). In the absence of wave and current action or related external forcing functions, theoretically, underwater slopes in cohesionless sediment should be stable to the angle of repose, which is the same in water and air. The angle of repose ranges from 38 to 40 degrees (about 1V: 1.25H) for gravel to 26 to 28 degrees for coarse silt (1V:2H). The effects of the dredge operations themselves and the influence of waves and currents may tend to reduce (flatten) the stable slopes by 3 to 5 degrees, resulting in post-dredge slopes of 1V:2.5H in silt and 1V:1.5H in gravel. The slopes could be flattened further through the effects of wave action or through the horizontal acceleration associated with earthquakes. Waves can influence slopes in two ways: 1) through sand transport as discussed in Section 2.3 above; and 2) through the process of liquefaction triggered by the cyclic pressure loading caused by wave action when the waves are large enough and the sediment is loose (Sumer and Fredsoe, 2002; Schapery and Dunlap, 1978). The amount of slope reduction would depend on the magnitude of the wave-induced pressure fluctuations and the local soil conditions.

Where a dredged pit consists of a muddy sediment cap over targeted clean sands the slope stability is increased. Underwater, all but the softest clay/silt (undrained shear strength less than 12.5 kPa) should theoretically stand at the angle excavated, up to vertical, to a height of 5 m (compared to approximately 2.5 m in air). It is unlikely that any stripping operations would exceed the removal of a 5-m cap of muddy sediment to expose the target sand below.

Based on this review it was concluded that an appropriate stable slope for the purposes of defining buffers, in the absence of any significant sand transport (i.e. that exerts another influence on pit evolution), would be 1V:7.5H. This is similar to the recommendation by LDNR (2004) of 1V:7H. This recommendation would only be valid for locations where there is little or no sediment mobility due to some combination of three factors: 1) low wave and tidal energy; 2) sufficiently deep water to limit the influence of waves on the bottom; and/or 3) sufficiently coarse sediment.

2.5 Pipeline Conditions and Characteristics

Pegasus International, a consultant serving the oil and gas pipeline sector in the Gulf of Mexico, completed a review of pipeline conditions and characteristics to address a series of key questions on this project. Their final report is provided in Appendix B and a summary is presented here.

The oil and gas infrastructure that may be susceptible to damage through possible changes to the seabed caused by dredging the OCS include: platforms, caissons, old wells that have been shutoff, pipelines, and cables.

The MMS requires that all cables, umbilical lines, and pipelines inshore of the 200 ft contour be buried at least 3 ft below the seabed surface (measured to the top of the pipe). This is achieved by trenching the pipelines through different approaches. In areas where the pipeline becomes exposed it is either retrenched or protected with an armor layer. The pipelines are not regularly inspected unless there is specific evidence of erosion and spanning (the latter referring to undermining of sections of the pipelines so that they no longer are in contact with the sea bed). In general, instances of spanning are thought to be rare in the Gulf of Mexico owing to the relatively mild slopes.

Current GPS surveying techniques would allow new pipelines to be positioned and mapped within +/- 5 to 10 m horizontally. However, many of the existing pipelines were laid many years ago and inaccuracies in mapped location could be as great as 1.5 km (either due to inaccuracy or error in historic mapping or due to movements of the pipeline caused by storms). A resurvey of all nearby pipelines should be completed prior to any dredging using acoustic, magnetometer, side scan, and sub-bottom survey techniques with results remapped in the project GIS file. Consideration should be given to determining the extent of cover of existing pipelines (i.e. whether it is indeed 3 ft or greater), as this information is not included in any database. The latter information would provide a baseline to determine whether the indirect influence of dredging has an impact on the cover or not (i.e. instead of simply assuming the cover prior to dredging is 3 ft or greater).

Baird contacted MMS to determine if there were any regulations or policy regarding the minimum cover requirement after installation. Based on feedback from MMS (Drucker, personal communication), it was determined that there is no policy on minimum cover requirements. Corrective action is only required when a pipe is exposed or undermined.

2.6 Other Pipeline Buffer Guidelines for Dredging

A review of buffers for dredging near pipelines for federal agencies and other jurisdictions was completed. To limit the effect on platforms, MMS currently requires that sand mining should be restricted to areas that are not likely to alter the platform strength or the future platform removal and site clearance. Since the site clearance is required within one-fourth mile (1,320 ft) from the platform, mining activity needs to be limited to areas outside the site clearance zone. MMS has recommended that all mining activity be limited to areas at least 1,500 ft from all platforms on the OCS (Personal communication, Tom Laurendine, MMS GOMR FO).

The US Army Corps of Engineers has no specific permit requirements for dredging near pipelines. Their requirements mostly relate to cover at pipeline crossings of dredged channels.

In the Netherlands there is a dredging exclusion zone of 500 m around pipelines, cables, platforms, and windmills (see Rijkswaterstaat, 2004). No background reports describing the technical justification for this exclusion zone were found. Also, the current policy in the Netherlands does not allow dredging for aggregate or beach nourishment sand and gravel in depths shallower than 20 m and pits can be no deeper than 2 m, however these two limitations are currently under review (Van Rijn et. al., 2005).

French regulations require that pits be no deeper than 3 m where they are allowed (Van Rijn et. al., 2005).

Royal Haskoning (2004) recently completed Best Management Practice (BMPs) guidelines for aggregate dredging in the UK. The document indicates that direct and indirect damage to pipelines and cables can be caused by offshore dredging, the latter associated with increased scour effects. It is indicated that the outputs of the physical process assessment required under the BMPs should enable the nature of this impact (scour) to be defined. An agreement exists between the UK Cable Protection Committee (UKCPC) and the Crown Estate (the agency that manages extraction of aggregate resources in the UK) that allows for a No Dredging Zone of 250 m to be implemented on either side of an in-service cable or pipeline. According to Royal Haskoning (2004), these zones should prevent any disturbance to submarine cables and pipelines from either direct or indirect effects of aggregate extraction. There is no documented technical justification given for the specified buffer zone width. The UK also has a 500 m buffer for vessels working nearby platforms and infrastructure that protrude above the sea level.

2.7 Summary of Field Survey Results and Review of Background Information

Understanding the evolution of dredged pits is an evolving area of science. In general, there is a lack of good field data consisting of repetitive surveys of borrow pits for several years after dredging; this was even the case for the $5 million European Community SANDPIT study. There are abundant hydrographic data on dredged channels but these do not provide clear insight to pit slope evolution processes owing to the role of regular maintenance dredging.

The EC SANDPIT study has significantly advanced the understanding of dredged pits both at a fundamental first principles level and at a practical level. However, this study has only considered pits in sandy settings and not muddy settings (where borrow sand is capped by mud). The SANDPIT study recognized the fundamental importance of defining the net and gross sand transport rates at a site due to tides (and other) currents and waves. These rates define the morphologic response time of a pit, and specifically, how fast it fills and whether and to what extent the pit slopes migrate. A variety of numerical modes applied during the SANDPIT study found that pit migration rates could be in the range of 10 to 100 m/year for conditions associated with the Dutch North Sea coast where there is a net transport due to a residual tidal current. If a pit is morphologically active (i.e. the sediment beyond the edge of the pit is mobile), the angles of the pit slopes are primarily governed by these sand transport processes. Pits with a gross annual transport rate greater than about 10 to 20 m^3/m/year are expected to be "morphologically active". The SANDPIT study pits had annual gross sand transport rates in the range of 15 to 110 m^3/m/year. The Nile River delta LNG Facility channel had slope edge erosion (or migration) rates in the range of 100 m/year with gross annual sand transport rates of about 300 m^3/m/year and a strong residual current.

Where pits are located in areas of little or no sediment mobility (i.e. less than about 10 m^3/m/year) the pit slope angles will remain unchanged from the state immediately following dredging and are in the range of 1V:5H to 1V:10H depending on the dredging approach (slopes associated with cutter suction dredges can be steeper than those created through trailing suction hopper dredges). The angle of these slopes is governed by geotechnical slope stability considerations and the dredging operations. A good example of little or no slope change due to low gross annual sand transport rates (less than 5 m^3/m/year) were the borrow pits dredged offshore Delray Beach, Florida. Of the many pits and channels investigated around the US coast, these were the only ones in a sandy setting that maintained steep slopes. Other locations that featured larger transport rates had slopes in the range of 1V:20H to 1V:100H or even flatter.

Dredged pit evolution for the condition of sand deposits capped with mud is even less understood. The Holly Beach dredge pit offshore Louisiana provides an opportunity to develop an initial understanding of how these pits evolve and this is the topic of Section 3.1 of this report.

MMS requires that oil and gas pipelines inshore of the 200 ft depth contour have a 3 ft cover between the seabed surface and the top of pipe when they are installed. The burial protects the pipe from damage related to anchors or fishing operations (and in turn prevents disruption to fishing operations) and also helps to avoid spanning of pipeline sections that can lead to breakages. The locations of the pipelines are well known in general terms, but not accurately. In addition, there is no database as to the true extent of cover of pipelines. In areas where the seabed is morphologically active, it is plausible that the cover could have changed with time. There is no specific requirement to maintain a minimum 3 ft cover. The MMS has no routine field inspection program to verify the state of pipe burial. After significant storms, for example Hurricane Ivan in September 2004, the MMS may call on operators to inspect their facilities and report results (MMS, 2004b). MMS (2004b), in a multi-project EA for dredging deposit on ship shoal recommended a setback of 1,000 ft from all pipelines. However, there is no current MMS regulation for buffers around pipelines and cables, and the primary purpose of this report is to recommend such buffers. Various jurisdictions, particularly in Europe, have adopted a blanket buffer to protect pipelines ranging from 250 m in the UK to 500 m in the Netherlands, on either side of pipelines. The large buffers recognize the potential mobility of dredged pits (i.e. the concern is not with dredges directly damaging pipelines during the dredging operations). In the Netherlands and France maximum pit depths are restricted to 2 and 3 m respectively, although this is currently under review in the Netherlands. No information was found for the scientific justification of any of these buffer requirements.

3.0 ANALYSIS AND NUMERICAL MODELING

This section provides the results of data analysis, theoretical analysis, and numerical modeling of the morphologic evolution for one existing and two proposed pits offshore Louisiana. Two of the sites feature sandy deposits buried by a mud cap (i.e. the existing Holly Beach pit and the proposed Sandy Point pit) and one of the sites is in a sandy setting (Block 88 on Ship Shoal). It was found that pits in muddy (sand deposit capped by mud) and sandy settings have different morphologic evolution characteristics. In muddy settings, suspended sediment transport is the main contributing process to pit evolution whereas sandy pits are more influenced by the bed load component of sand transport and to a lesser extent suspended load, depending on the local conditions. Pits in muddy settings feature rapid infilling with a level pit floor combined with pit margin erosion, although little pit slope change. In contrast, pits in sandy settings feature more localized changes in the immediate vicinity of the pit slope. The findings of these three investigations and the implications for specifying buffers around oil and gas infrastructure are discussed in Section 3.4.

3.1 Holly Beach Dredge Pit (Existing)

This section is subdivided into an analysis of the pit slope evolution (Section 3.1.1) and numerical modeling of the evolution of the pit (Section 3.1.2). Section 3.1.3 provides a summary of how the evolution of muddy-capped pits differs from pits in sandy settings.

3.1.1 Analysis of Holly Beach Pit Evolution

The pre-dredging, post-stripping, post-dredging, and December 2004/January 2005 surveys of the Holly Beach Dredge Pit are shown in Figures 3.1 to 3.4 in the form of surfaces created in GIS. Figures 3.5, 3.6(a) and (b) provide a description of the stratigraphy in the vicinity of this pit.

The pit is located in a water depth of approximately 8 m and is about 7 km offshore Holly Beach in western Louisiana in federal waters. Approximately 1 m of muddy sediment was stripped to expose the underlying sand. However, beyond the edges of the pit the silt and clay cap increases to 2 to 4 m thick in some areas. The pit was 9 to 11.5 m deep immediately after dredging in April 2003. Not all of the area that was stripped was dredged. There was evidence of a small disposal mound for stripped sediment immediately beyond the northwest corner of the pit. Whereas the pit floor varied in depth from 15 m (50 ft) to 18 m (60 ft) immediately after dredging, the December 2004/January 2005 survey taken 20 months later reveals an almost level pit floor at 14.6 m (48 ft).

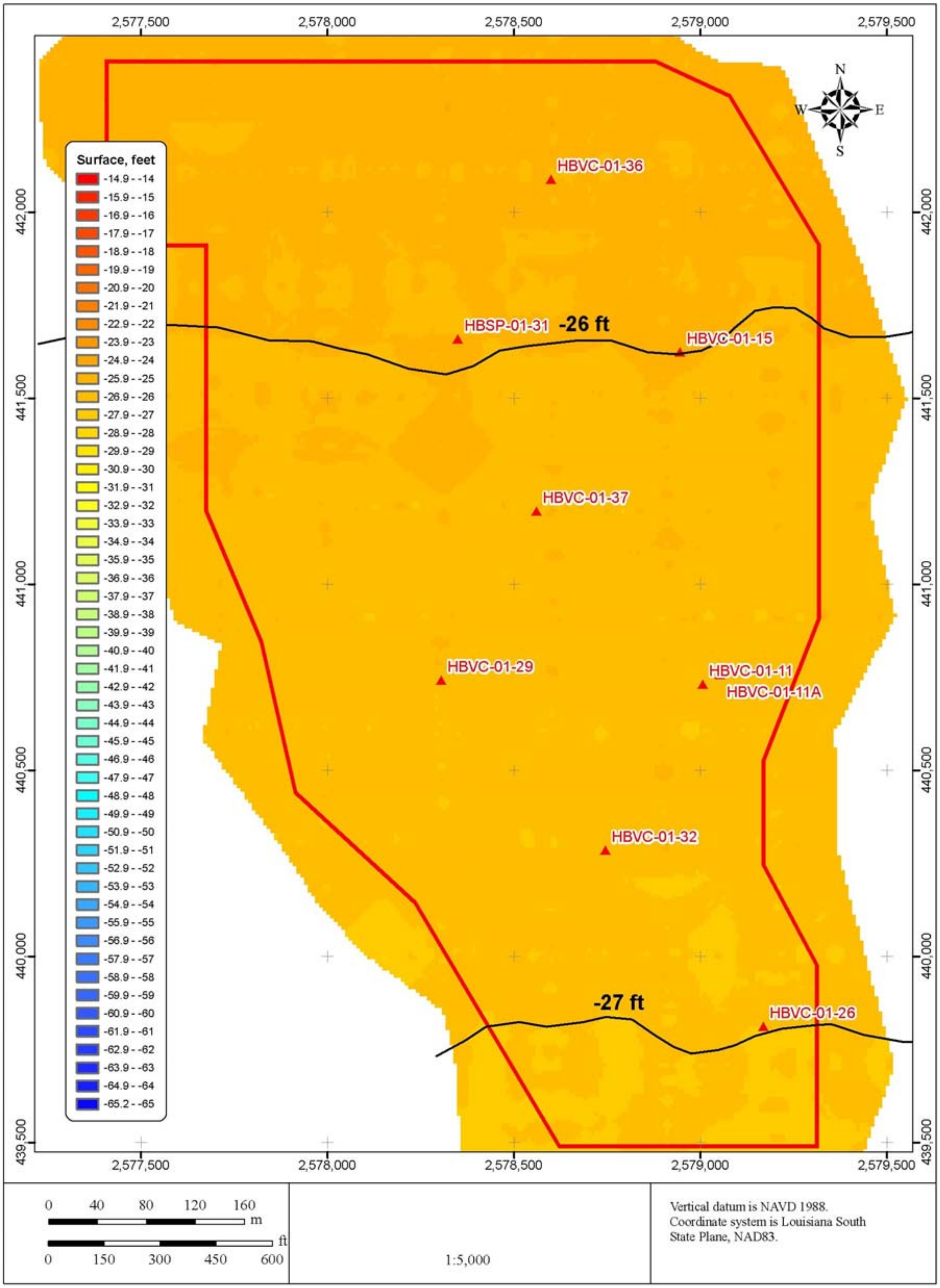
Figure 3.7 shows the surface comparison of the after-dredging survey taken in April 2003 and the December 2004/January 2005 survey. There was greater infilling in the deeper eastern part of the pit (up to 14 ft or 4.2 m) with the least infilling was observed in the southwest sector of the pit (2 to 4 ft or 0.6 to 1.2m) which was dredged to a shallower depth initially. Another key observation is that beyond the localized slope erosion, there was 1 to 2 ft (0.3 to 0.6 m) of erosion outside the edge of the pit with the exception of the area beyond the northwest quadrant of the pit that was stripped but not dredged where there was 0 to 0.3 m of accretion.

The pit evolution can also be investigated through direct profile comparisons. The advantage of profile comparisons is that direct data comparisons are possible (whereas surface comparisons rely on interpolation of the point data). Also, the pit slope evolution can be evaluated in more detail in this manner. Twelve cross-sections were selected to be representative of different conditions within the pit. The profile locations are shown in Figure 3.7 and the profile comparisons are shown in Figures 3.8(a) to (h). The different surveys were all registered to the same vertical (NAVD88) and horizontal datums and although there may have been minor inaccuracy in both the survey data and the conversion process, the resulting uncertainty would most certainly be much less than the extent of the observed erosion and deposition (0.3 m to many meters).

These surveys reveal several interesting features relevant to the issue of slope stability and slope evolution. The flattest slopes (in December 2004) appear in the South 1 and North 1 cross-sections, at about 1V: 4.3H. South 2 and West 3 have slopes at about 1V: 3.25H. The rest are all steeper, up to near vertical in East 1. The change in slope over the 20-month period from April 2003 to December 2004 was, in half the cases, minor. However, on closer inspection there are other revealing observations.

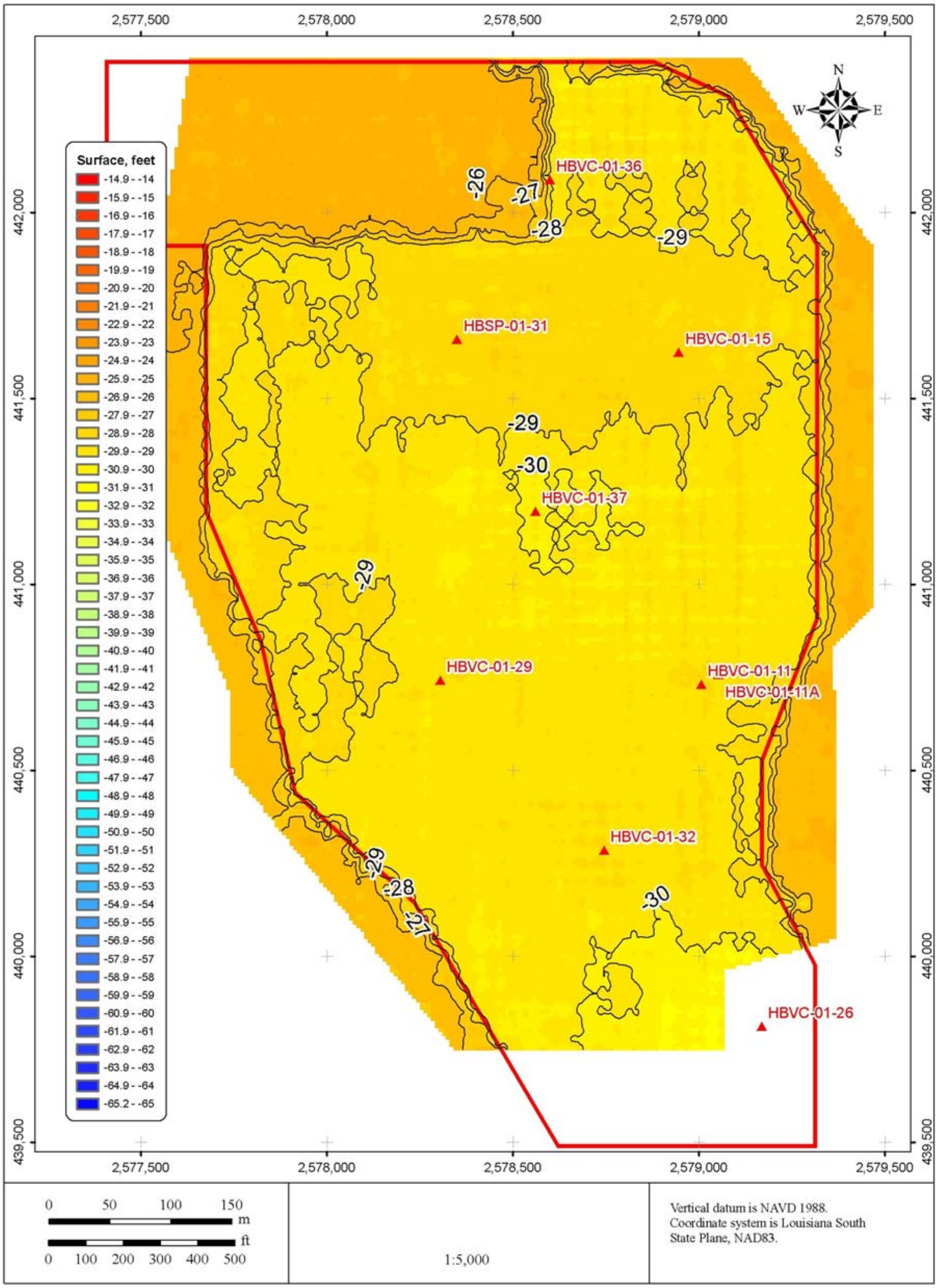
For the East 1 profile, the level nature of the base on the pit is evident; there is no correlation between the initial depth and the infilled depth (see Figure 3.8a). There has been little or no change to the 1V: 1.5H slope. Approximately 3 ft (1 m) of mud was stripped up to the edge of the pit slope. Beyond the edge of the pit, the pit margin has eroded by 2 to 3 ft (vertically) for a distance of at least 200 ft (61 m) (the post dredging survey does not extend beyond 200 ft from the edge of the pit).

The North 1 profile also shows little change to the 1V: 3.7H slope in the 20 months since dredging (see Figure 3.8b). However, once again there has been 1 to 2 ft of erosion for more than 400 ft (120 m) beyond the edge of the pit. The erosion has occurred within the muddy sediment beyond the edge of the pit. The West 1 to 4 profiles all show little slope change with anywhere between 80 to 175 ft (25 to 50 m) of pit margin erosion of 1 to 2 ft (0.3 to 0.6 m). It is likely that the pit margin erosion extended further but this was the limit of the data. The South 1 and South 2 profiles are located in part of the pit that was stripped beyond the edge of the actual dredged pit (see Figures 3.8c and d). Therefore, the seabed surface beyond the edge of the pit would have been sandy immediately following dredging. The South 1 profile is the only one of the eight that featured measurable slope flattening (from 1V: 2.3H to 1V: 5.4H). The pit margin erosion area was small at less than 100 ft (30 m). This form of slope change is compatible with the sandy pit evolution processes investigated in the SANDPIT study (see Section 2.3). The South 2 profile shows some flattening and very limited pit margin adjustment.



Vertical datum is NAVD 1988.
Coordinate system is Louisiana South
State Plane, NAD83.

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



Vertical datum is NAVD 1988.
Coordinate system is Louisiana South State Plane, NAD83.

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

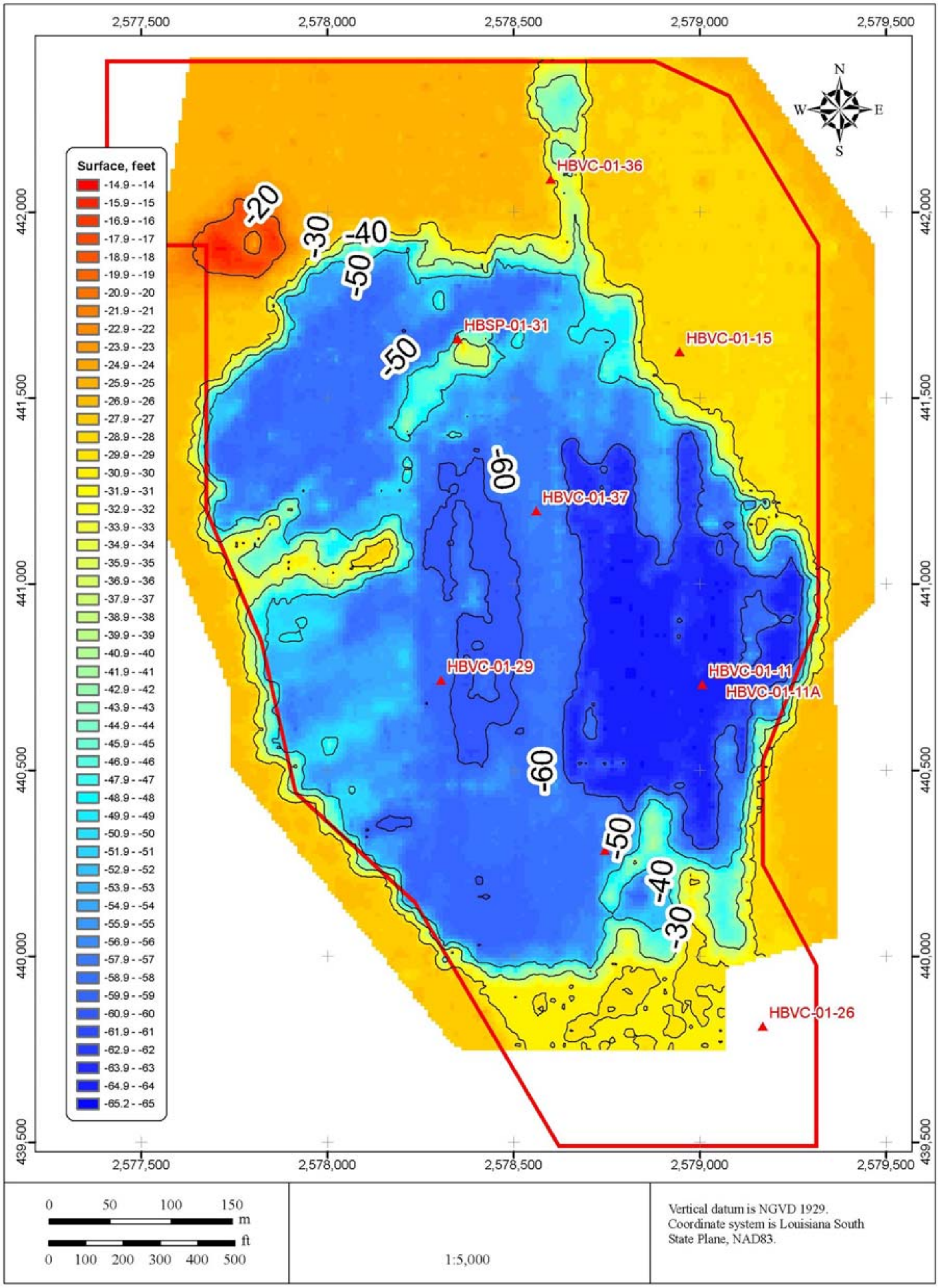


FIGURE 3.3. Holly Beach Dredge Pit – Bathymetry After Dredging (April 2003).

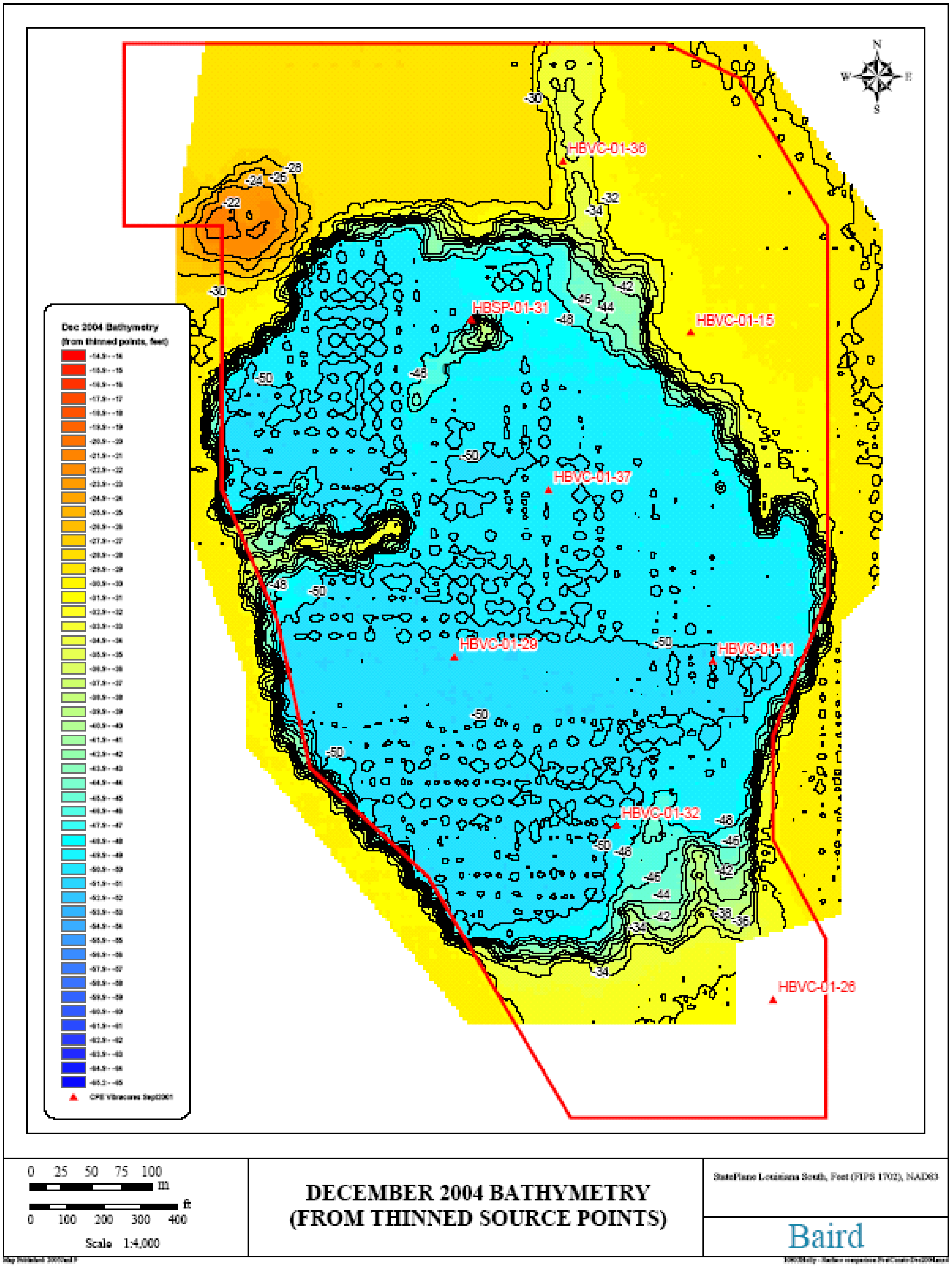


FIGURE 3.4. Holly Beach Dredge Pit – Pit Change After 20 Months (Dec 2004/Jan 2005).

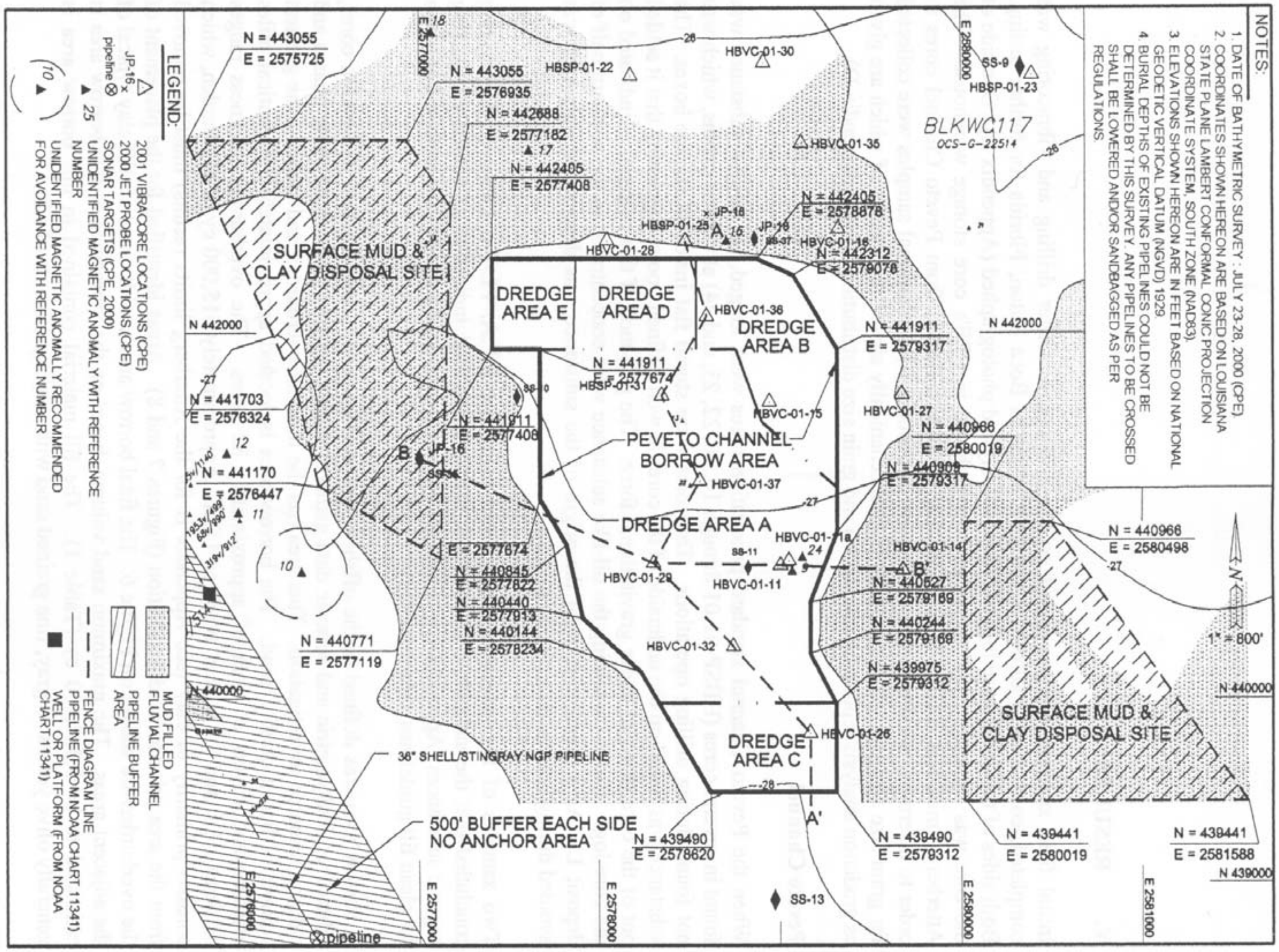


FIGURE 3.5. Holly Beach Dredge Pit – Plan of Geophysical Information (from Coastal Planning & Engineering, 2002).

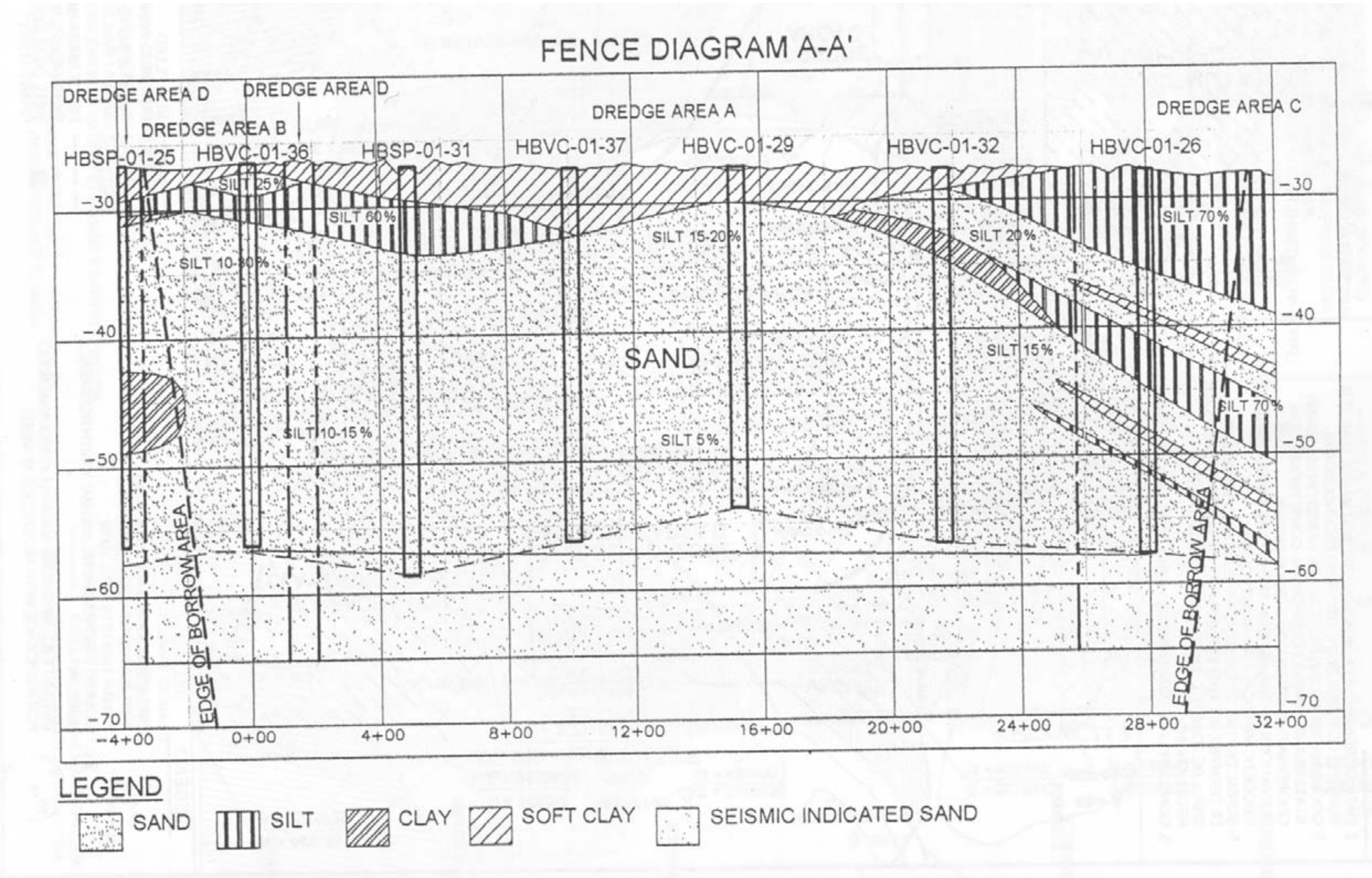


FIGURE 3.6.a. Holly Beach Dredge Pit – Stratigraphy Cross-Section A’-A’ (from Coastal Planning & Engineering, 2002).

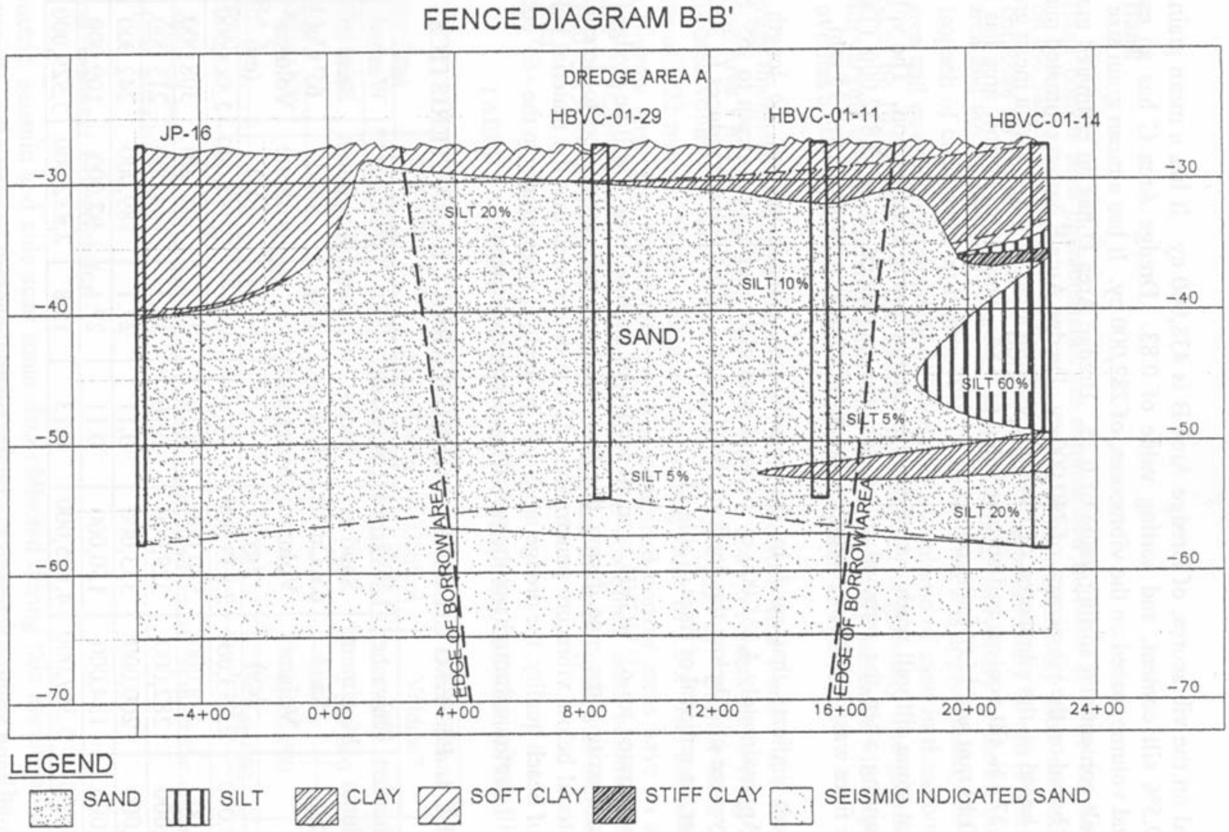


FIGURE 3.6.b. **Holly Beach Dredge Pit – Stratigraphy Cross-Section B'-B' (from Coastal Planning & Engineering, 2002).**

The Northeast 1 to 4 profiles are located in the only other part of the pit where the surface of the sea bed beyond the edge of the pit is sand (as shown through a comparison of Figures 3.2 and 3.3) owing to the area being stripped but not dredged. The response is very similar to what was observed for the South 1 profile in particular. The slope of the pit at Northeast 1 changed from 1V: 3H to 1V: 6.3H between April 2003 and December 2004. Also, there was up to 3 ft (0.9 m) of erosion at the top of the pit. At the toe of the flatter slope in December 2004, the pit floor was sloping (at about 1V: 60H) which is significantly different than the near level pit floor in areas where the infilled sediment was assumed to be mud. Only the presence of sandy sediment at the toe of the slope could explain the sloping pit floor. At the Northeast 2 profile the slope has become slightly flatter, but there has been significant erosion beyond the pit edge and apparent deposition of sand on the pit floor, which has a slope of 1V: 33H. The Northeast 3 profile shows little or no infilling, a slight flattening of the slope from 1V: 1.5H to 1V:3H, and about 3 ft (0.9 m) of erosion at the top of the pit. The Northeast 4 profile features a change in slope from 1V: 2.3H to 1V: 5.5H in the first 20 months after initial dredging. Erosion of about 3 ft to 4 ft (0.9 to 1.2 m) has occurred beyond the new top of slope for a distance of at least 100 ft (30 m) with less erosion beyond that point. The accumulation of a sloping sand surface at the toe of the Northeast 4 slope is not visible, probably because it is buried with mud deposits that would have accumulated in this originally deeper area of the pit. In contrast to the South profiles in a sandy area, the Northeast profiles showed vertical erosion of 2 to 3 ft (0.6 to 0.9 m) over a distance of at least 200 to 300 ft (60 to 90 m) beyond the edge of the pit. It may be that this is due to offshore-directed transport, which would not have influenced the evolution of the profiles at the south edge of the pit (South 1 and 2).

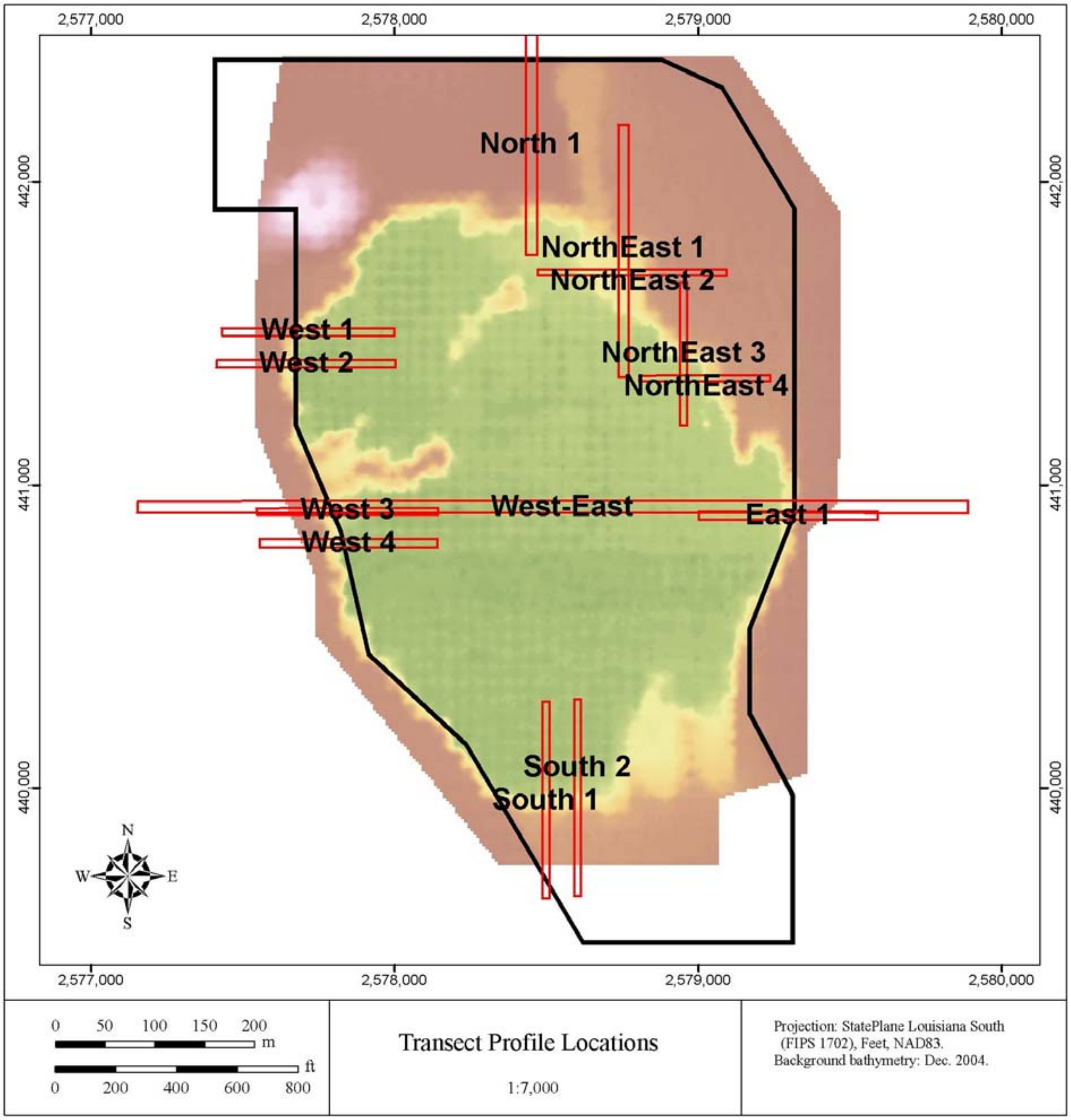


FIGURE 3.7. Location of the Twelve Profile Comparisons for the Holly Beach Dredge Pit.

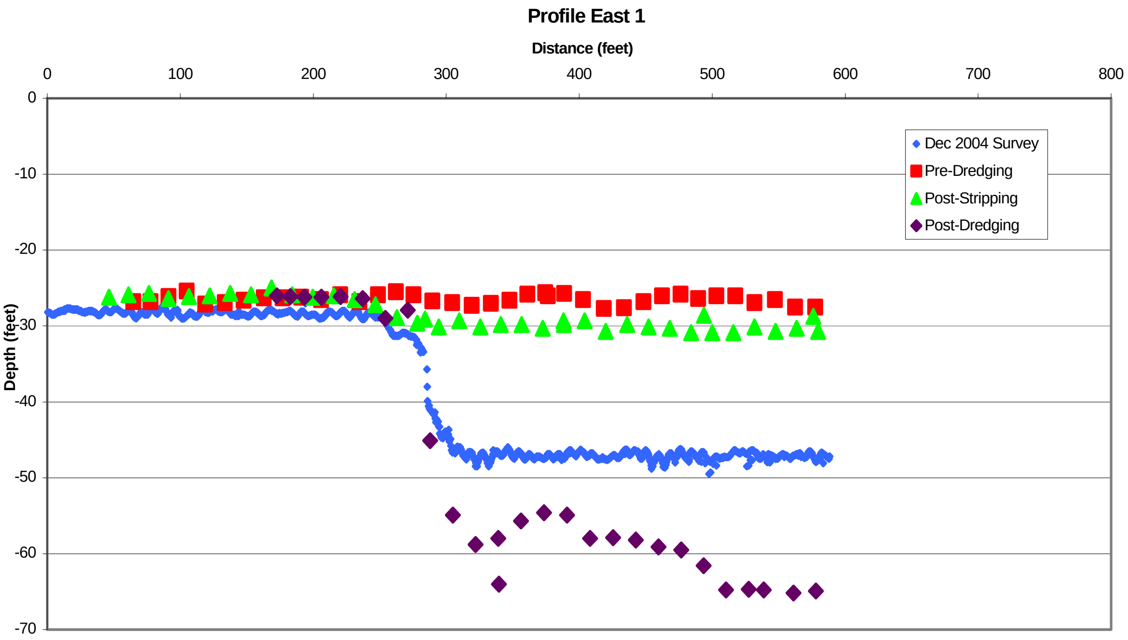


FIGURE 3.8.a. Profile East 1

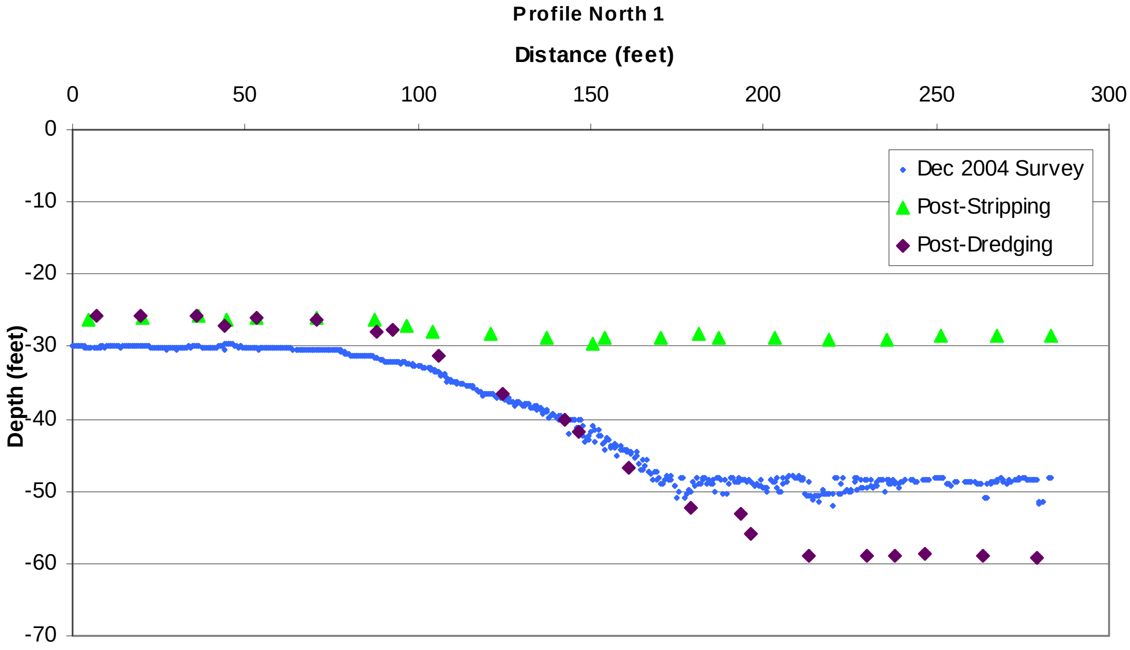


FIGURE 3.8.b. Profile North 1.

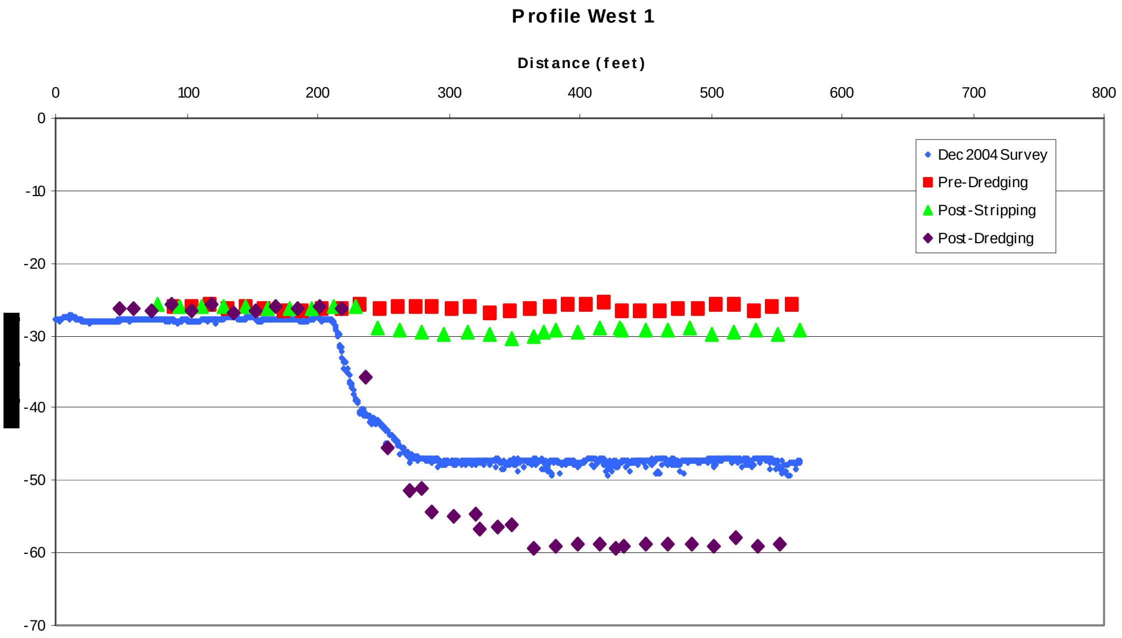


FIGURE 3.8.c. Profile West 1.

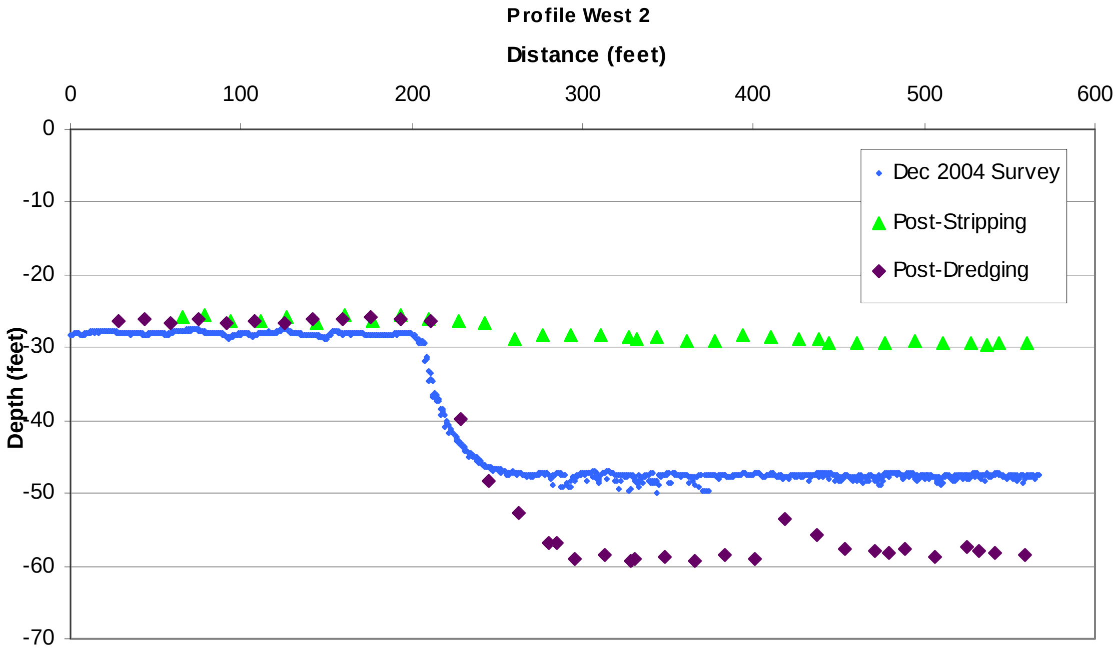


FIGURE 3.8.d. Profile West 2.

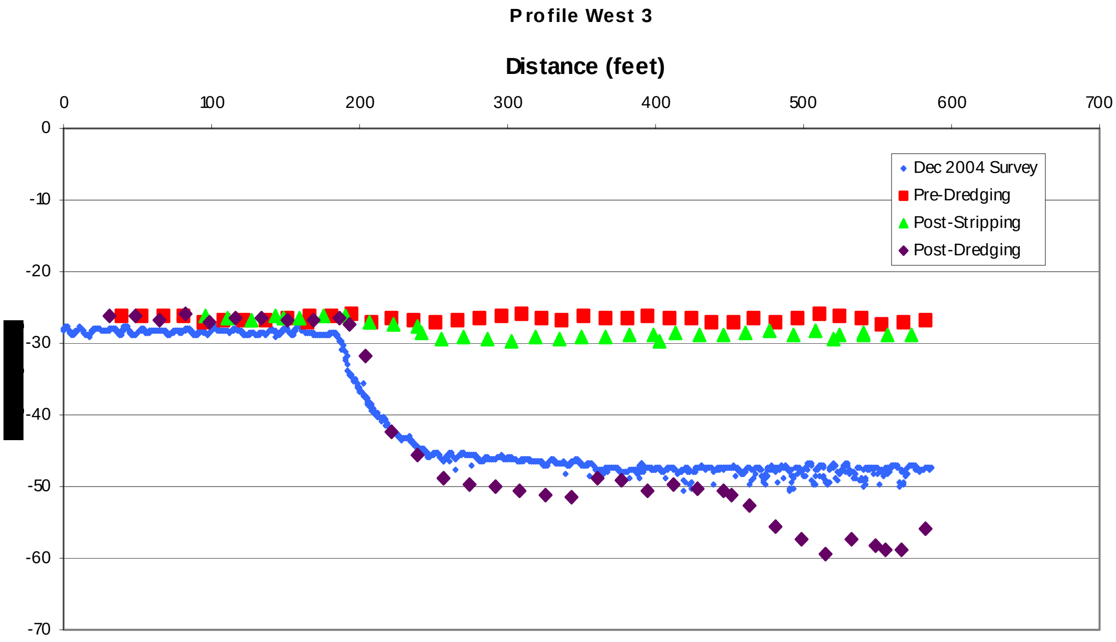


FIGURE 3.8.e. Profile West 3

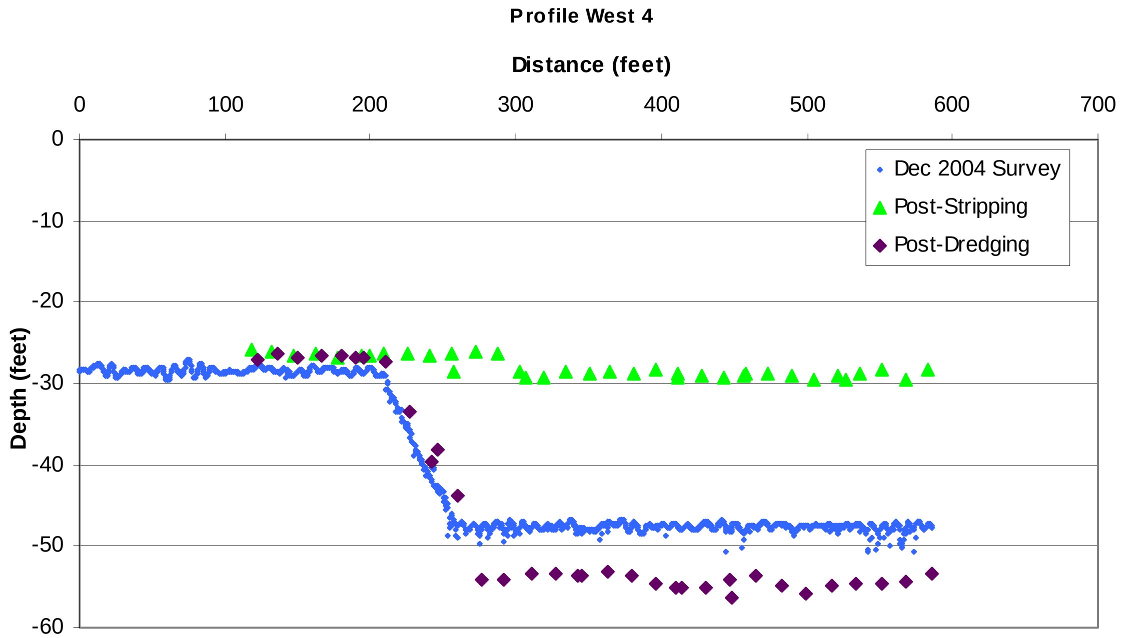


FIGURE 3.8.f. Profile West 4

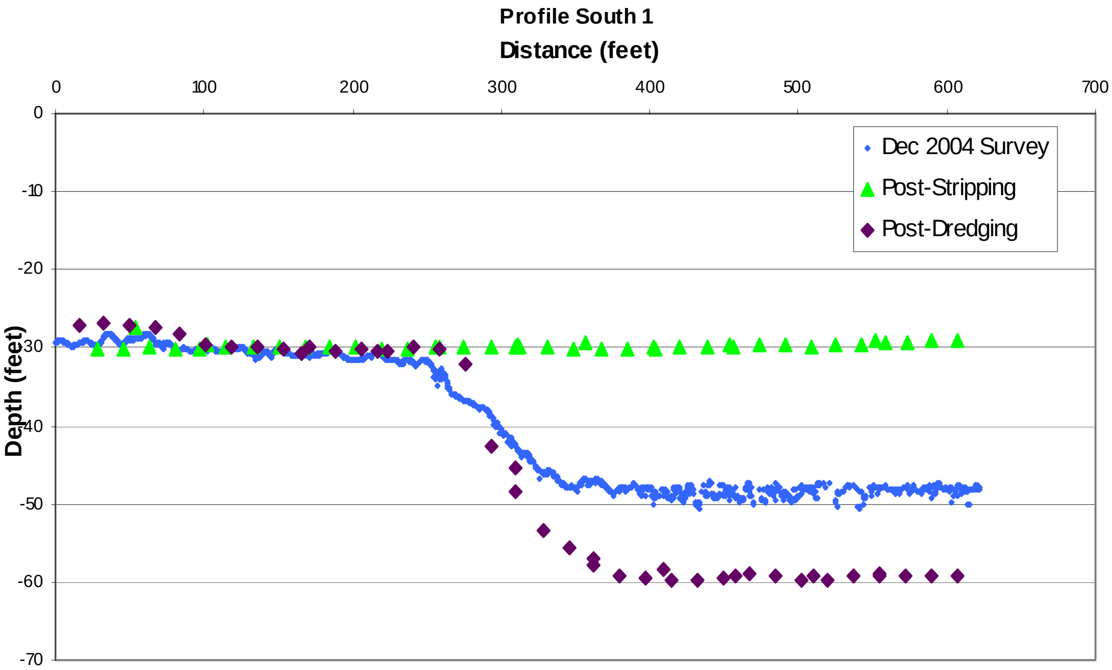


FIGURE 3.8.g. Profile South 1.

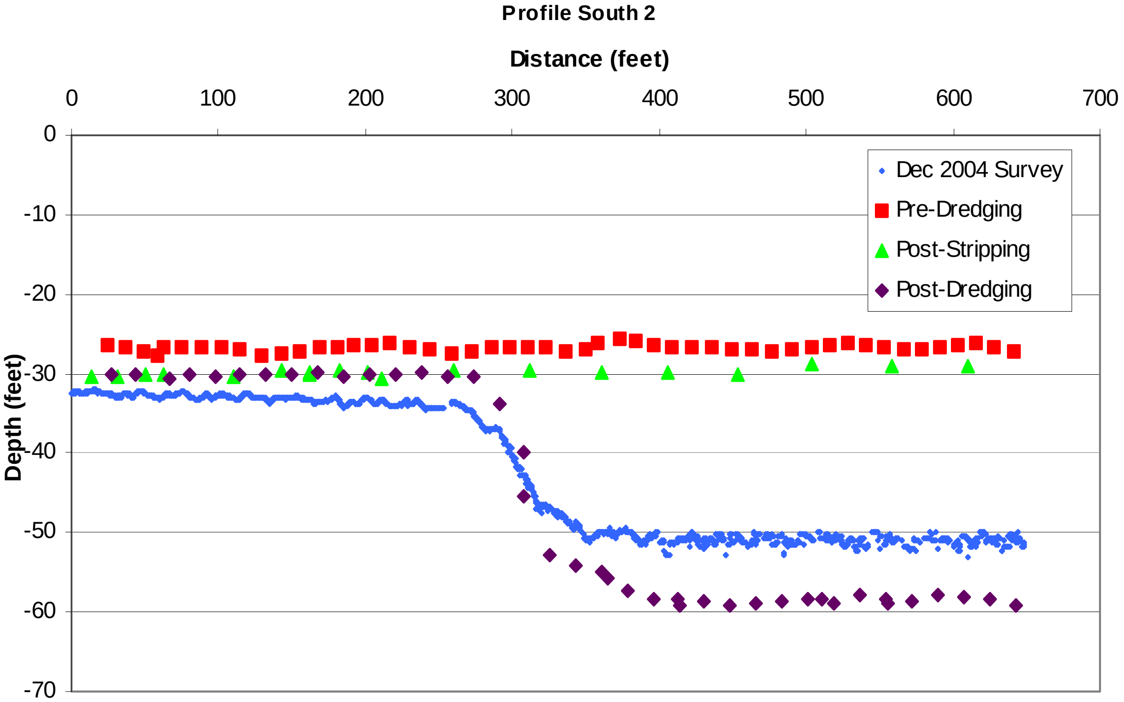


FIGURE 3.8.h. Profile South 2.

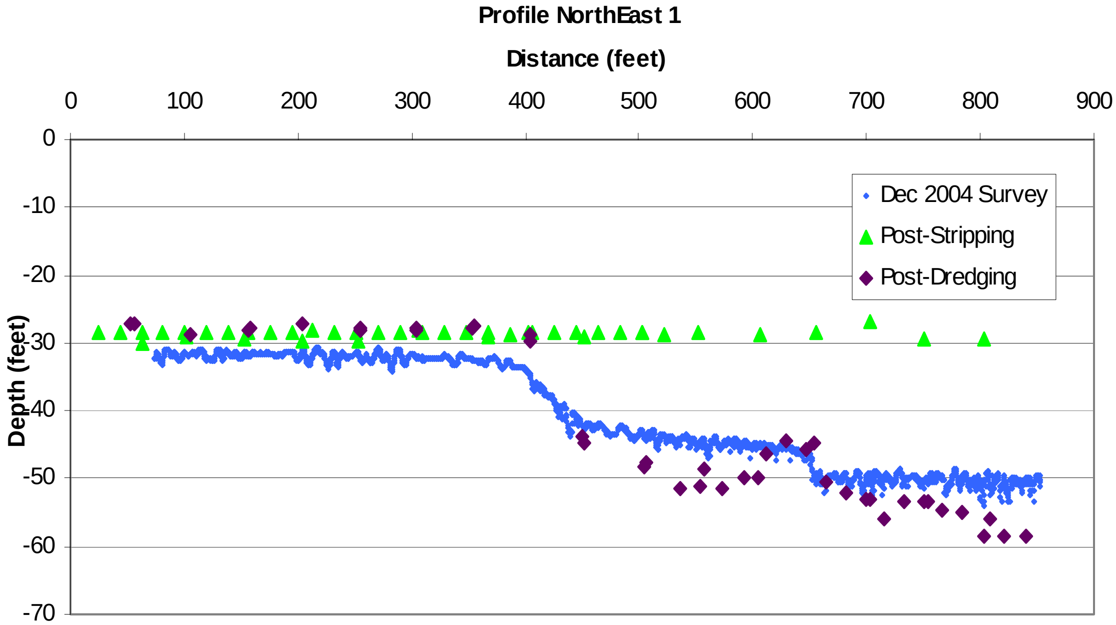


FIGURE 3.8.i. Profile Northeast 1

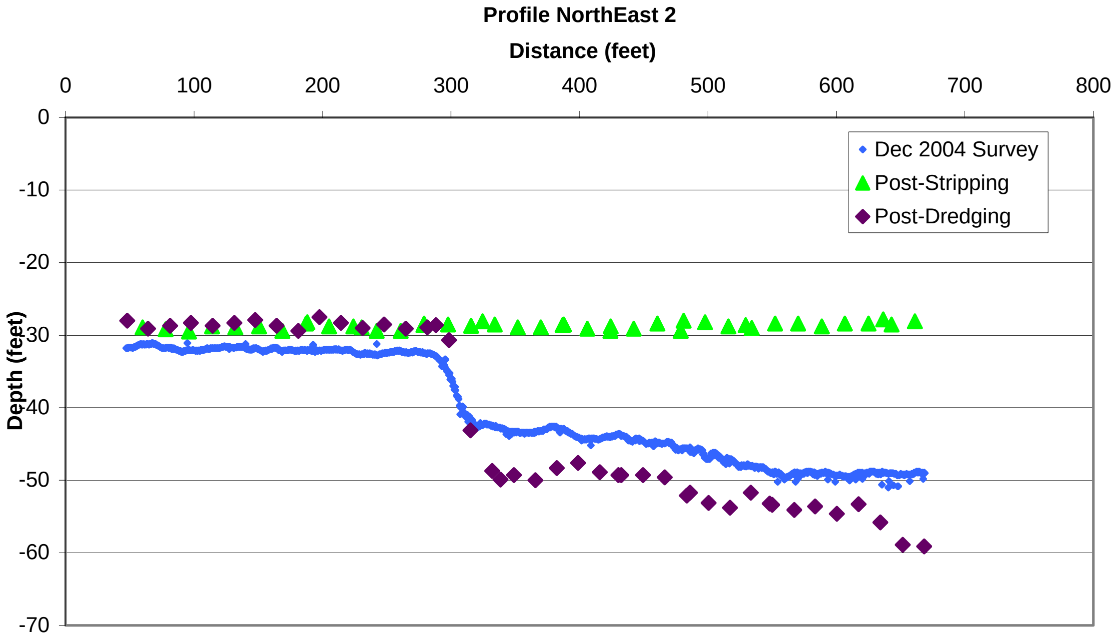


FIGURE 3.8.j. Profile Northeast 2

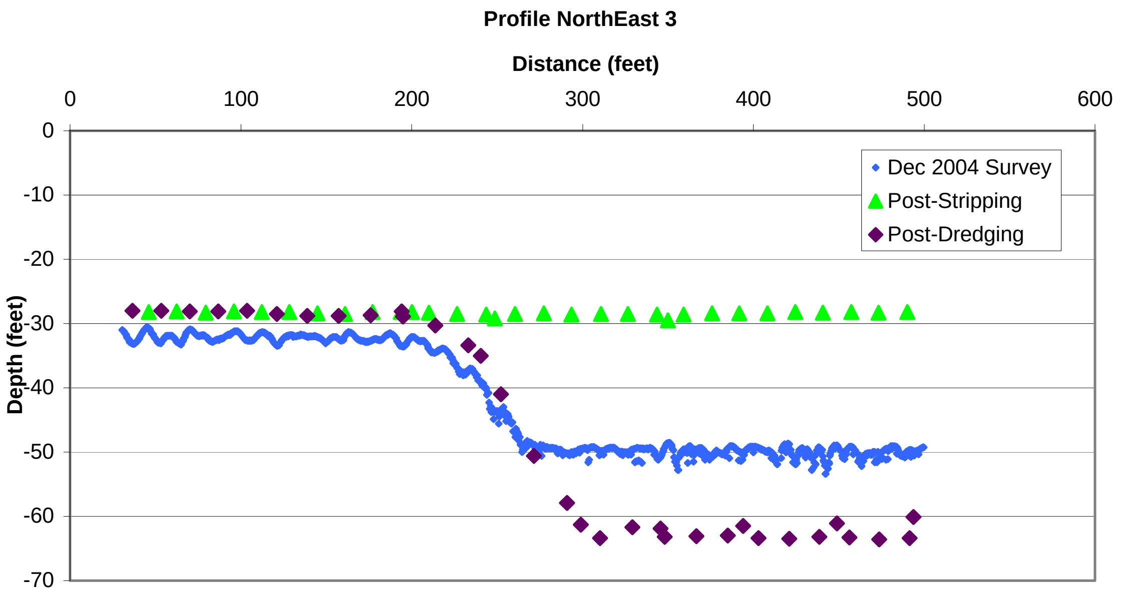


FIGURE 3.8.k. Profile Northeast 3

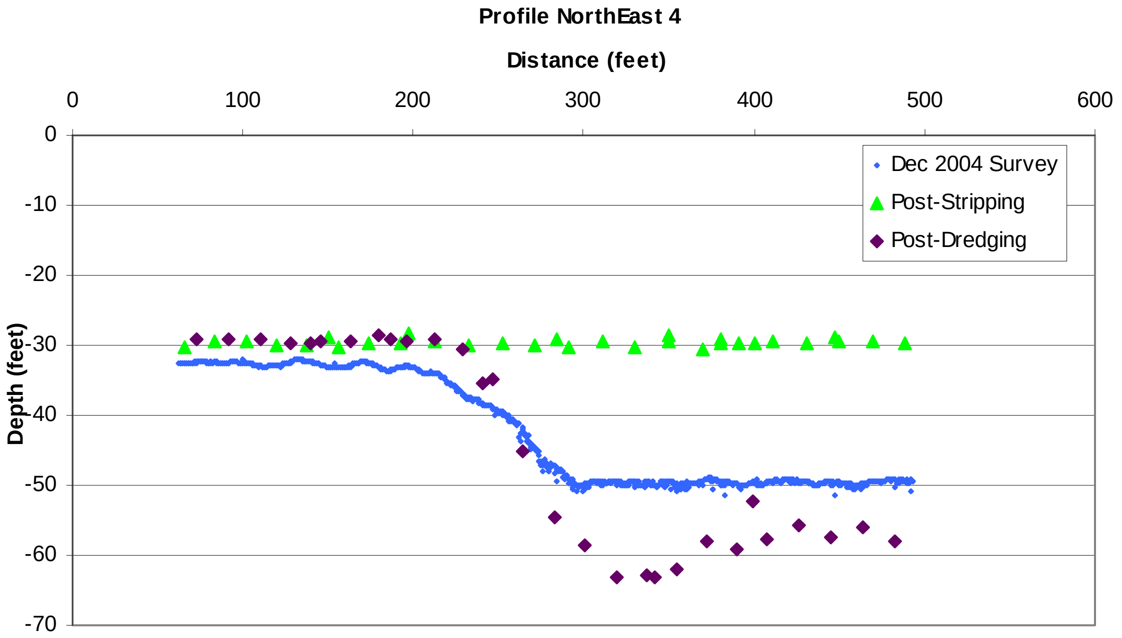


FIGURE 3.8.l. Profile Northeast 4.

The Louisiana DNR and Coastal Planning & Engineering provided data from a limited survey of the Holly Beach Dredge Pit completed in May 2004. Figure 3.7 shows the location of an East-West full pit transect and the May 2004 survey points together with other data. Figure 3.9 shows the data in profile format. The pit floor was about 2 ft (0.6 m) lower (i.e. less infilling) at that time compared to the December 2004/January 2005 survey. Also, less erosion had occurred in the pit margin zone at this earlier snapshot.

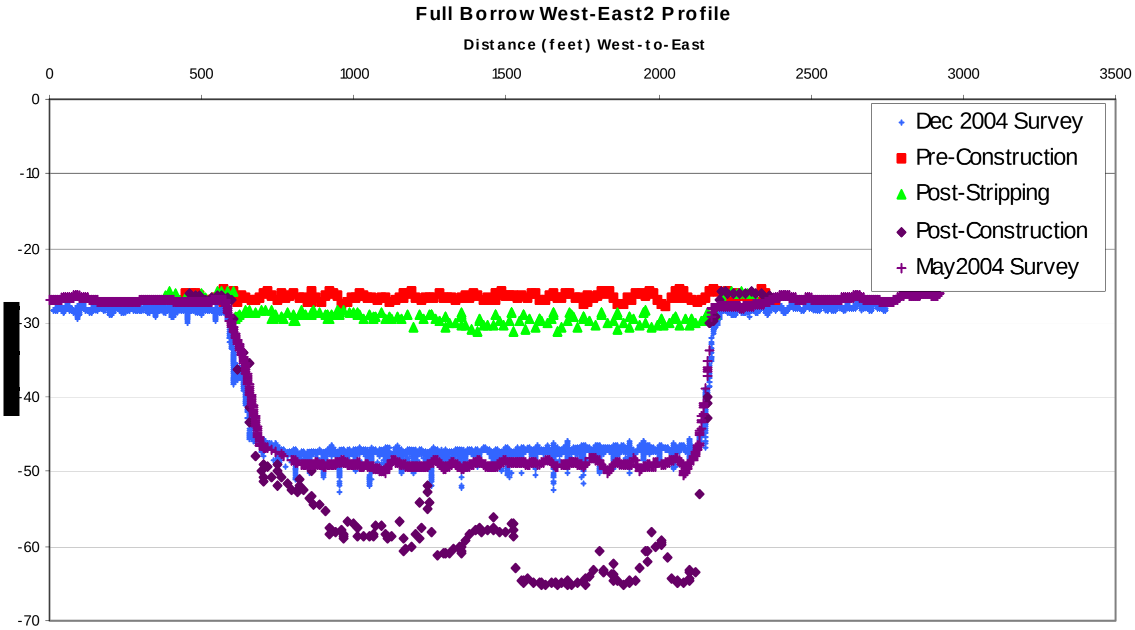


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FIGURE 3.9. Full East-West Pit Transect with May 2004 Data

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 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.

3.1.2 Theoretical Analysis of Pit Evolution in Muddy Seafloor Settings

Suspended sediment load, and possibly in some cases turbidity currents and/or slumping, are the main forms of sediment transport for dredged pits in muddy seafloor settings. In these settings, prior to dredging the sea bed elevation is stable in the long-term (or only very slowly changing). As a muddy seabed is in reality constantly eroding and depositing due to frequent re-suspension events, it is in a state of dynamic equilibrium. Though instantaneous peaks in sediment concentration may occur in response to energetic wave or current events, the long-term averaged suspended sediment concentration under a dynamic equilibrium condition should represent the average sediment load capacity of ambient waves and currents.

The dynamic equilibrium is disrupted when a pit is dredged. Larger water depth over the pit reduces flow speed and in turn reduces the sediment load capacity of the flow. In addition, the potential for re-suspension of sediment at the floor of the pit by waves or currents is reduced or altogether eliminated (depending on the depth of the pit). As a result, sedimentation or pit infilling occurs. Owing to the fact that most sediment in suspension is fine with a settling velocity much smaller than the flow velocity, only a small fraction of the suspended sediment actually deposits in the pit as the sediment-laden flow passes over the pit. Therefore, the reduction in suspended sediment concentration caused by deposition along the flow path over the pit is small and can be neglected, at least in terms of the sedimentation rate. As a result, the sedimentation rate is only dependent on the flow speed reduction caused by the increase in water depth. That is, the deposition rate is only a function of water depth over the pit. In other words, sedimentation rate increases with water depth. Therefore, if the pit floor is undulating immediately following dredging, more sediment will deposit in the deeper areas and less sediment will deposit in the shallow areas of the pit. Ultimately, this leads to a horizontally level pit floor, regardless of the initial topography of the floor. This is exactly the morphologic condition that was found to exist at the Holly Beach Dredge Pit 20 months after dredging in the December 2004/January 2005 hydrographic survey.

Although the reduction in suspended sediment concentration over the pit is small enough so as not to influence the rate of sedimentation, this reduction does lead to an imbalance between re-suspension and deposition for some distance beyond the edge of the pit, which is compensated through pit margin erosion. This pit margin erosion has also been observed around the Holly Beach dredge pit when the after-dredging and December 2004/January hydrographic surveys are compared.

Finally, since the erosion and sedimentation processes in muddy settings are almost completely driven by suspended load transport, the relaxation time or distance to a change in sediment transport capacity in response to changing flow characteristics is large or long (see Galappatti and Vreugdenhill, 1985). In contrast, relaxation distances are short for sandy sediment that moves in bed load or at least where the suspended load is concentrated closer to the bed. This explains why pit evolution in sandy sediments is more focused spatially on the point of change in flow and transport conditions, that is, the slope itself. In contrast, for muddy pits the process is more decoupled between the pit margin erosion over a large area and sedimentation within the pit.

Owing to this distinctive morphologic evolution process of pits in muddy settings (compared to sandy pits), the approaches used to estimate infilling rates and pit evolution for sandy pits are not suitable for muddy pits. An analytical approach is developed for the infilling rate and pit margin erosion as described below. For the purposes of this study the ultimate goal is to define the extent of pit margin erosion. However, this is intrinsically related to the pit infilling process as will be explained.

Infilling Rate

a. Equation Formulation

The empirical equation developed by Jiaju Liu (Liu and Zhang, 1992) is suitable for mud infilling in a dredged channel. The equation was developed from detailed sedimentation studies over more than ten sites in China and has been well verified in engineering practice. The equation can be used to estimate the siltation thickness per tide in a navigation channel oblique to the flow in a muddy environment. The siltation thickness is calculated in transverse and longitudinal directions separately to distinguish the impacts of channel orientation on the flow. The equation is written as:

$$\begin{aligned}
\Delta Z_b &= \Delta Z_{b,tran} + \Delta Z_{b,long} \\
\Delta Z_{b,tran} &= k_1 C_0 \omega_s T \frac{1}{\rho_{dry}} \left[1 - \left(\frac{h_0}{h_1} \right)^3 \right] \sin(\alpha_0) \\
\Delta Z_{b,long} &= k_2 C_0 \omega_s T \frac{1}{\rho_{dry}} \left[1 - \frac{1}{2} \left(\frac{h_0}{h_1} \right) \left(1 + \frac{h_0}{h_1} \right) \right] \cos(\alpha_0)
\end{aligned} \tag{1}$$

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

$\Delta Z_{b,tran}$ is siltation thickness per tide contributed in transverse direction (m);

$\Delta Z_{b,long}$ is siltation thickness per tide contributed in longitudinal direction (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 and k_2 are empirical coefficients (k_1=0.35 and k_2=0.13);

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 inside the excavated channel or pit (m);

ρ_{dry} is dry bulk density (kg/m^3);

α_0 is the angle between mean flow direction and channel orientation. $\alpha_0 = 90°$ if the flow direction is perpendicular to the channel and $\alpha_0 = 0°$ if the flow direction is parallel to the channel orientation;

Though the above equation was originally developed for channels, it can also be applied to assessing the infilling rate in a dredged pit. The flow over a dredged channel will increase if the channel is parallel to the flow as the deepening of the channel reduces the bottom friction. However, if the channel is perpendicular to the flow, the flow over the dredged channel will decrease in response to the greater water depth. The latter condition is the case for most dredged pits. The flow could be considered to be always perpendicular to the channel (or pit) in all directions regardless of flow direction. Therefore, the equation for pit infilling rate can be rewritten as:

$$\Delta Z_b = k_1 C_0 \omega_s T \frac{1}{\rho_{dry}} \left[1 - \left(\frac{h_0}{h_1} \right)^3 \right] \qquad (2)$$

The term $\left[1 - \left(\frac{h_0}{h_1} \right)^3 \right]$ in the equation accounts for the reduction of sediment load capacity due to flow reduction as water depth increases over the pit.

b. Parameter determination

The key parameters for the infilling rate calculation are average significant wave height, average tidal current, and the background concentration.

The flow velocity in the equation should be the depth averaged flow velocity during flood or ebb tides. The measurements at WAVCIS Station CSI-03 between 2001 and 2004 suggest an average tidal flow speed of 0.3 m/s. The NCOM model results shown in Figure 2.8 indicate that the flow speed at the Holly Beach Dredge Pit should be in the same order as that measured at Station CSI-03. Therefore, an average tidal flow speed of 0.3 m/s is used for this calculation.

Using the data measured at WAVCIS Station CSI-03 and the data extracted at WIS Station 094, the average significant wave height is about 0.3 m. The wave height at the Holly Beach pit is likely in the same order as measured at the above stations (see Figure 2.13 – wave height distribution from satellite images). Therefore, an average significant wave height of 0.3 m is used for the calculation.

Another key parameter in Equation (2) is the background suspended sediment concentration (C_0), which should represent the long-term averaged suspended sediment concentration for the surrounding area. The most direct way to determine the background concentration is through long-term measurements at the site. If the seabed is in an equilibrium state (i.e. with no ongoing deposition), C_0 can be determined by using an empirical equation with average current and wave height (Liu, 1992), van Rijn (1994)). If the seabed is in a depositional environment, the background concentration (C_0) will consist of two parts: a) the concentration generated by currents and waves (equilibrium concentration); and b) the concentration delivered by external sources through advection/dispersion processes; the primary example being plumes from river discharge.

Unfortunately, there are no site measurements of suspended sediment concentration at the Holly Beach dredge pit. The background concentration can only be determined using the data collected from the surrounding area. As mentioned in Section 2.2.2, the turbidity measurements at Station CSI-03 (for the period April, 2003 to December, 2004) correlate well with wave height at lower concentrations (<200 mg/l) but not as well at higher concentrations (>200 mg/l); the latter are likely influenced by sediment plumes from the Achafalaya River (CSI-03 is located close to the mouth of the river). For the Holly Beach pit, the Achafalaya plume influence should be limited as the mouth of the river is located 200 km to the west and therefore is not considered in this analysis. In order to filter out the plume impact, only measurements during the periods when the concentration correlated with wave height (i.e. the sediment plume had little or no impact on the concentration at the Station CSI-03) were used to estimate the long-term average. The resulting value of about 70 mg/l should represent the background annually-averaged concentration induced solely by local tide and wave conditions. The background concentration was also calculated by using Liu's equation, written as:

$$C_0 = 0.0273 * \rho_s \frac{(U_c + U_w)^2}{gh} \tag{3}$$

where ρ_S is sediment density (=2650 kg/m^3), 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). The calculated average concentration is about 80 mg/l using an average significant wave height of 0.3 m and an average tidal current speed of 0.3 m/s. This compares well to the estimate derived from the CSI-03 measurements with the sediment plume effect filtered out.

Settling velocity is 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 lab 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 20 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 diurnal tide is dominant in the Gulf of Mexico so a tidal period of 24.8 hours is used in this calculation.

c. Results and sensitivity tests

Equation (2) is used to calculate the infilling rate for Holly Beach pit. Figure 3.10 shows the bed elevation change with time. The solid line represents the calculated bed elevation (from mean sea level to bottom) starting from the average bed elevation immediately following dredging. The dotted lines represent the calculated bed elevation starting from a high and low initial bed elevation representative of the range of depths that existed immediately following dredging. The symbols represent the measured bed elevation on May 2004 and December 2004 extracted from the hydrographic data for those two surveys. The calculated bed elevations agree well with the bed elevation measured on December 2004, but are slightly higher than that measured in May 2004, which could be explained by seasonal variation in the infilling process (i.e. this simple theoretical approach assumes a linear infilling rate through the year).

Figure 3.11 shows the pit sedimentation rate in percent filled with time. This indicates that the pit was about 45% full by the end of 2004 and will be almost completely filled in 2008 or 2009.

Since the settling velocity and dry density were estimated, they could be regarded as the calibration parameters for this calculation. Sensitivity tests were performed for these two parameters. Figure 3.12 shows bed elevation change with time for four different settling velocities. The pit fills faster when a larger settling velocity is used. Figure 3.13 shows the calculated bed elevation change using four different depth-averaged dry densities for the deposited sediment. Unlike settling velocity, the solution is less sensitive to variation in dry density. An assumption of higher dry density (i.e. more consolidation) slightly reduces the infilling rate.

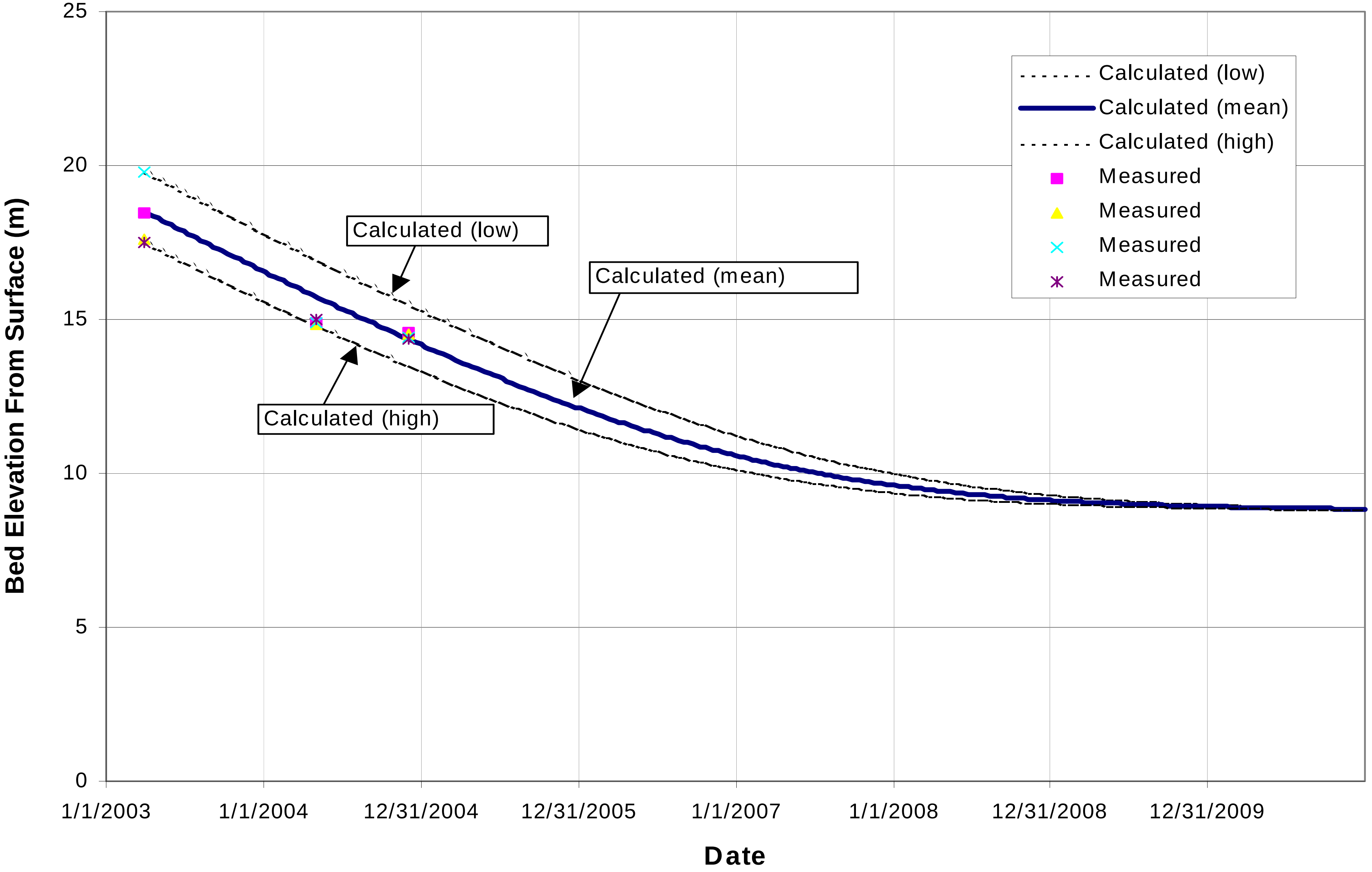

FIGURE 3.10 Holly Beach Dredge Pit - Measured vs. Predicted (with the 1D model) pit infilling since initial dredging.

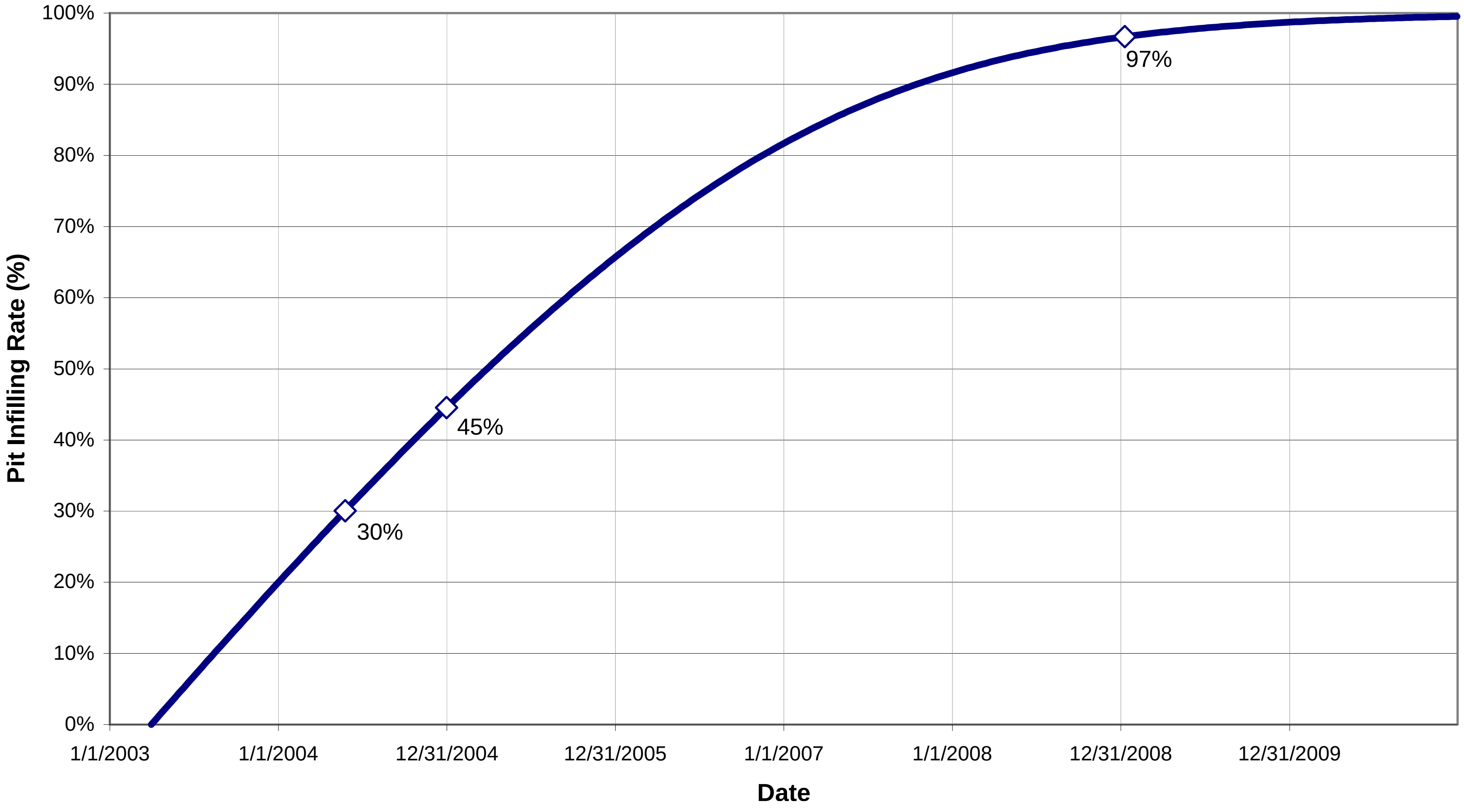

FIGURE 3.11. Holly Beach Dredge Pit - % Infilled with time predicted by the 1D model

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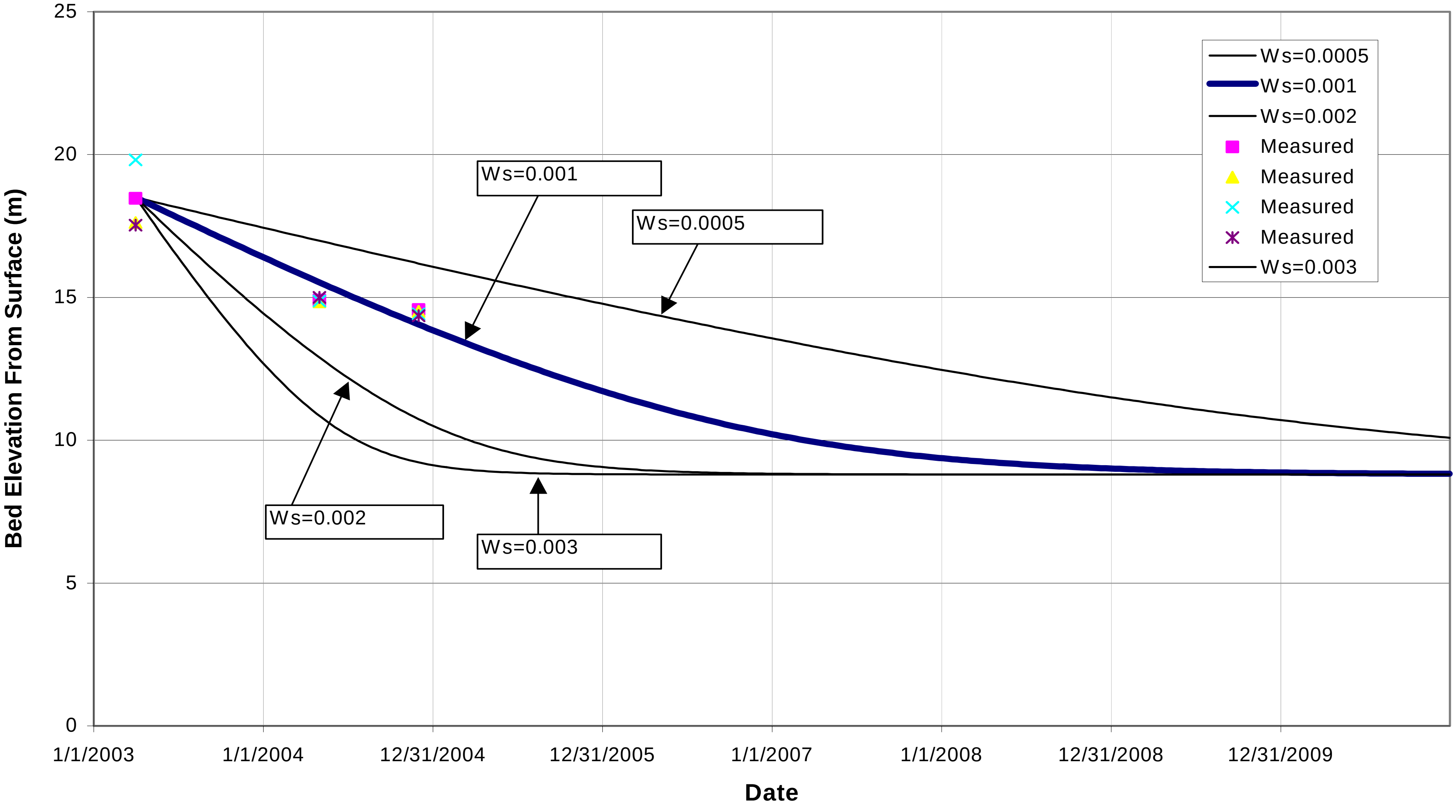

FIGURE 3.12. Holly Beach Dredge Pit - Sensitivity of 1D model prediction of pit infilling to sediment fall velocity.

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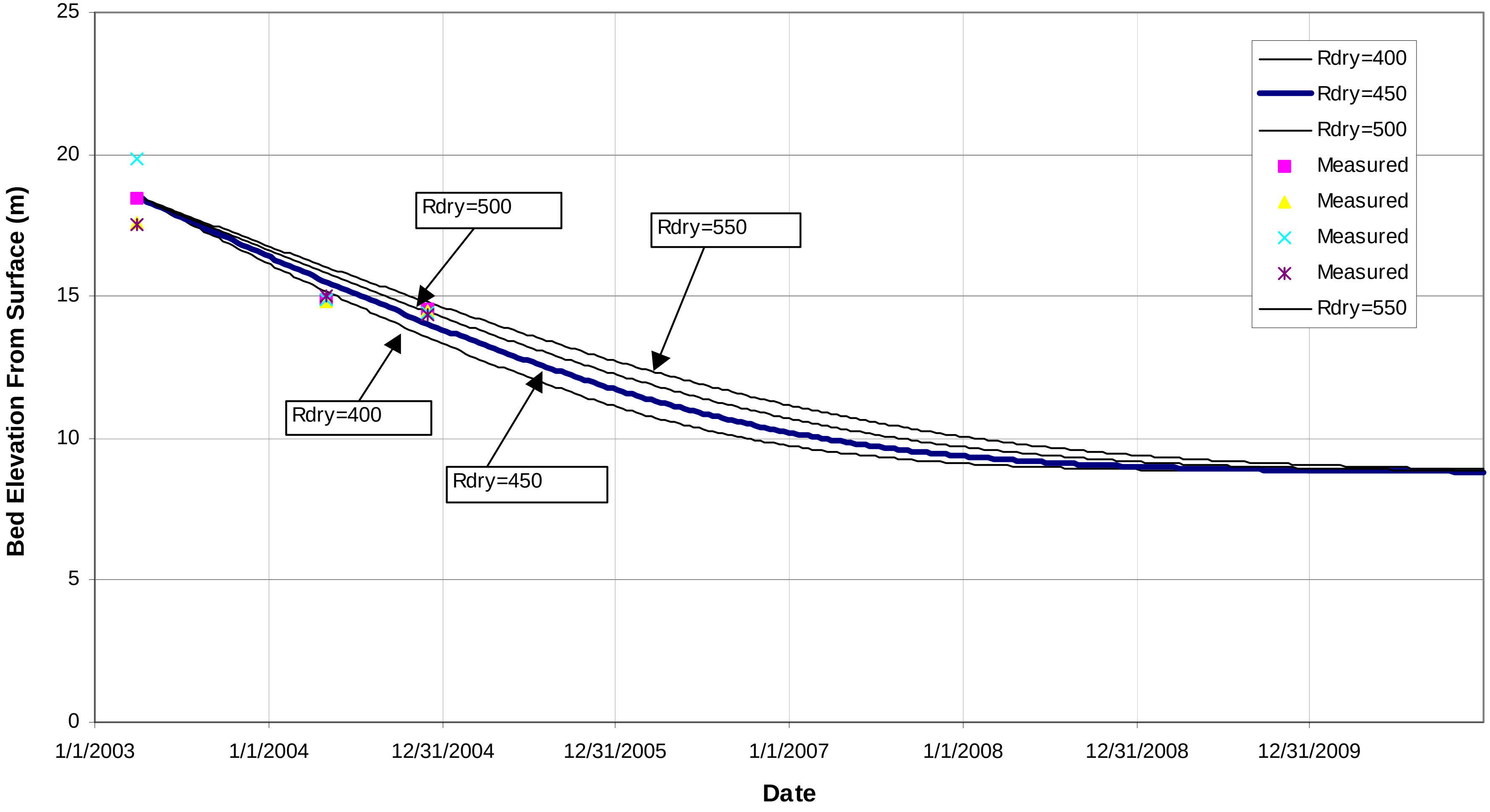

FIGURE 3.13. Holly Beach Dredge Pit - Sensitivity of 1D model predictions of pit infilling to dry density of sediment in the pit

Pit Margin Erosion

At the Holly Beach Dredge Pit erosion was observed in the pit margin area. As flow leaves the pit and water depth is reduced, the flow speed increases to match the ambient flow speed in the absence of the pit. The sediment load capacity of the flow at the outgoing edge is similar to the load capacity at the incoming edge. However, the suspended sediment concentration at the outgoing edge is less than capacity once the flow accelerates to ambient flow speed due to deposition in the pit. This results in bed erosion beyond the outgoing edge to restore sediment concentration to an equilibrium level. An equation to estimate pit margin erosion was developed on the basis of one-dimensional sediment transport, which is written as

$$\frac{\partial q_s}{\partial x} = \beta \omega_s \left(c_b - c_{0,b} \right) \tag{4}$$

where c_b is sediment concentration near the bed. It can be expressed as $c_b = \eta C$, in which C is depth-averaged sediment concentration and η is an adjustment parameter for non-uniform vertical distribution of sediment concentration;

$c_{0,b}$ is equilibrium near bed sediment concentration. It can be also expressed as $c_{0,b} = \eta C_0$;

x is distance in the flow direction;

q_s is total suspended sediment load, which is expressed by

$$q_s = \int_0^h ucdz = \alpha UhC$$

in which, u is flow velocity and c is concentration, U is depth averaged flow velocity, h is water depth, and α is the adjustment parameter for non-uniform vertical distribution of sediment load.

The one-dimensional bed change equation is expressed as

$$\rho_{dry} \frac{\partial Z_b}{\partial t} = \frac{\partial q_s}{\partial x} \tag{5}$$

where Z_b is the bed elevation. Using depth-averaged values for all variables in the above equation, the equations can be rewritten as

$$\alpha \frac{\partial (UhC)}{\partial x} = \beta \eta \omega_s \left(C - C_0 \right) \tag{6a}$$

$$\rho_{dry}\frac{\partial Z_b}{\partial t}=\alpha\frac{\partial(UhC)}{\partial x} \tag{6b}$$

In order to determine the pit margin erosion, suspended sediment concentration at the outgoing edge is first determined by applying Equation (6b) to determine the reduction in sediment concentration through deposition across the pit (see Figure 3.14). Note that the flow velocity and water depth at the incoming edge should be the same as the outgoing edge. Therefore, the above equation can be rewritten as:

$$\rho_{dry}\frac{\Delta Z_{b,pit}}{\Delta t}=\alpha\frac{U_0h_0C_0-U_0h_0C_1}{\Delta x_{pit}} \tag{7}$$

where U_0 is depth averaged flow velocity at the edges, C_0 is the depth averaged concentration at the incoming edge, C_1 is the depth averaged concentration on the outgoing edge, and Δx_{pit} is the length of pit in the flow direction. By simplifying the above equation, the concentration on the outgoing edge is determined by

$$C_1=C_0-\frac{\rho_{dry}\Delta Z_{b,pit}\Delta x_{pit}}{\alpha U_0h_0\Delta t} \tag{8}$$

in which, $\Delta Z_{b,pit}$ is the bed elevation change in the pit which is calculated by Equation (2). Then, the pit margin erosion and the outgoing concentration are estimated by applying Equations (6a) and (6b) to each reach on the outgoing edges, for example between Cross-section 1 and 2 as shown in Figure 3.14. Therefore, the concentration at Cross-section 2 is calculated by

$$\begin{aligned} C_2 &= C_1-\gamma\frac{\omega_s\Delta x}{U_0h_0}\left[C_1-C_0\left(\frac{h_0}{h_1}\right)^m\right] \\ \Delta Z_{b,edge} &= \lambda\frac{U_0h_0(C_2-C_1)\Delta t}{\Delta x\rho_{dry}} \end{aligned} \tag{9}$$

where $\gamma=\beta\eta/\alpha$, is a combined constant relevant to the bed erodibility.

m is a constant accounting for sediment load capacity change due to pit margin erosion (depth change);

λ is a combined constant representing the difference between bed sediment consolidation on the pit margin and in the pit.

In order to increase the calculation resolution, Equation (9) should be applied to a number of reaches along the flow direction until there is no further bed erosion. All these constants should be determined and calibrated using measured data.

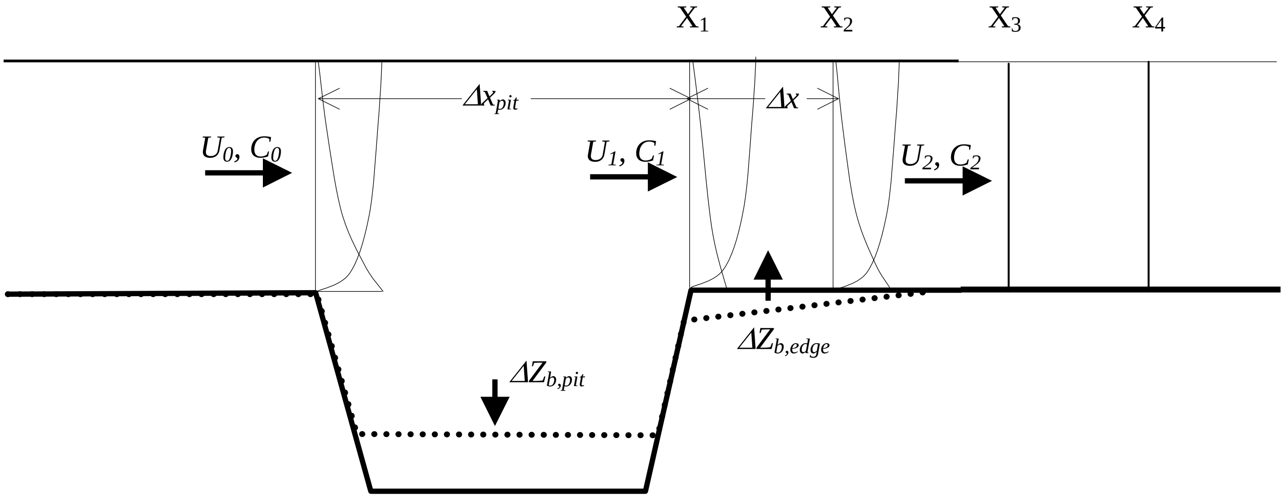

FIGURE 3.14. Pit Infilling and Pit Margin Erosion Processes Conceptual Diagram.

The constant α represents the ratio of total suspended sediment load calculated by using non-uniform distribution of sediment concentration and flow velocity through the water column to that calculated by using depth-averaged concentration and flow velocity. A value of 1 represents sediment load under a uniform distribution of concentration and flow velocity through the water column. Therefore, the value of α should be larger than 1 because a higher sediment load near the bed enhances sediment exchange and erosion/deposition processes. Since the concentration profile depends on settling velocity and the vertical diffusivity coefficient, the constant is a function of sediment grain size and the strength of turbulence. The constant should be larger for coarser sediment.

The constant γ depends on: the probability of settling; an adjustment parameter for non-uniform distribution of sediment load (i.e. constant α); an adjustment parameter for non-uniform distribution of sediment concentration; the flow condition; and the bed material. Since there are no direct data to determine the constant and it has a complicated physical meaning, it can only be determined through calibration.

The constant m represents the reduction of the load capacity of the flow as the water depth of the pit margin increases due to erosion. Since the vertical measure of pit margin erosion is much smaller than the rise of the pit floor due to infilling, this factor is not considered in the calculation, i.e. m=0.

The value of 0.3 is used for λ representing the ratio of consolidation of deposited material in the pit versus eroded material from the pit margin.

Figure 3.15 shows the bed change across pit margin with distance from the pit edge calculated using Equation (9) from April 2003 (after initial dredging) to the end of

December of 2004. The measured bed change for this period between the two surveys is also shown. The predicted pit margin erosion agrees well with the measurements. Figure 3.16 shows the predicted bed change with distance from the pit edge for three selected snap shots (May 2004, December 2004, and December 2008). Note that the pit margin erosion on December 2008 may be over-predicted since the pit margin erosion would have been reversed earlier in time as the pit floor level reaches the same bed elevation as the pit margin. This effect was not considered in the development of Equation 9. Figure 3.17 shows predicted bed change with time at various distances from the edge of the pit (20 m, 100 m, 300 m, 600 m, and 1000 m). These results show that the greatest erosion (about 1.0 to 1.2 m) occurs within 100 m of the edge and beyond that point the erosion decreases with distance. In theory, and according to the assumptions inherent in Equation 9, it is possible that the pit margin erosion could extend 1000 m from the edge for the Holly Beach Dredge Pit. Again, it is very likely that this is over-predicted because of the neglect of the pit infilling influence on pit margin infilling (once the pit floor rises to a similar level to the pit margin zone).

3.1.3 Numerical Modeling of Holly Beach Pit Evolution

Two numerical models were developed to simulate hydrodynamics, sediment transport, and morphologic changes in and around the pit. The objective of the numerical modeling analysis was to verify the simple analytical approach described above and to develop an improved understanding of the process. A three-dimensional hydrodynamic and sediment transport model, called MISED, was used for these two model runs.

MISED is a three-dimensional finite element model that simulates tidal flow, temperature, salinity, sediment transport, morphology, and water quality in rivers, estuaries, and coastal and open sea areas. The model utilizes a new numerical method that is highly efficient and unconditionally stable. This numerical method allows for much larger time steps than other models such as MIKE3, ADCIRC, POM, and RMA2. The model is equipped with a robust drying up technique to deal with drying and wetting processes on flat floodplains and wetland. It can be applied to simulate tidal circulation in large areas, wind driven currents, stratified flow, sediment transport, erosion and deposition of sandy and cohesive sediments, advection-dispersion of thermal plumes, pollutants and contaminants, and to assess the impacts of a variety of coastal engineering structures including floating and submerged structures on surrounding environments. Details of the model are presented in Lu and Wai (1998).

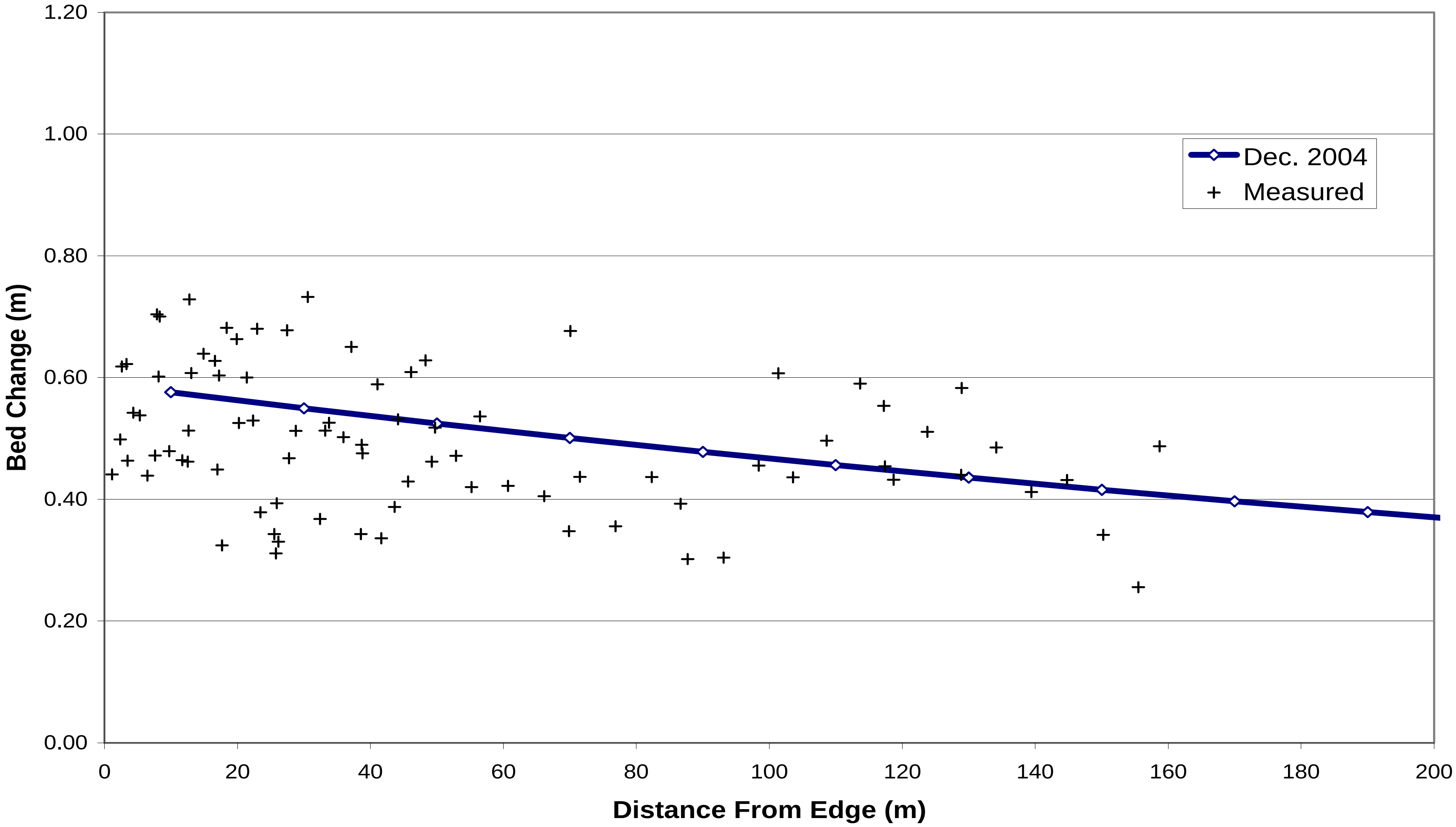

FIGURE 3.15. Holly Beach Dredge pit - Calibration of Predicted (with the 1D model) Pit Margin Erosion Using Measured Data.

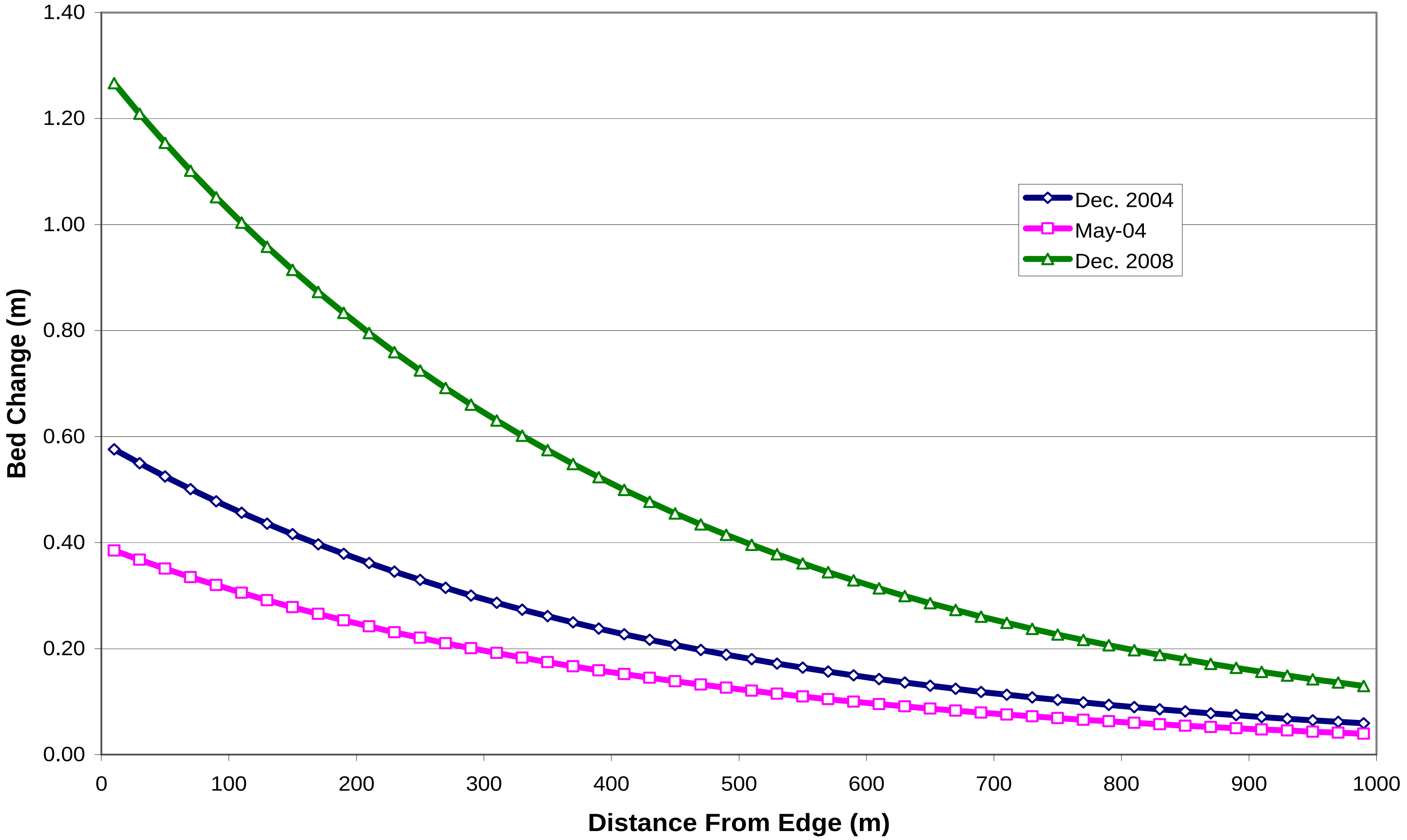

FIGURE 3.16. Holly Beach Dredge Pit - 1D Model predictions of pit margin erosion for three snapshots in time.

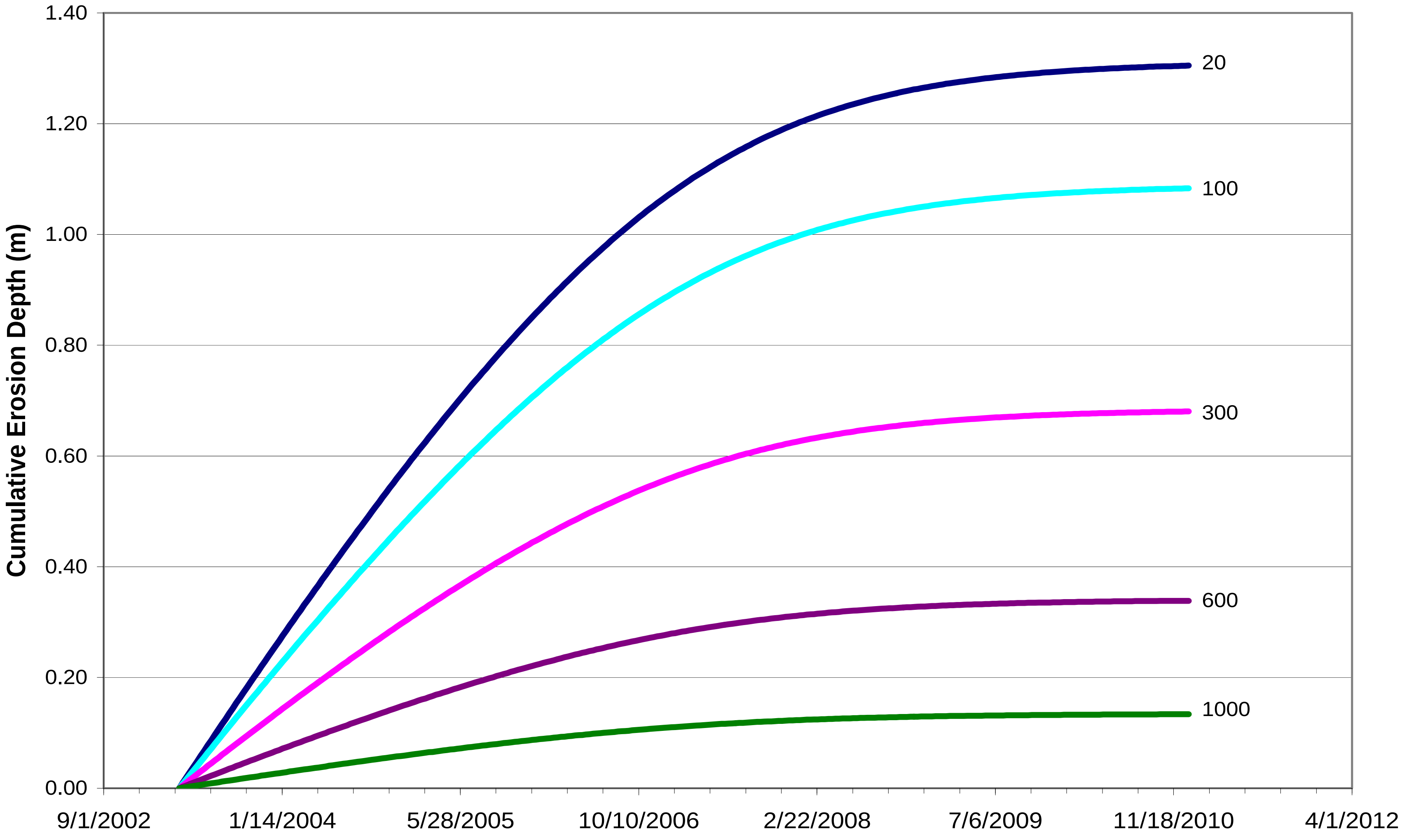

FIGURE 3.17. Holly Beach Dredge Pit - 1D Model predictions of pit margin erosion of specified locations through time.

3.1.3.1 MISED Hydrodynamic and Particle Tracking Model

This model was applied to simulate the three dimensional hydrodynamics in the pit and surrounding areas. The model was set up using the bathymetry for the pit and surrounding area measured immediately after dredging in April 2003. The model domain and pit location are shown in Figure 3.18. The grids in the vicinity of the pit were resolved to 75 m to capture the influence of the pit. There were 11 layers in the water column. The model boundaries on three sides (see Figure 3.19) were controlled by tides extracted from the US Army Corps of Engineers regional ADCIRC model. Large time steps of 600 seconds were used for the simulation. The simulation period is about 5 days and included spring tides and neap tides.

The model was used to investigate the detailed hydrodynamics in the pits and to estimate the possible sources of the sediment deposited in the pit. Specifically, the objective was to determine how far from the edge the re-suspended sediment could be carried and deposited within the pit under the range of tidal excursions. On a long-term average basis, pit margin erosion at any given location would likely occur if the re-suspended sediment from that location has a significant probability of deposition in the pit. Therefore, a particle-tracking model was used to track the particle movement. Figure 3.20 shows the final locations of neutrally buoyant particles, which were continuously released at the surface at two locations 300 m east and west of the pit edge for 5 days. It is clear that a significant fraction of the particles re-suspended from the seabed within 300 m of the pit can be deposited in the pit. As mentioned above, this implies that bed erosion will occur to a distance of at least 300 m from the edge of the pit. Figure 3.21 show the final locations of particles 5 days after the initiation of release from four different locations that are about 1000 m from the pit edge. Only the particles released 1,000 m from the west edge of the pit have any chance of deposition in the pit, and the probability is much smaller than particles released 300 m from the edge. The reason that the particles from the distant westerly release point (i.e. 1,000 m) away reach the pit and those released from the easterly point do not is related to the selection of a limited 5-day tidal period (from spring to neap tide). Therefore, this simple particle tracking application of a complex 3D hydrodynamic model suggests the limit of pit margin erosion is somewhere between 300 and 1,000 m from the edge of the pit and that the extent is greater in the main east-west tidal flow direction. The particle tracking approach likely over-estimates the extent of influence of the pit because the particles were neutrally buoyant and released near the surface where the velocity is highest and tidal excursion greatest. Figure 3.22 shows the complex flow patterns in the pit and large vertical velocity components are clearly present in the pit.

Since there is insufficient information to set up boundary conditions for sediment transport, which require detailed time series sediment concentration, the simulation of sediment transport and morphologic change was not performed with the 3D model.

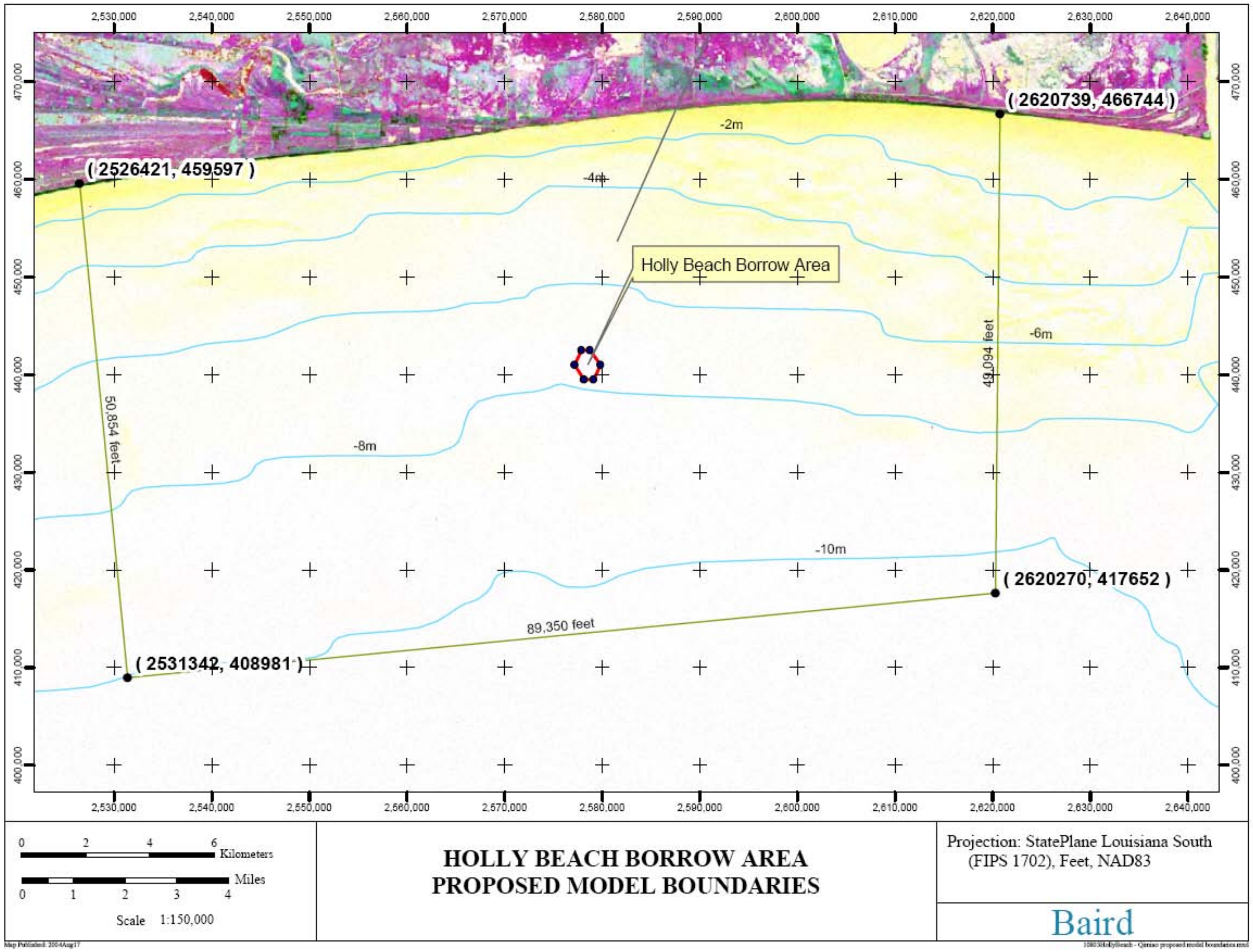

Figure 3.18. Holly Beach Dredge Pit – Domain for the MISED 3D hydrodynamic and particle tracking model.

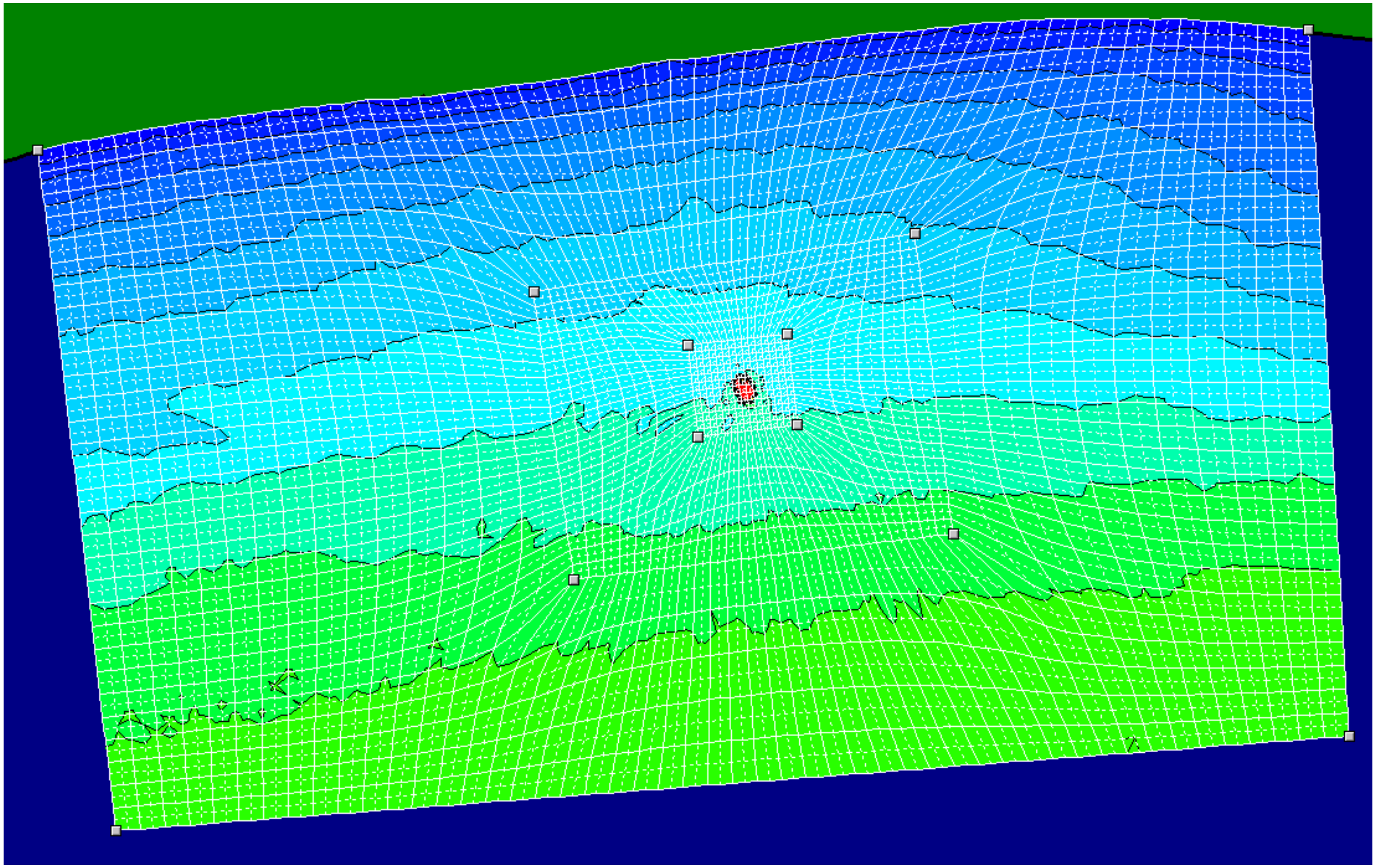

FIGURE 3.19. Holly Beach Dredge Pit – MISED (3D) Model Grid for hydrodynamics and particle tracking.

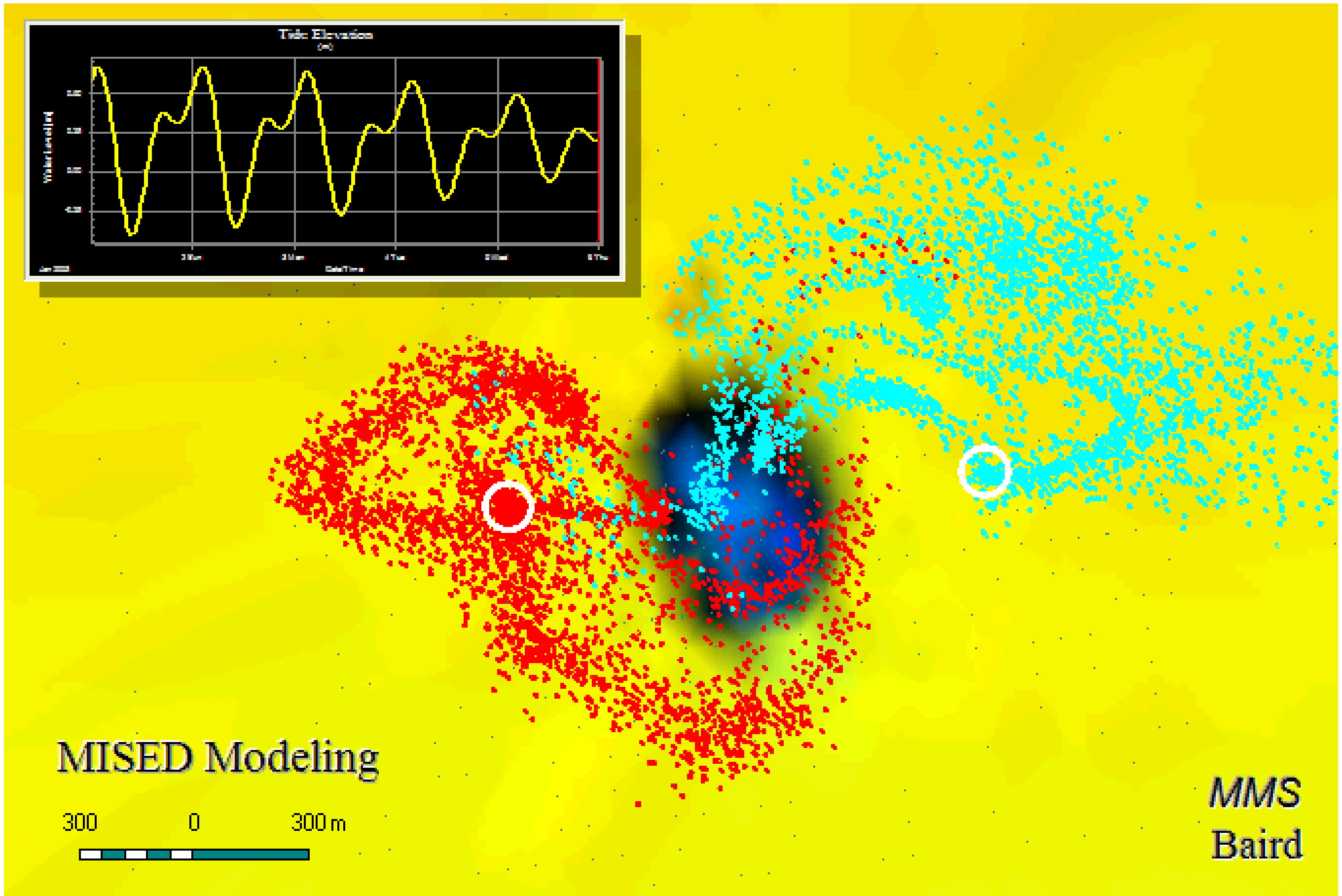

FIGURE 3.20. Holly Beach Dredge Pit – MISED (3D) Model results particle tracking after 5 days (with two releases of neutrally buoyant particles).

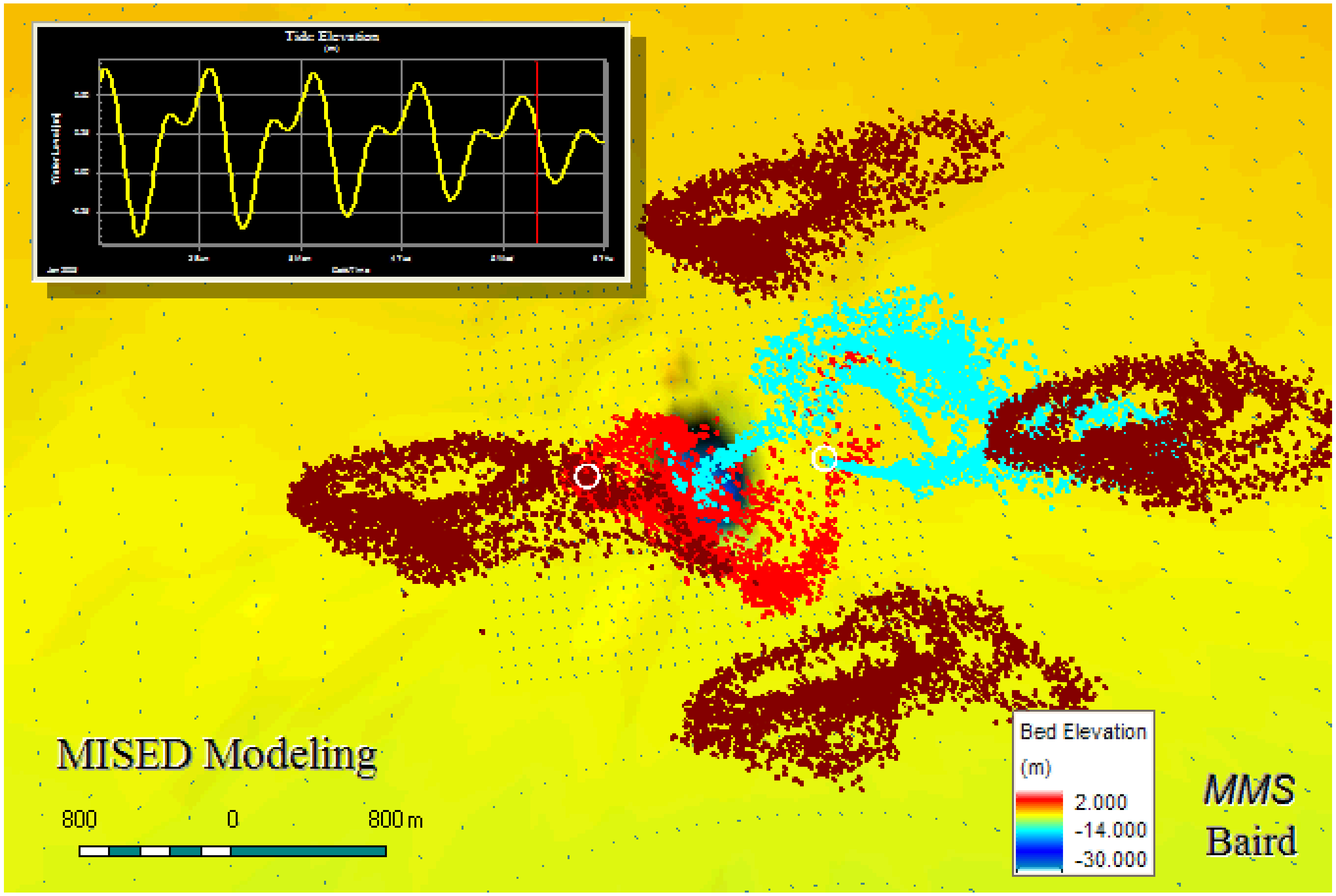

FIGURE 3.21. Holly Beach Dredge Pit – MISED (3D) Model results for particle tracking after five days (with six release points, 4 at 1,000 m away and two at 300 m away)

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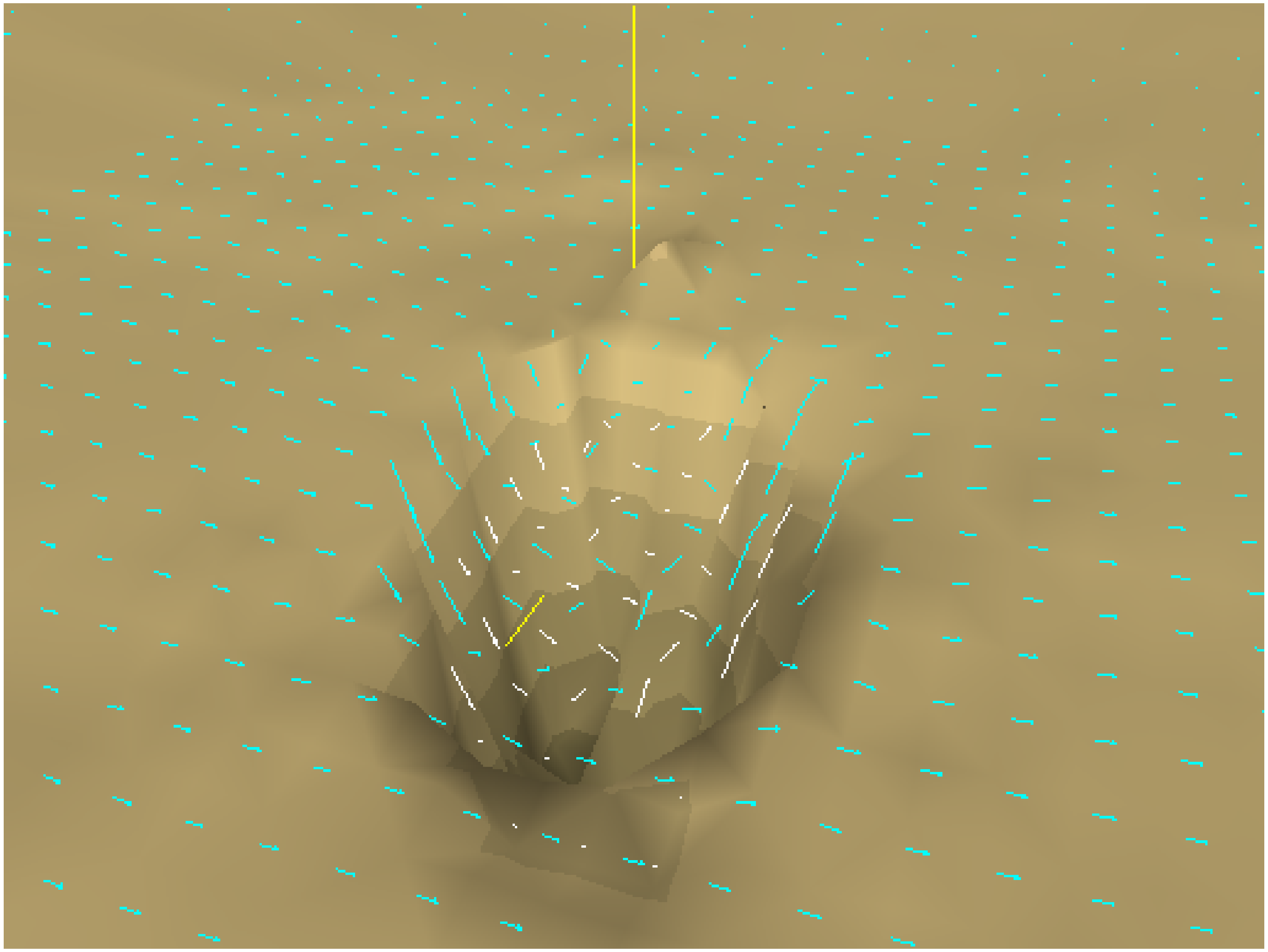


FIGURE 3.22. Holly Beach Dredge Pit – Complex 3D flow pattern around and within the pit of predicted by the MISED (3D) model.

3.1.3.2. MISED Morphological Model Tests

The MISED 3D numerical model was applied in 2DV format (like a laboratory flume test) to simulate long-term morphological change across a profile cut through the middle of the pit. The horizontal dimensions of the model domain were 2,000 m long and 500 m wide. The initial bed elevation is -8.8 m at the edge and –18.5 at the center of the pit. The pit is located at the center of the flume with dimensions of 500 m x 500 m. Tidal flow is generated by the difference in fluctuating water levels at the two boundaries (two ends of the flume). The water levels at both boundaries are calculated with the tidal constituents extracted from the US Army Corps of Engineers regional ADCIRC model. The median grain size of suspended sediment was assumed to be 0.001 mm. The model considered both tide- and wave-induced sediment re-suspension. Since there are insufficient data to input time series wave data, a constant wave height and period was applied for the entire model simulation period. The incoming concentration at the boundaries was controlled by the same constant concentration used in theoretical analysis. The model simulation period was ten years, which was long enough for the pit to fill completely. Since the MISED model is unconditionally stable and highly efficient, a very long time step (3,600 seconds) was used for the simulation and it took about an hour to perform a ten-year morphologic simulation with a Pentium 4 PC (3.1 Ghz).

Figure 3.23 shows the predicted bed elevation change with time and indicates that the model results agree well with the bed elevation measured in the pit. However, the model results indicate that the pit is almost completely filled in between 2010 and 2011, which is longer than predicted by the theoretical analysis (an explanation for this difference is provided towards the end of this section). The main objectives of this 2DV or flume test were to evaluate the pit margin erosion, which is more complicated to predict than the pit infilling, and to verify the analytical results. Figure 3.24 provides a comparison of the bed elevation predicted with the model and the measured bed elevation on December 2004; 20 months after initial dredging. After some calibration the model reproduced well the morphologic changes associated with pit infilling and pit margin erosion. The slight flattening of the pit slope in the model results is due to the resolution of the grids. The parameter that required calibration was the diffusion coefficient and the value selected from the calibration process was within the expected physical range for this parameter. A smaller diffusion coefficient will result in less diffusion. Diffusion essentially concentrates the influence of the pit in a smaller area by reducing the gradient in concentration between the area over the pit and the adjacent areas. Without diffusion the pit margin erosion zone would be much wider than currently predicted, or observed at the Holly Beach dredge pit.

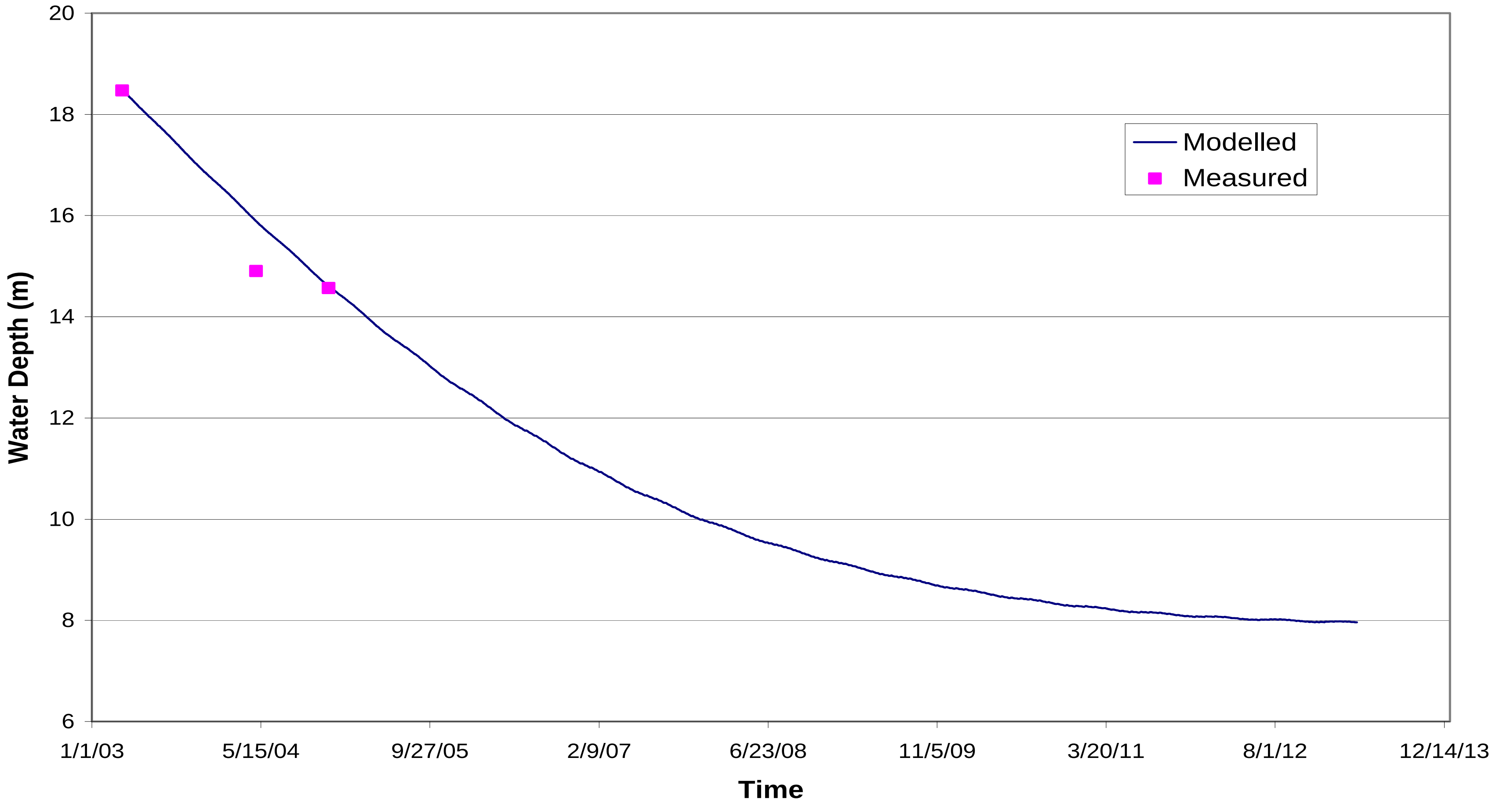


FIGURE 3.23. Holly Beach Dredge Pit - MISED (2DV version) model predictions of pit infilling compared to measurements.

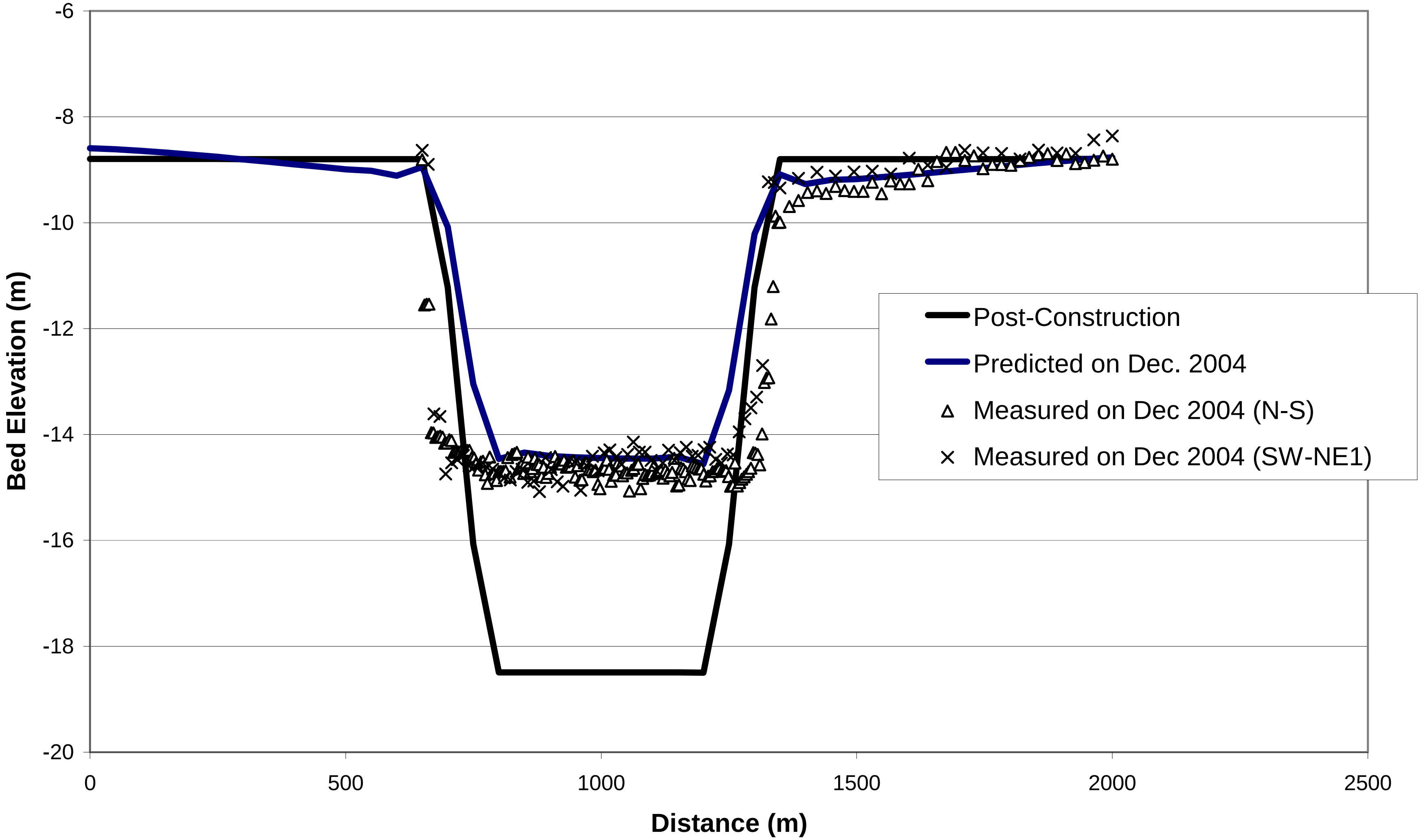


FIGURE 3.24. Holly Beach Dredge Pit - Predicted (with the MISED 2DV model version) versus measured data.

Figure 3.25 shows the predicted bed elevations for different snapshots in time moving forward from the end of 2004 until the pit is completely filled. The model predicts that pit margin erosion extends no further than about 550 m from the edge of the pit and the maximum pit margin erosion depth is about 0.5 m. The distance of influence and the extent of erosion are about half as much as that predicted by the theoretical analysis.

Clearly the model is over-predicting the extent of deposition at the edges of the model domain. This result may be caused by using a constant concentration to control the model boundaries. Since the concentration at the boundaries does not vary with time, deposition would be over-estimated during periods of low tidal flow. The deposited material may not be re-suspended in a balancing manner during higher tidal flows because the critical shear stress for erosion is higher than the critical shear stress for deposition. These results imply that the model was reproducing a slightly depositional environment (versus the existing dynamic equilibrium). Therefore, the model results may under-predict the pit margin erosion. In contrast, as indicated above, the theoretical analysis does not consider the reversal of pit margin erosion once the pit floor reaches a similar level as the eroded pit margin, and may over-predict pit margin erosion.

The over-prediction of the deposition at the edge of the model also affects the predicted time for the pit to infill as the pit effectively becomes deeper with deposition at the edge of the model domain outside the pit. When this is considered, the filling time is closer to the 2008 to 2009 estimate of the 1D model.

At this time, there is insufficient information to attempt to improve the calibration of the 2DV model. At the very least, the variability of suspended sediment through one or more tidal cycles for a given wave condition at the boundary of the model would be required. This demonstrates the importance of local data on waves, currents, bed sediment characteristics and suspended sediment concentration to determine the site-specific pit margin erosion.

3.1.4 Evolution of Muddy-Capped Pits

Muddy-capped pits evolve very differently than sandy pits. The difference is primarily related to the dominance of suspended sediment transport in muddy settings compared to bed load and near bed suspended load transport in sandy settings. Whereas sandy pit evolution involves, and occurs in close proximity to, the pit slopes, muddy capped pits involve pit infilling and pit margin erosion that only have direct morphologic interaction towards the end of pit infilling (when the pit floor reaches a similar level to the pit margin erosion zone). Slopes of muddy-capped pits may not change at all due to the lack of bed load and the ability of cohesive sediment slopes to remain near vertical for up to 5 m in height. Therefore, muddy-capped pits do not migrate, as may be the case with sandy pits where there is a net or residual sediment transport rate.

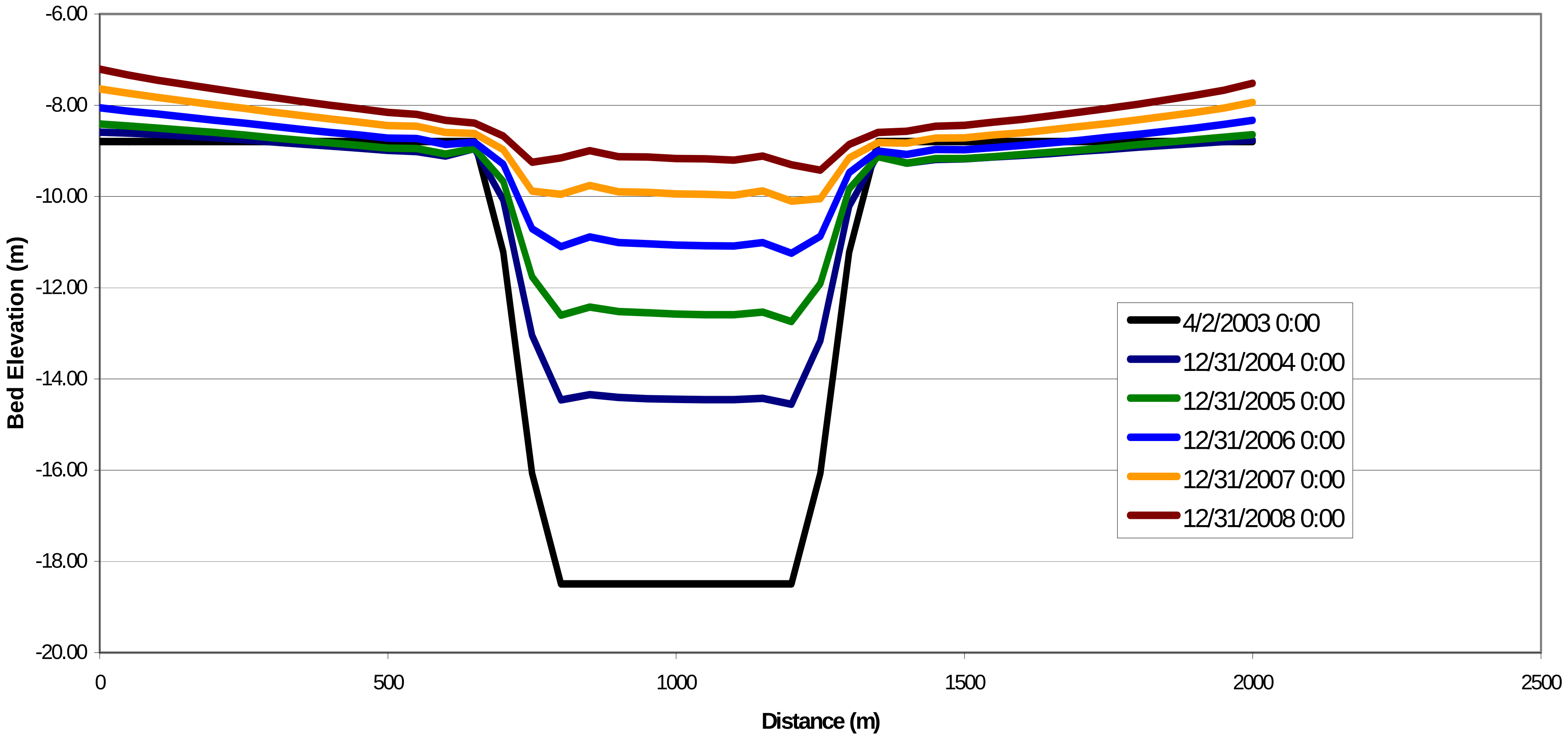


FIGURE 3.25. Holly Beach Dredge Pit - MISED (2DV version) model results of morphologic change 2004 to 2008

In the absence of external sources of sediment such as discharges from rivers, there will be a local balance between the infilling of the pit and the erosion of the neighboring pit margin area. In other words, all of the material for pit infilling is derived from local re-suspension, at least initially. Pit margin erosion will be reduced and less than the total quantity of pit infilling where there is an external source of suspended sediment. Also, pit margin erosion is temporary as with the pit itself any depression in a seabed in dynamic equilibrium will eventually be filled.

The rate of pit infilling can be predicted relatively well with information on the average tidal and wave conditions and where there are no external influences. Pit infilling is accelerated but more difficult to predict where the influence of plume advection/dispersion from river mouths must be predicted. The extent of pit margin erosion is more difficult to predict because, in contrast to pit infilling, which involves a rapid and large change in sediment load capacity in a pre-defined area, the pit margin process is driven by a small difference in sediment load capacity that occurs over an indefinite area. Pit infilling is also much easier to measure because of the greater rate of change in bed elevation and the fact we know precisely where to look. In contrast, pit margin erosion in muddy settings has not been investigated previously and is more difficult to measure because it involves relatively small changes occurring over a long period of time. The pit margin erosion process of pits in muddy settings has not been recognized, investigated in detail or described in the literature, to our knowledge.

Measurements of change to the morphology of the Holly Beach Dredge pit indicate that it was about 45% full 20 months after dredging at the end of 2004. The available hydrographic survey data is insufficient to determine the full extent of pit margin erosion. The available information suggests that 0.3 to 0.6 m (1 to 2 ft) of erosion has occurred to the full extent of overlapping hydrographic data in time, with the greatest extent being 120 m to the north of the pit (the extent of data coverage was much more limited in the west, east and south directions). A theoretical 1D analysis of pit margin erosion found that a maximum vertical erosion of 0.9 m would occur 100 m from the edge of the pit with up to 20 cm of erosion 1000 m from the edge of the pit (both in the direction of tidal flow). The pit was predicted to be completely filled by 2008 using the 1D analysis. The estimates of pit margin erosion with the 1D theoretical approach are likely over-predicted because they neglect the reversal of pit margin erosion once the pit floor elevation reaches the bed level in the pit margin erosion zone. A 3D numerical model of hydrodynamics was applied in particle tracking (full 3D) and 2DV full sediment transport modes. The particle tracking application suggested the extent of pit margin erosion would be between 300 m and 1,000 m from the edge of the pit in an east-west direction. The 2DV application indicated that the maximum limit of the pit margin erosion zone was 550 m from the edge of the pit and the maximum vertical erosion was predicted to be 0.5 m. However, the 2DV predictions of the pit margin erosion are likely under-predicted in horizontal extent and maximum vertical erosion due to over-estimated sedimentation at the edge of the model domain by 1.5 m. The 2DV model results predicted that the pit would be completely filled by 2010 to 2011, or 2008 to 2009 if the unrealistic deposition at the edge of the model domain is considered.

3.2 Sandy Point Dredge Pit (Proposed)

Two dredge pits have been proposed at the Sandy Point borrow area located on the west flank of the Mississippi River delta (see Figure 3.26). The proposed Northwest and Southeast borrow pits are shown in Figure 3.27. The proposed Southeast Pit is the primary target for the CWPRA Pelican Island Restoration project (Syed Khalil, LA DNR, pers. comm.). Design drawings of the borrow area produced by Coastal Planning & Engineering for LA DNR are shown in Figures 3.28 and 3.29. This pit is located between the 34 and 35 ft contours (10.4 to 10.7 m). The pit is generally 1,150 to 1,480 ft (350 to 450 m) wide in the east-west direction to 5,900 to 6,500 ft (1,800 to 1,980 m) in the north-south direction. Two pit depths have been considered: the design depth shown in Figure 3.27 of 55 ft below NAVD, giving a pit depth of about 20 ft (6.1 m) and the "potential depth limit of a deep borrow area" to 75 ft below NAVD giving a pit depth of 40 ft (12.2 m). The closest pipeline is located about 300 m northwest of the northwest tip of the pit.

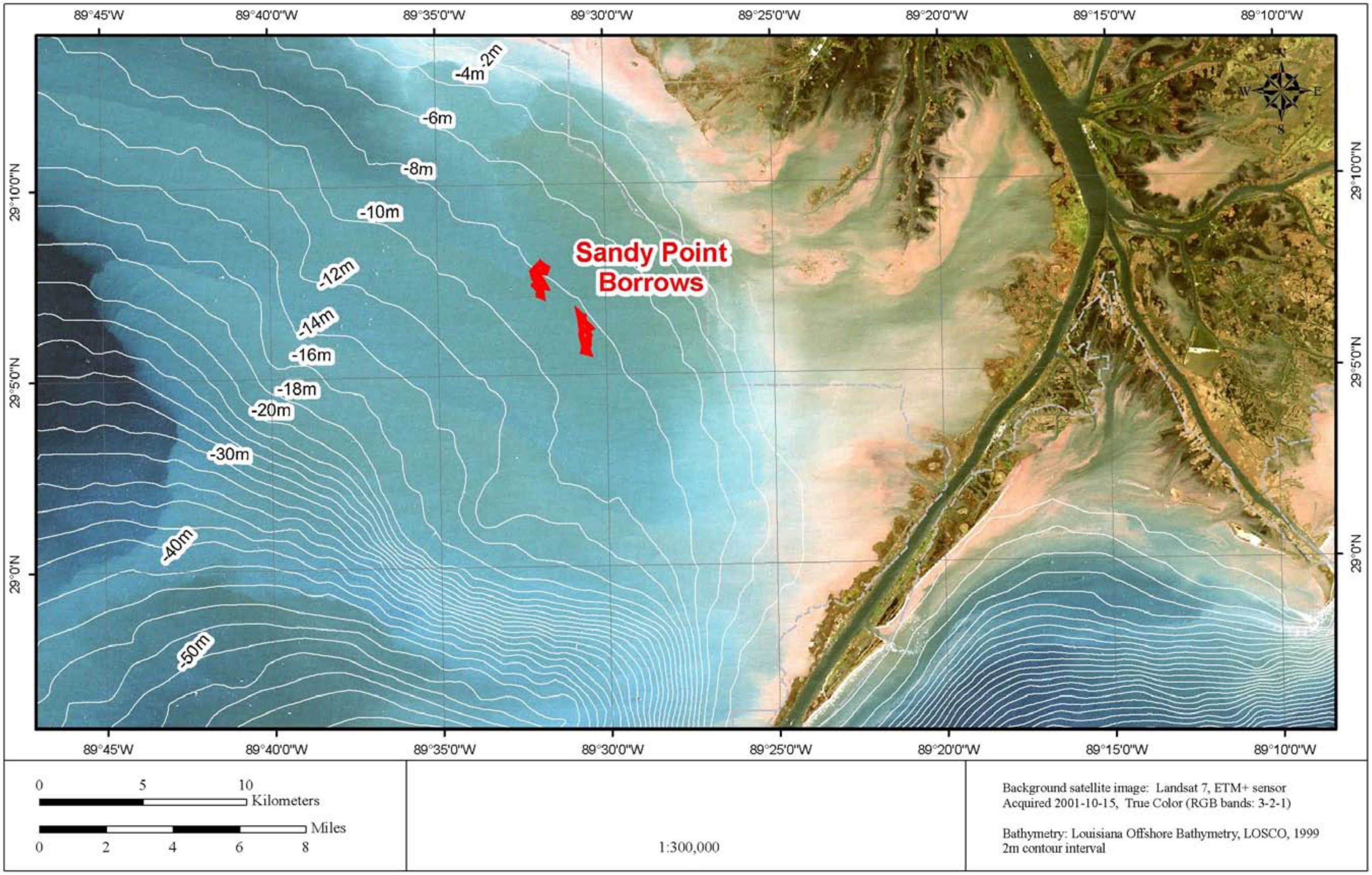
The Sandy Point Dredge site is also a mud-capped area and the predictive 1D equation developed for the Holly Beach Dredge Pit can be applied to estimate the pit evolution. However, the hydrodynamics and sediment dynamics at the Sandy Point site are much more complicated than the conditions at the Holly Beach Pit. Unfortunately, site-specific measurements of these processes at the Sandy Point site are not available.

3.2.1 Analytical approach

Local information on currents, waves, and suspended sediment concentration is essential for predicting the pit infilling rate and pit margin erosion for the proposed Sandy Point pit. Without site-specific measurements these key parameters must be estimated from the data presented in Section 2.

Currents

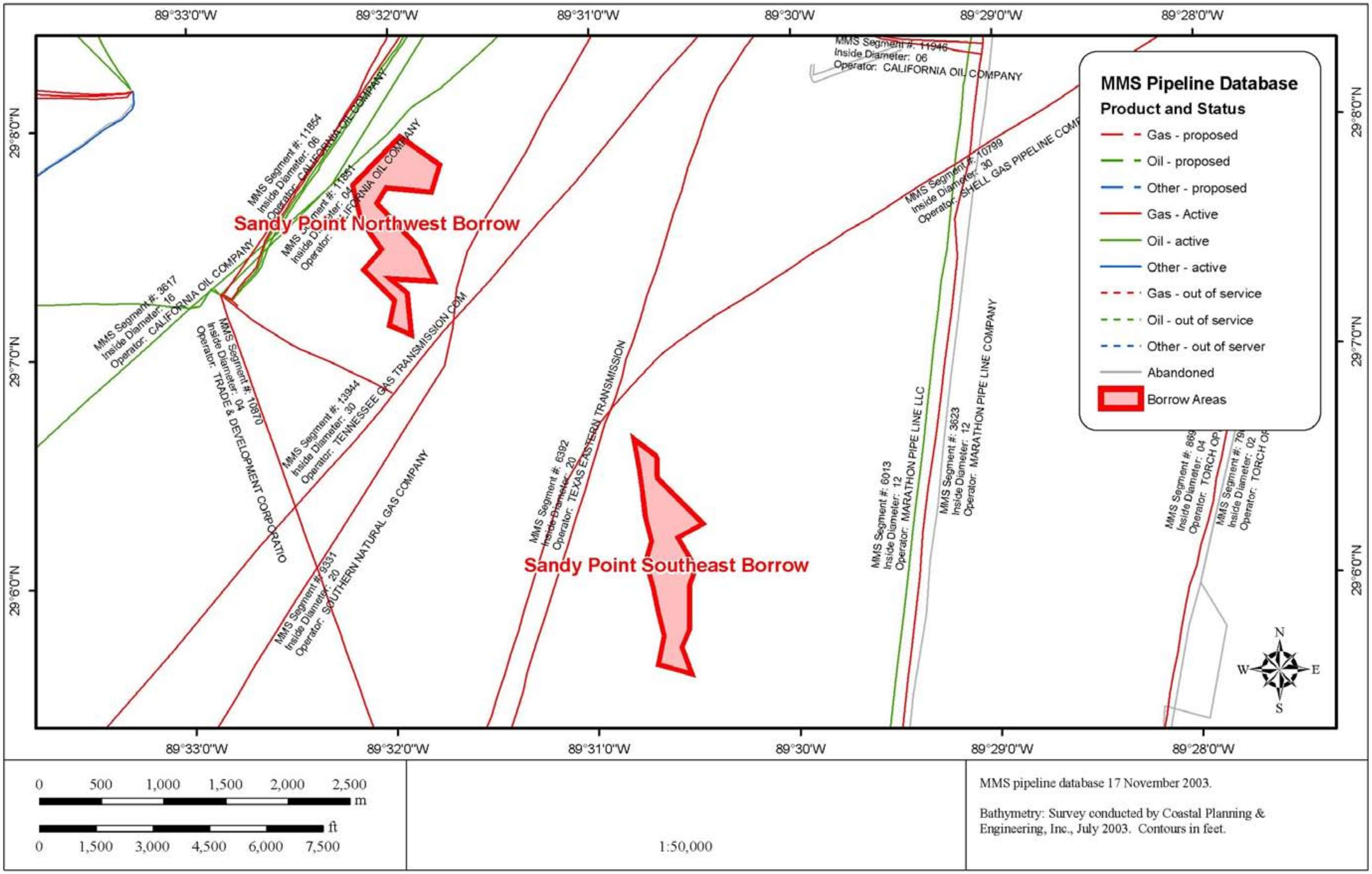
The Sandy Point site is located in the lee of the west flank of the Mississippi River Delta. The long extension of the Southwest Pass produces a shelter zone that induces large eddies when longshore currents set towards west (see the summary of ADCP current measurements in this area in Figure 2.9). Current speed and direction at the proposed pit location will vary with tide and wind conditions. The flow direction would be towards south or southeast when an eddy develops in the lee of the west flank of the delta and possibly towards northeast or southwest during flood or ebb tide, respectively. Based on the NOAA ADCP data, the magnitude of the tidal currents ranges from 0.1 m/s to 0.5 m/s. Since there is no detailed information available, a long-term average tidal current speed of 0.3 m/s is used for this analysis.



Background satellite image: Landsat 7, ETM+ sensor
Acquired 2001-10-15, True Color (RGB bands: 3-2-1)

Bathymetry: Louisiana Offshore Bathymetry, LOSCO, 1999
2m contour interval

FIGURE 3.26. Regional location map for the Sandy Point borrow area.



MMS pipeline database 17 November 2003.

Bathymetry: Survey conducted by Coastal Planning & Engineering, Inc., July 2003. Contours in feet.

FIGURE 3.27. Map of the Sandy Point borrow areas with oil and gas infrastructure.

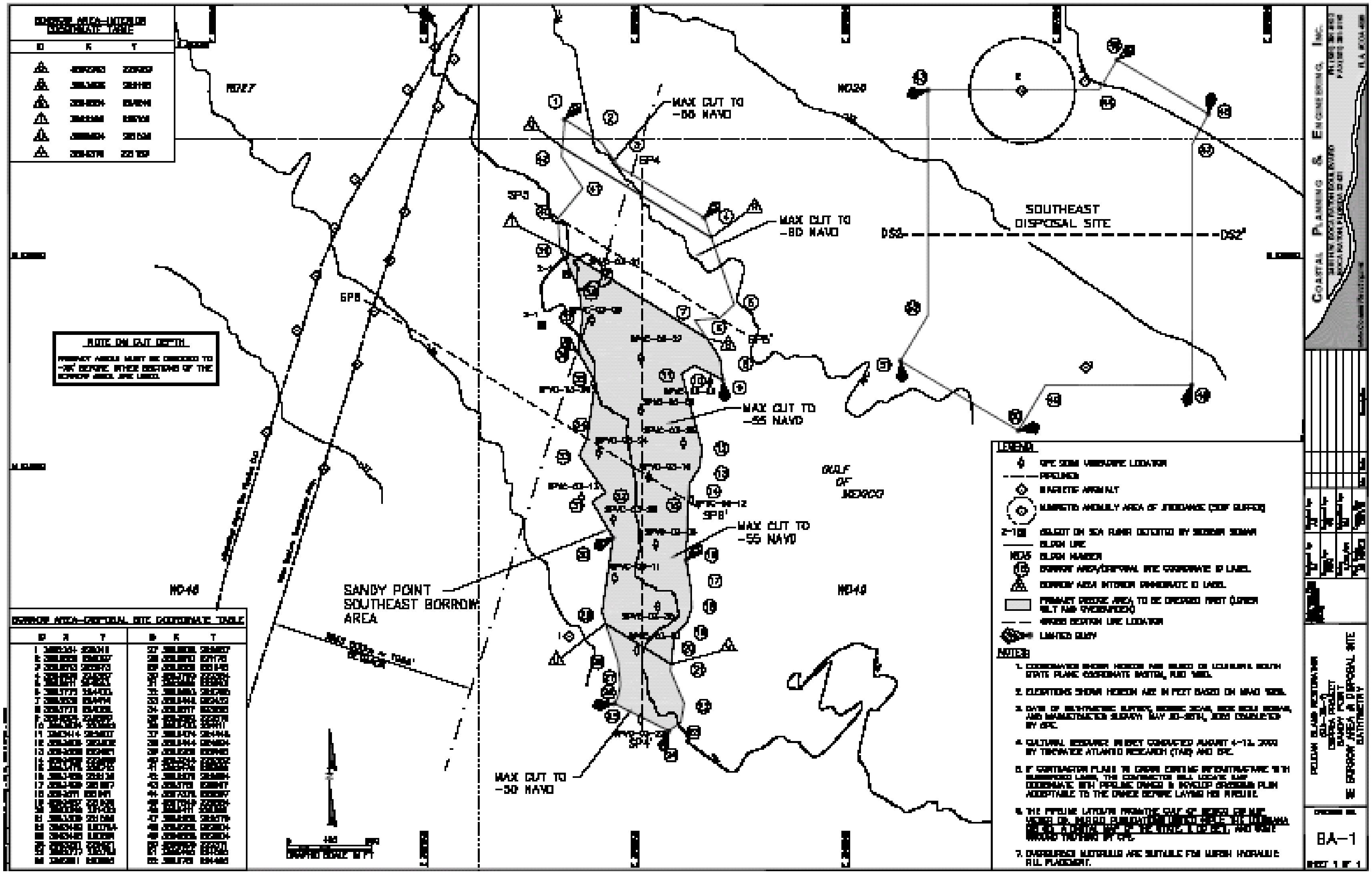


FIGURE 3.28. Layout of the Southeast Sandy Point borrow design (from LA DNR and Coastal Planning & Engineering).

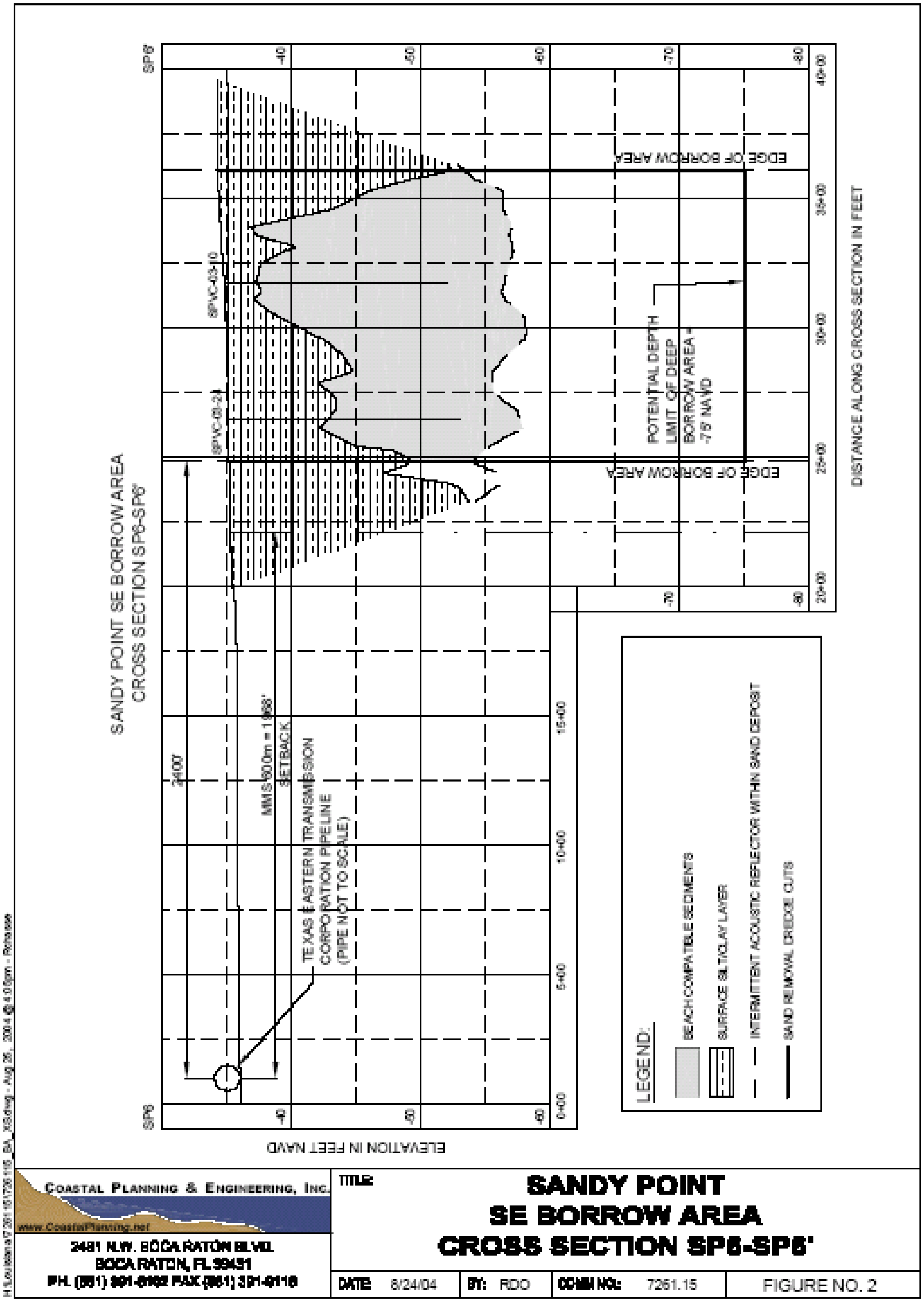


FIGURE 3.29. Cross-Section of the Southeast Sandy Point borrow design (from LA DNR and Coastal Planning & Engineering).

Waves

Wave data were obtained for the nearest WIS Station 132, which is located southwest of the pit and in a depth of 19 m. Data from this station were transferred into the 10 m depth contour at the pit location using linear refraction and shoaling. The average wave height at the station is about 0.4 m and average wave period is about 5 seconds, which are used in this calculation. Details of the summary wave data are presented in Appendix A.

Suspended Sediment Concentration

Suspended sediment concentration at the pit is influenced by tidal currents, winds, waves, flow, and sediment condition in the Mississippi River. From the satellite images presented in Section 2, it is evident that the sediment plume from the Mississippi River influences the sediment concentration at the pit when the longshore currents are towards the west. Therefore, estimation of suspended sediment concentration at this site must consider two components: 1) sediment concentration associated with the local re-suspension of sediment by currents and waves; and 2) sediment concentration associated with the advection/dispersion of sediment plumes from the Mississippi River. Using the estimated average values for current and wave conditions in Equation (3), the sediment concentration related to local re-suspension is estimated to be about 70 mg/l. This average equilibrium concentration could be augmented by plume effects. The increase in concentration may be estimated by applying a dilution factor to the suspended sediment concentration measured within the river. NOAA cruise data (with the exception Cruise IV) indicates that the concentration at the mouth of the Mississippi River is about 65% of the concentration measured at the USGS gage further upstream and the concentration at the cruise stations located near Sandy Point are only about 1.5% of the concentration measured at the USGS gage (see Table 3.1). There are two key assumptions in the estimate of the 1.5% dilution from the USGS gage in the Mississippi River: 1) that the plume had some influence at the cruise sampling stations at the time of measurement (this cannot be verified as satellite images are not available for the time of the cruise surveys between 1982 and 1984); and 2) that the measured concentration at the cruise sample locations had no contribution from local re-suspension by waves and currents. Therefore, the 1.5% dilution must be considered to be a very rough estimate, at best.

Based on the range of concentrations measured at the USGS gage, the concentration at the cruise sampling stations (II-11 and III-14) could be as high as 36 mg/l (see Table 3.2). Note that the Sandy Point pit is located closer to the river mouth than the two NOAA cruise stations. Therefore, the concentration related to the plume would be higher than that measured at the cruise stations. Furthermore, high concentration in the vicinity of the Sandy Point pit was often observed in the satellite images when the wind-induced longshore current is towards the west. Therefore, the average increase of concentration at the pit due to the river plume is very roughly estimated to be about 30 mg/l. Added to the concentration component due to local re-suspension by currents and waves, a total average background concentration of 100 mg/l is roughly estimated and used in the following theoretical and numerical modeling analyses.

TABLE 3.1. Estimate of the Mississippi River Plume to Concentration at Sandy Point.

Cruise	Concentration (mg/l) and Relative Dilution (%)					
	Mississippi River	Atchafalaya River	At Mouth of Mississippi River		At Station Near Sandy Point	
	Concentration (mg/l)	Concentration (mg/l)	Concentration (mg/l)	Relative Dilution (%)	Concentration (mg/l)	Relative Dilution (%)
Cruise I	293	396	189	64%		
Cruise II	282	349	190	67%	4.6	1.6%
Cruise III	266	292	166	62%	3.9	1.5%
Cruise IV	267	295	20	7%		

TABLE 3.2. Concentrations Expected at Sandy Point Based on the Range for the Mississippi River (mg/l).

	Mississippi River (07373293)	At Mouth of Mississippi River	At Station Near Sandy Point
Minimum	38	24	1
Mean	400	256	6
Maximum	2400	1560	36

Prediction of the Infilling Rate

Since no information is available to determine the parameters or coefficients described in the derivation of the 1D analysis approach in Section 3.1, the calibration values from the Holly Beach pit are used for this analysis.

The shape of the proposed pit is a long rectangle with a north-south orientation. The assumed dimensions of the pit for this analysis are 1,980 m long by 450 m wide. Two pit depths are considered with total water depths of: 55 and 75 ft (16.8 and 22.9 m). As mentioned above, the flow directions at the pit could range from a north-south (NS) direction if an eddy is present to an east-west (EW) direction with no eddy and pure tidal flow. It is noted that the north-south flow direction is probably mostly a southerly flow (as this would be the direction when an eddy sets up). However, the Mississippi River plume dispersion pattern Figure 2.17 provides some indication of a northerly flow in the vicinity of the proposed Sandy Point dredge pit. Therefore, two scenarios are investigated in the analysis consisting of north-south and east-west flow directions for the two pit depths. Figure 3.30 shows the bed elevation change in the pit due to infilling with time for both scenarios' flow directions. According to this 1D analysis approach the deeper pit fills faster and in both cases the pit is predicted to be completely filled in 9 to 10 years after initial dredging. The % infilled with time is shown in Figure 3.31 for both pits depths and flow directions. This gives a better perspective on the rate of filling and the influence of pit depth. While both pits appear to take about the same time to fill completely from Figure 3.30, Figure 3.31 shows that the shallower pit is 75% full at least a year earlier. Since the equation for the rate of infilling does not account for the influence of pit size (pit length), the prediction for two flow direction scenarios is the same. However, in reality, increasing the pit length along the flow direction will reduce the infilling rate, and this response is simulated by the numerical modeling presented later in this section.

Prediction of Pit Margin Erosion

Erosion of the pit margin was predicted using the equation developed in Section 3.1. The calculations are again performed for the two current flow condition scenarios: 1) flow in a north-south direction; 2) flow in an east-west direction. Figures 3.32a and b show the pit margin bed erosion as a function of distance from the pit edge for NS scenario and the shallow (55 ft) and deep (75 ft) pits respectively. The results indicate that maximum erosion near the pit edge could be up to about 1.2 m for the shallow pit and 2.3 m for the deep pit. The pit margin is predicted to have 1 m of vertical erosion at a distance of 125 m from the edge of the shallower pit and 690 m for the deep pit. Figures 3.33a and b show the pit margin erosion with time at distances of 20, 100, 200 500, 1,000, 1,500 and 2,000 m from the pit edge for the NS flow and the shallow and deep pits, respectively.

Figures 3.34a and b show the pit margin erosion with the distance from the pit edge for the EW flow direction scenario and the shallow and deep pits, respectively. The maximum erosion near the edge is about 0.25 m for the shallow pit and 0.5 m for the deep pit. Figures 3.35a and b show the pit margin erosion with time at distances of 20, 100, 200 500, 1,000, 1,500 and 2,000 m from the pit edge for the EW flow and the shallow and deep pits, respectively. The greater the dimension of the pit in the direction of the flow, the more the suspended sediment concentration is decreased, and in turn the greater the potential for erosion from the pit margin zone when the flow emerges from the pit.

It is important to note that the approach presented above is too simplistic to represent reality. It assumes that the flow pattern is in an east-west direction all the time or in a north-south direction all of the time. In reality the flow would only occur in either of these direction for some fraction of time during the year and the predicted erosion would be reduced. For example, if these two flow combinations occurred for equal periods of time (50% each) during the year, the predicted erosion on the north/south and east/west sides of the pit would be reduced by half. Also, as noted above, it is likely that the frequency of flows in the north-south direction is dominated by southerly flows (as this is the direction induced by eddies during westerly flows). Therefore, more erosion would occur on the south side of the pit than the north side. There is insufficient information at the site on wind and tide driven currents.

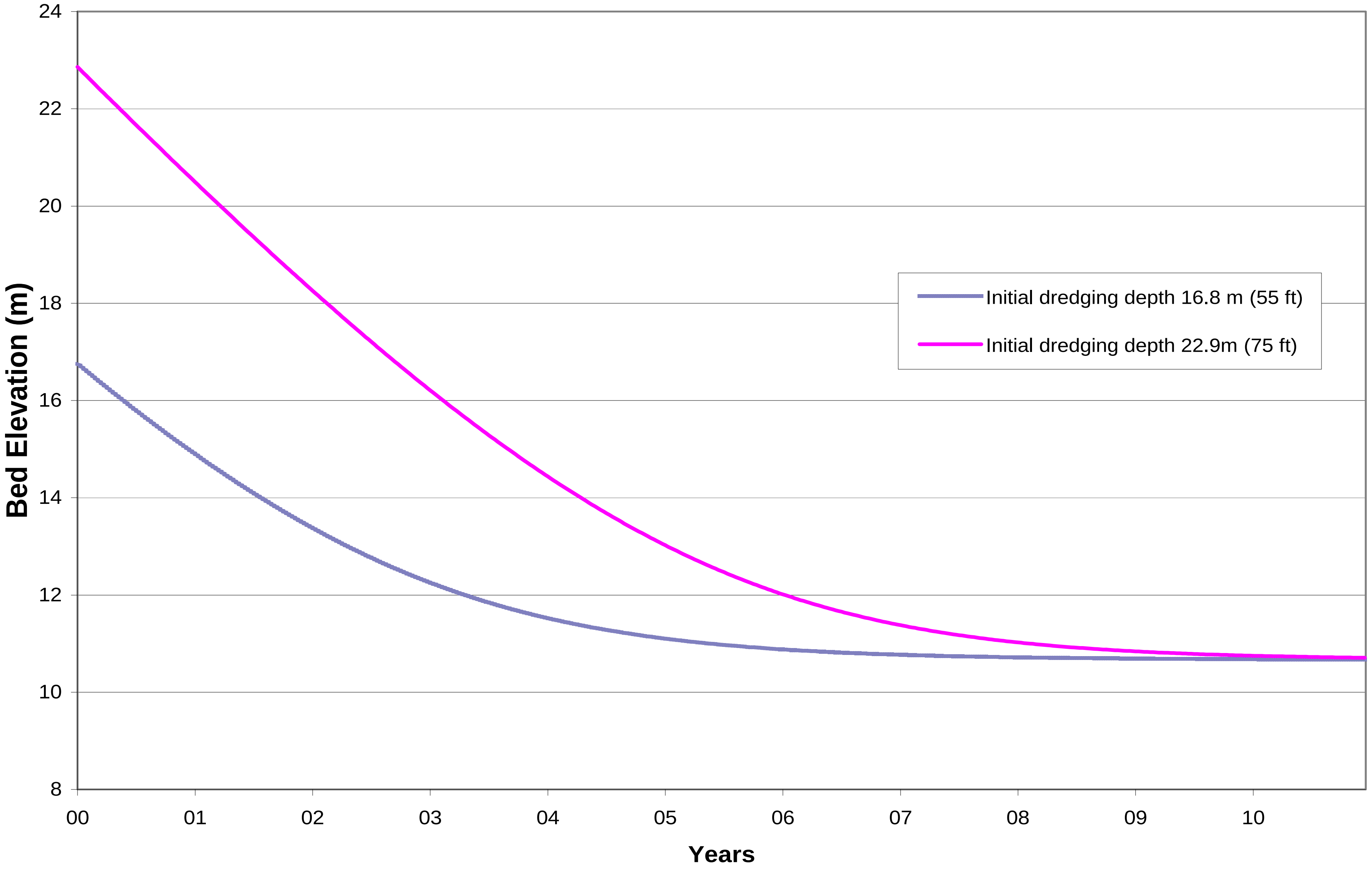


FIGURE 3.30.Sandy Point - Pit margin erosion as a function of time for the Sandy Point pit (for two different pit depths) under both EW and NS currents using the 1D analytical approach (the response is the same for both directions).

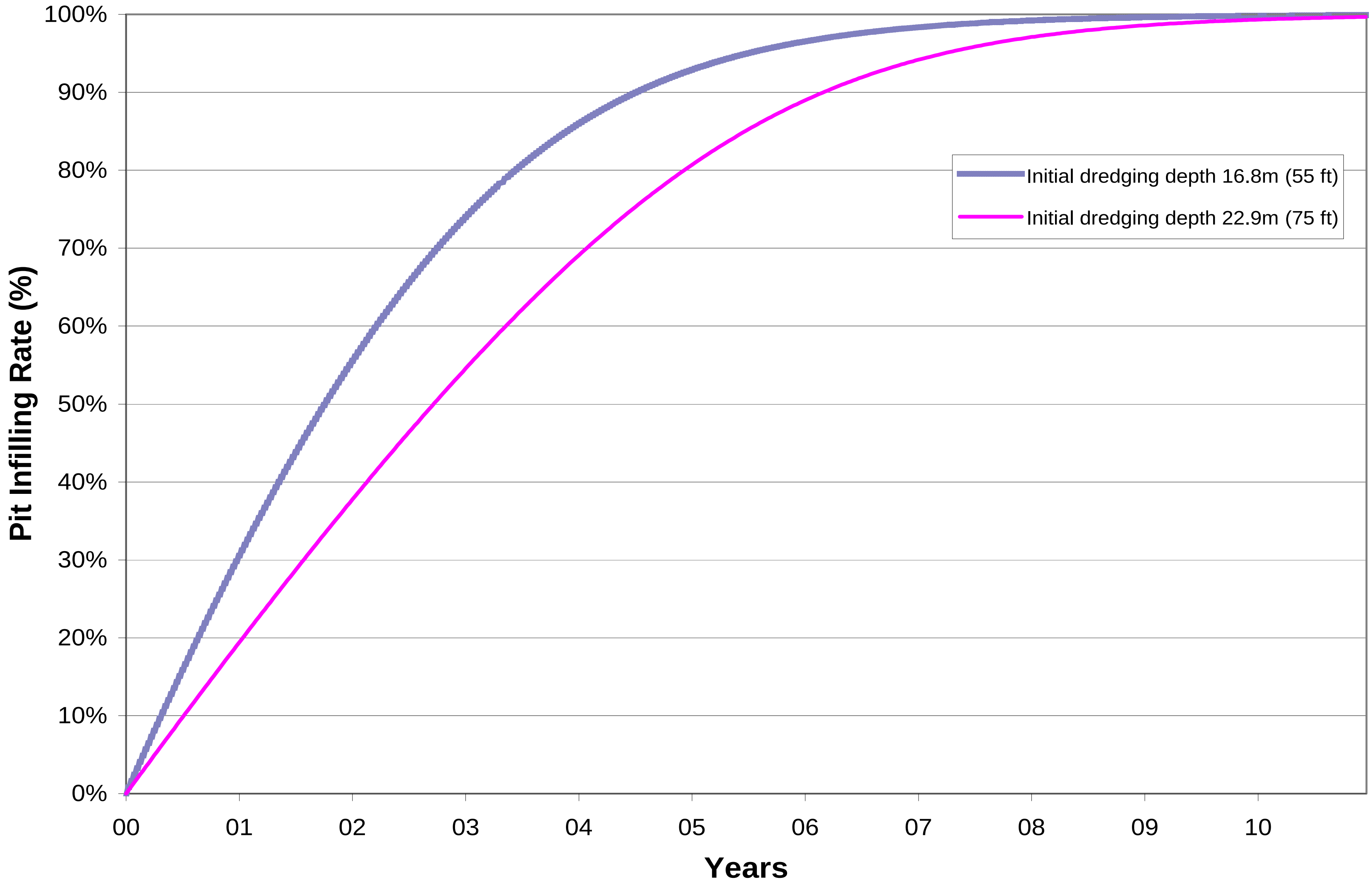


FIGURE 3.31. Sandy Point – Percent pit infilling with time based on the 1D analytical approach (result is the same for EW and NS flow directions).

Nevertheless, keeping in mind the approximate nature and simplicity of this approach, some very approximate estimates of buffer requirements can be made assuming that neither that east-west or north-south flow direction occur all of the time, and that it is likely that east-west flow directions are more common. For the 55 ft deep pit it is approximated that no more than 0.9 m of vertical erosion occurs for distances of more than 50 to 100 m from the edge of the pit. For the 75 ft pit it is approximated that no more than 0.9 m of erosion occurs for distances of more than 150 to 200 m from the pit edge. Therefore, buffers of 100 m or 200 m for 55 ft and 75 ft pits respectively might be recommended (if 0.9 m of temporary erosion was acceptable over pipelines). These estimates are approximate and require more information on currents and suspended sediment concentrations.

3.2.2 Numerical Modeling Tests

Two numerical runs were performed with Baird's 3D MISED model applied in 2DV format to simulate 10 years of morphologic change for the four combinations of two pit depths and two flow direction scenarios. The same parameters developed through the calibration tests at the Holly Beach pit were used for these model applications at Sandy Point. Figures 3.36a and b show both the pit infilling and the pit margin erosion (at two locations) with time for the 55 ft pit and the NS flow scenario in terms of total depth change and bed elevation change, respectively. A maximum vertical erosion of 1 m is predicted at 200 m from the edge of the pit. Figures 3.37a and b show the EW flow results for the 55 ft pit in the same manner. For this case the pit infills in about five years and there is ongoing sedimentation in the pit margin zone where background sedimentation outpaces erosion. The prediction of background sedimentation within the margin zone (vs. erosion observed at the Holly Beach Dredge Pit) results from the contribution of the Mississippi River plume to the background concentration. This contribution brings the local concentration (suspended by waves and currents) out of balance, resulting in background sedimentation. There is no information available to evaluate whether this background sedimentation rate is correct or not, although it is unlikely to be this high, if any. Revised model runs were completed with the 55 ft pit and an EW flow direction and a background suspended sediment concentration of 70 mg/l shown in Figures 3.37c and d show maximum vertical erosion of about 0.8 m at 200 m from the edge of the pit and 1.2 m at 50 m from the edge of the pit. No deposition in the pit margin is predicted with this assumed background concentration.

Figures 3.38a/b and 3.39a/b show the numerical model results for the 75 ft pit and the NS and EW flow directions, respectively (for both the different presentation formats). The deeper pit infills in about 6 to 7 years for the NS flow direction and 5 to 6 years for the EW direction. For the NS flow direction the pit erodes a maximum of about 2.2 m at 50 m from the edge of the pit (and 1.8 m at 200 m from the edge) three years after the pit is dredged and infills thereafter. With the EW flow direction the maximum erosion is a little over 0.5 m one to two years after dredging at a distance of 50 m. There is only 0.2 m of erosion a little after one year post-dredging and deposition thereafter for this condition at a distance of 200 m from the edge of the pit.

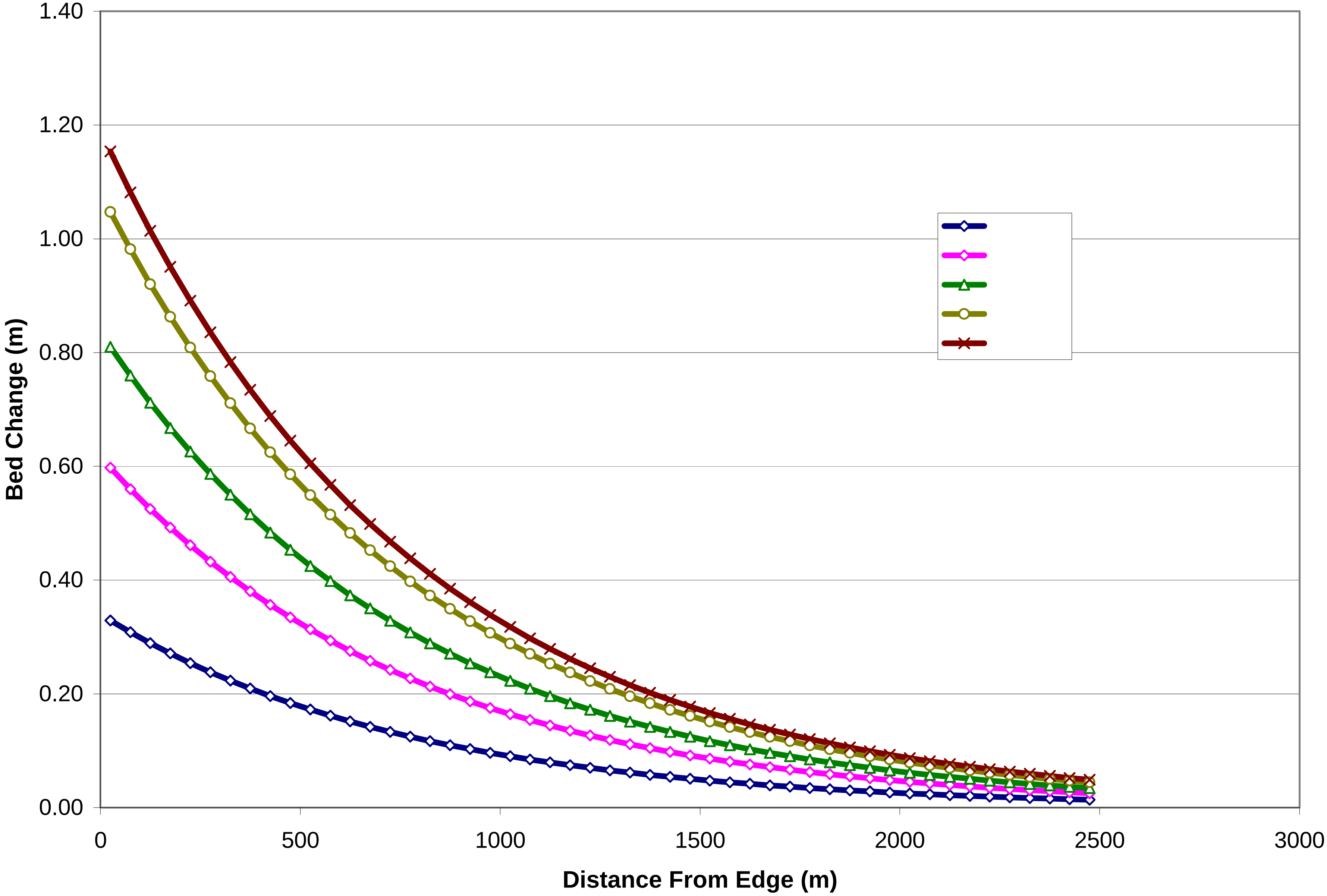


FIGURE 3.32.a. Sandy Point (with 55 ft total water depth in pit) Predicted pit margin erosion with distance from the edge of the pit for the NS flow condition using the 1D analytical approach.

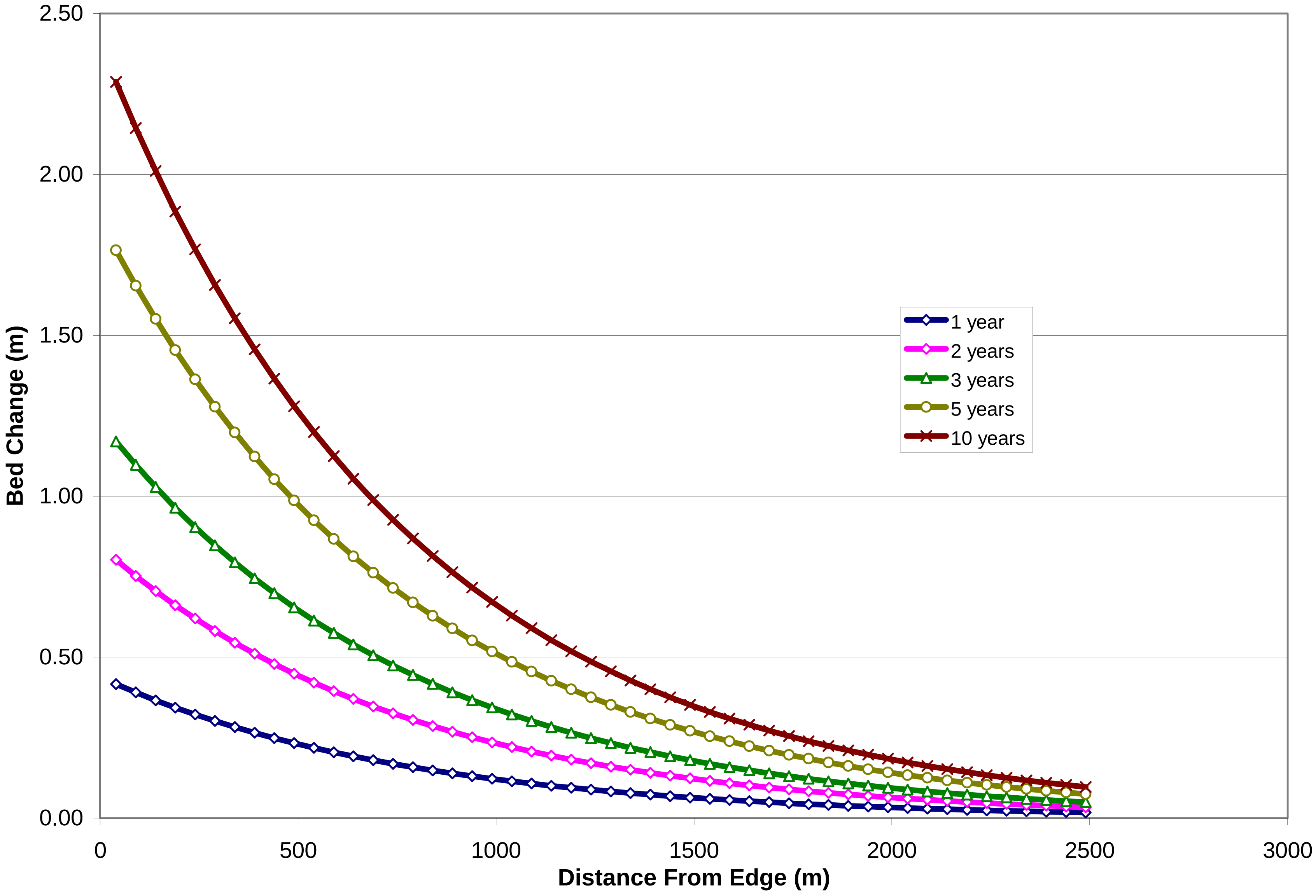


Figure 3.32.b.Sandy Point (with 75 ft total water depth in pit) - Predicted pit margin erosion with distance from the edge of the pit for the NS flow condition using the 1D analytical approach.

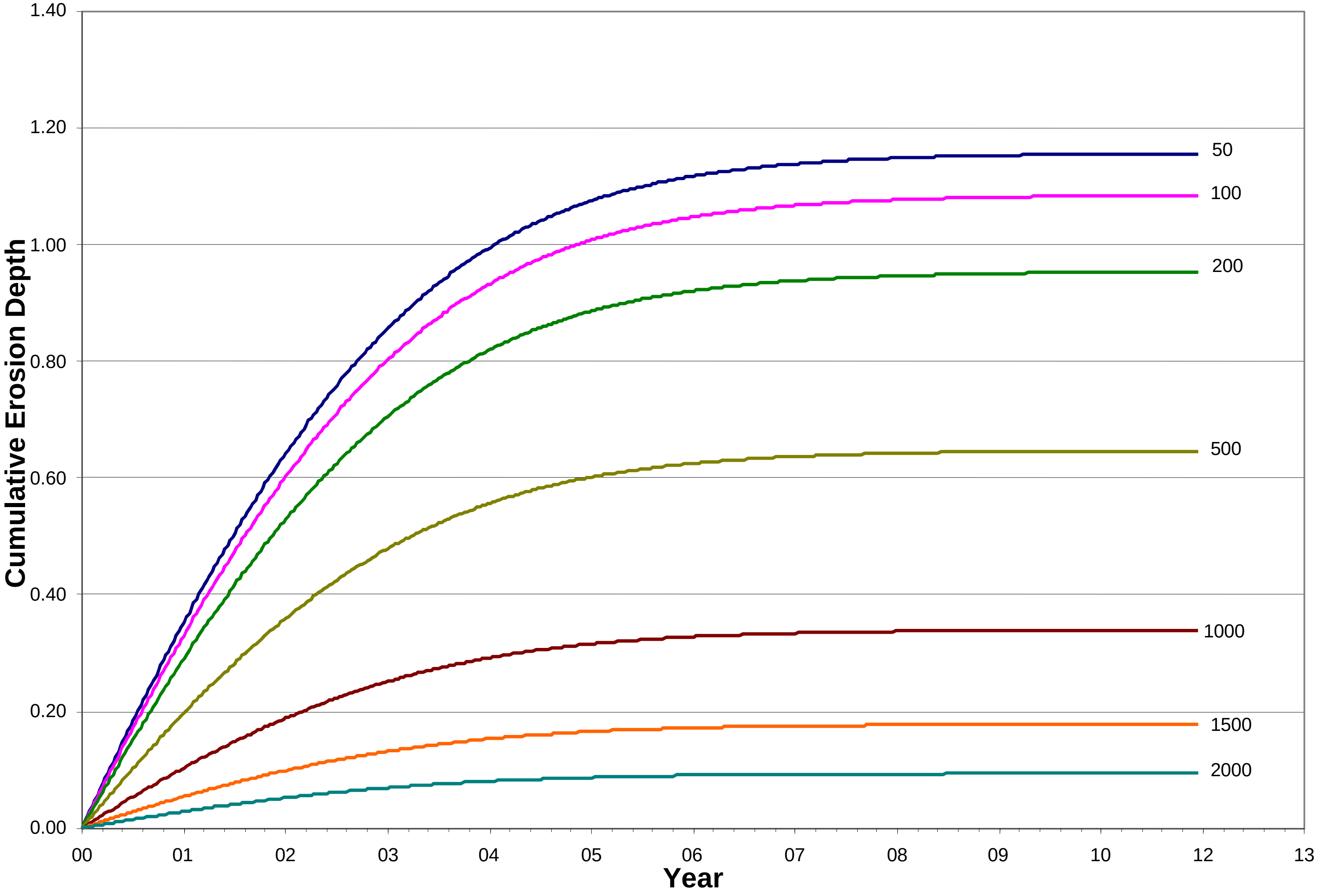


FIGURE 3.33.a. Sandy Point (with 55 ft total water depth in pit)
Predicted pit margin erosion with time at several distances from the edge of the pit for the NS flow condition using the 1D analytical approach.

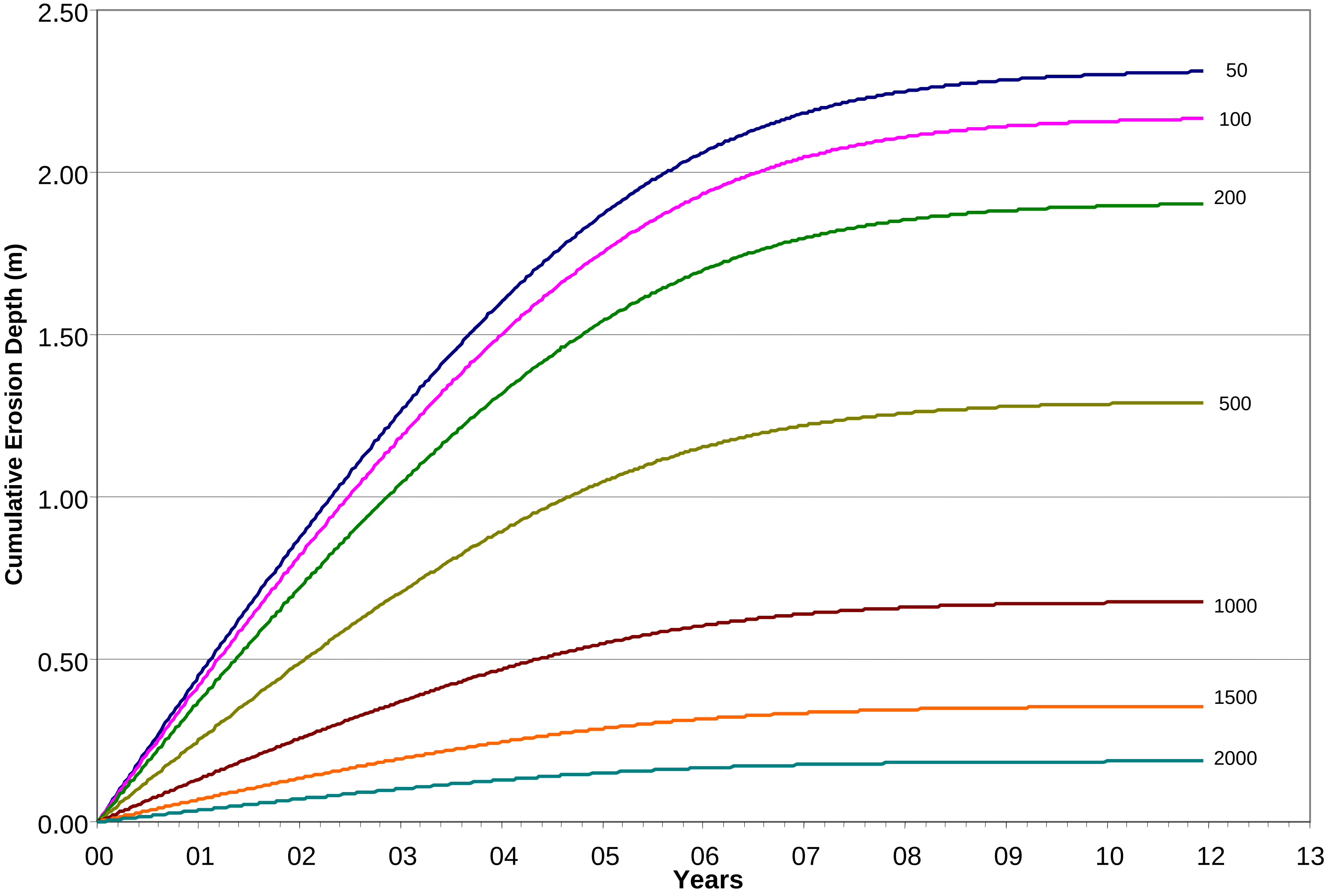


FIGURE 3.33.b.Sandy Point (with 75 ft total water depth in pit) – Predicted pit margin erosion with time at several distances from the edge of the pit for the NS flow condition using the 1D analytical approach.

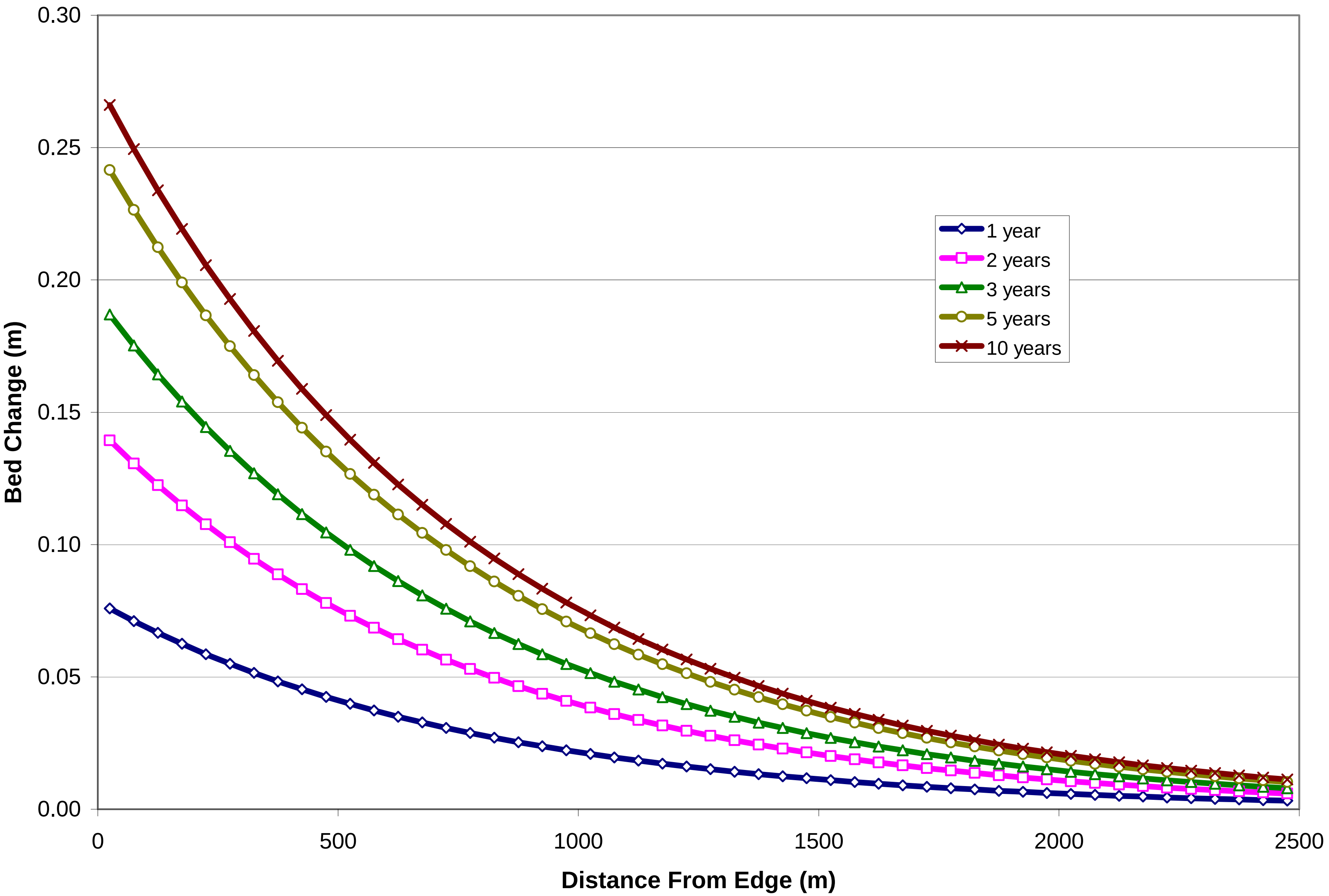


FIGURE 3.34.a.Sandy Point (with 55 ft total water depth in pit) - Predicted pit margin erosion with distance from the edge of the pit for the EW flow condition using the 1D analytical approach.

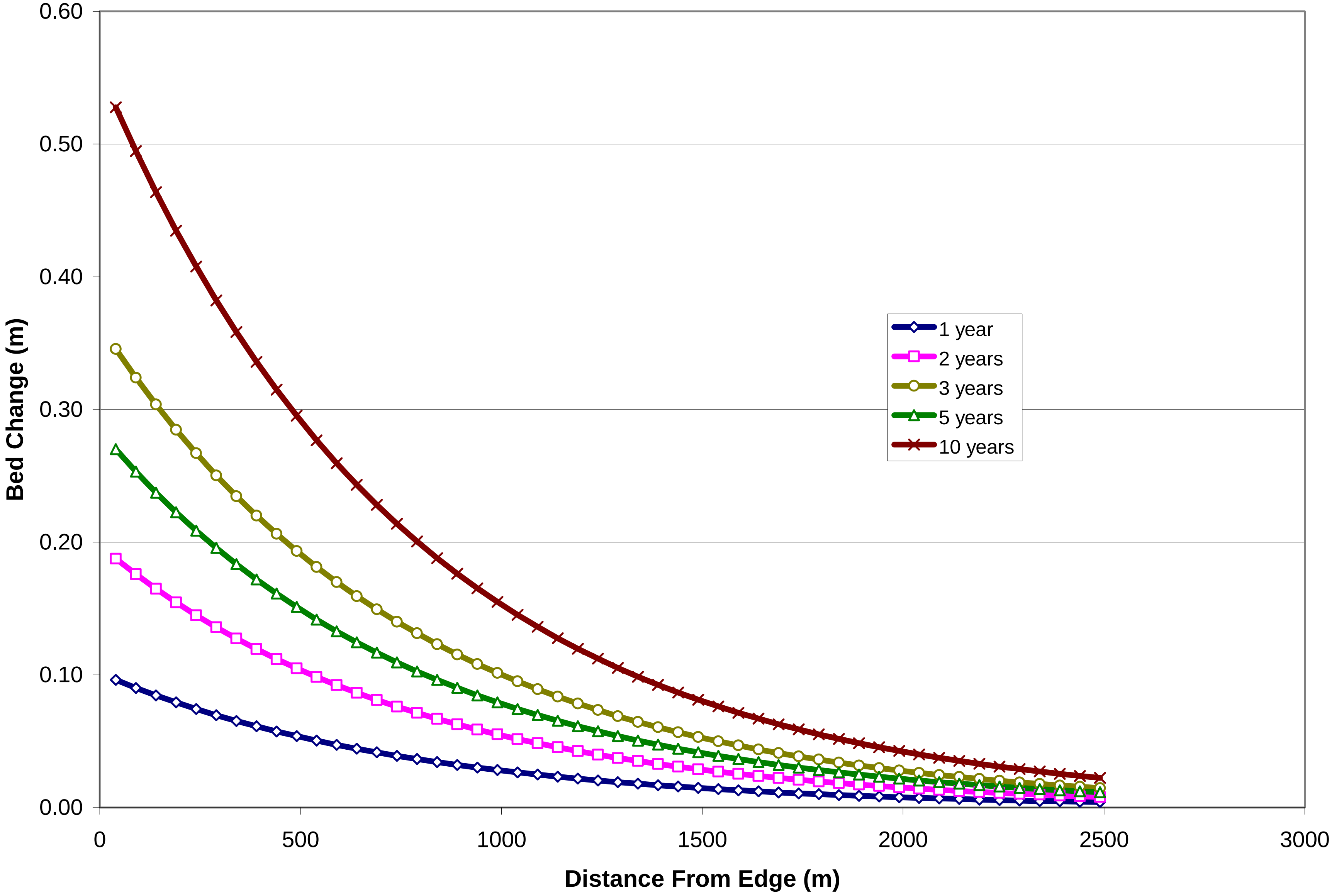


FIGURE 3.34.b.Sandy Point (with 75 ft total water depth in pit) - Predicted pit margin erosion with distance from the edge of the pit for the EW flow condition using the 1D analytical approach.

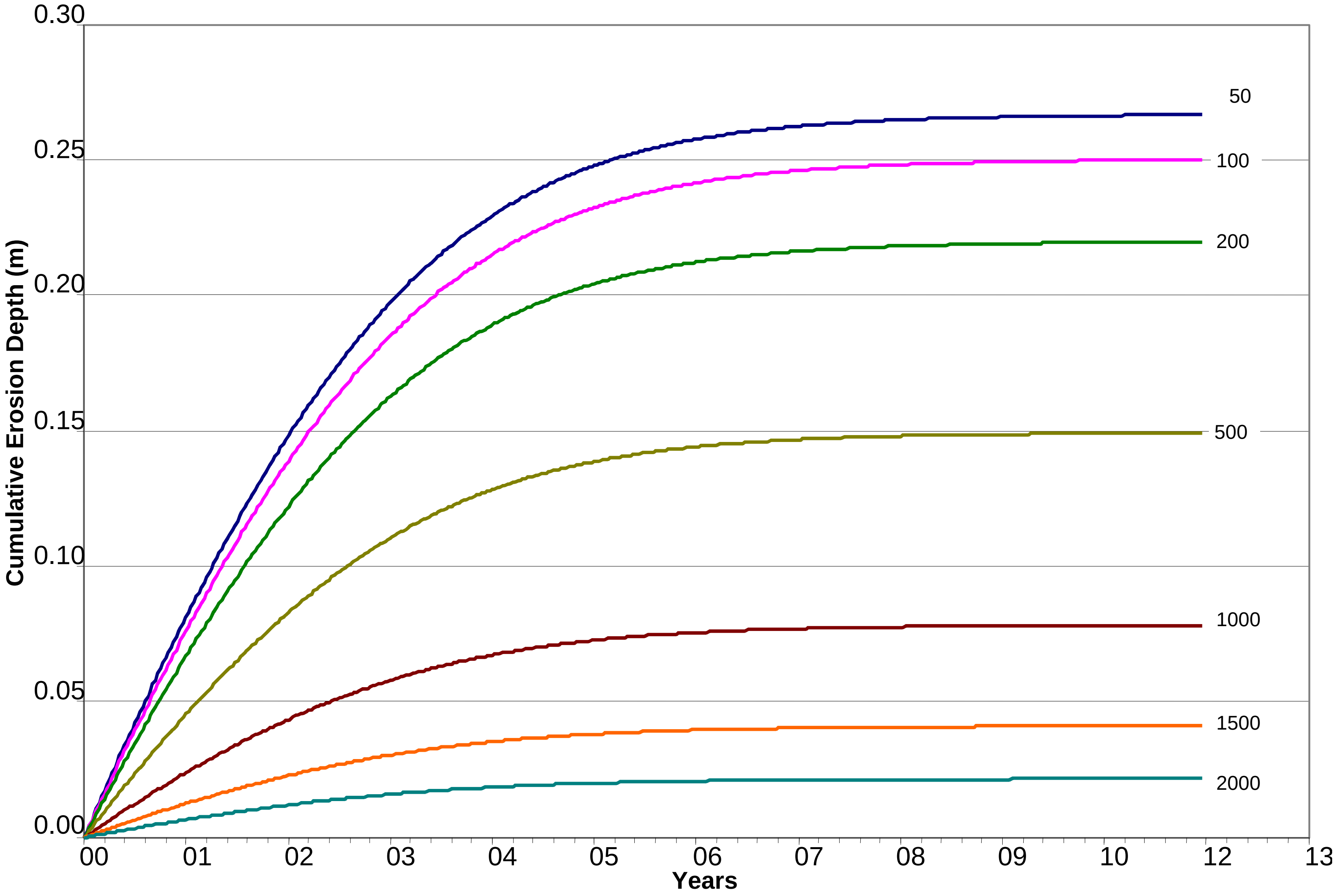


FIGURE 3.35.a.Sandy Point (with 55 ft total water depth in pit) – Predicted pit margin erosion with time at several distances from the edge of the pit for the EW flow condition using the 1D analytical approach.

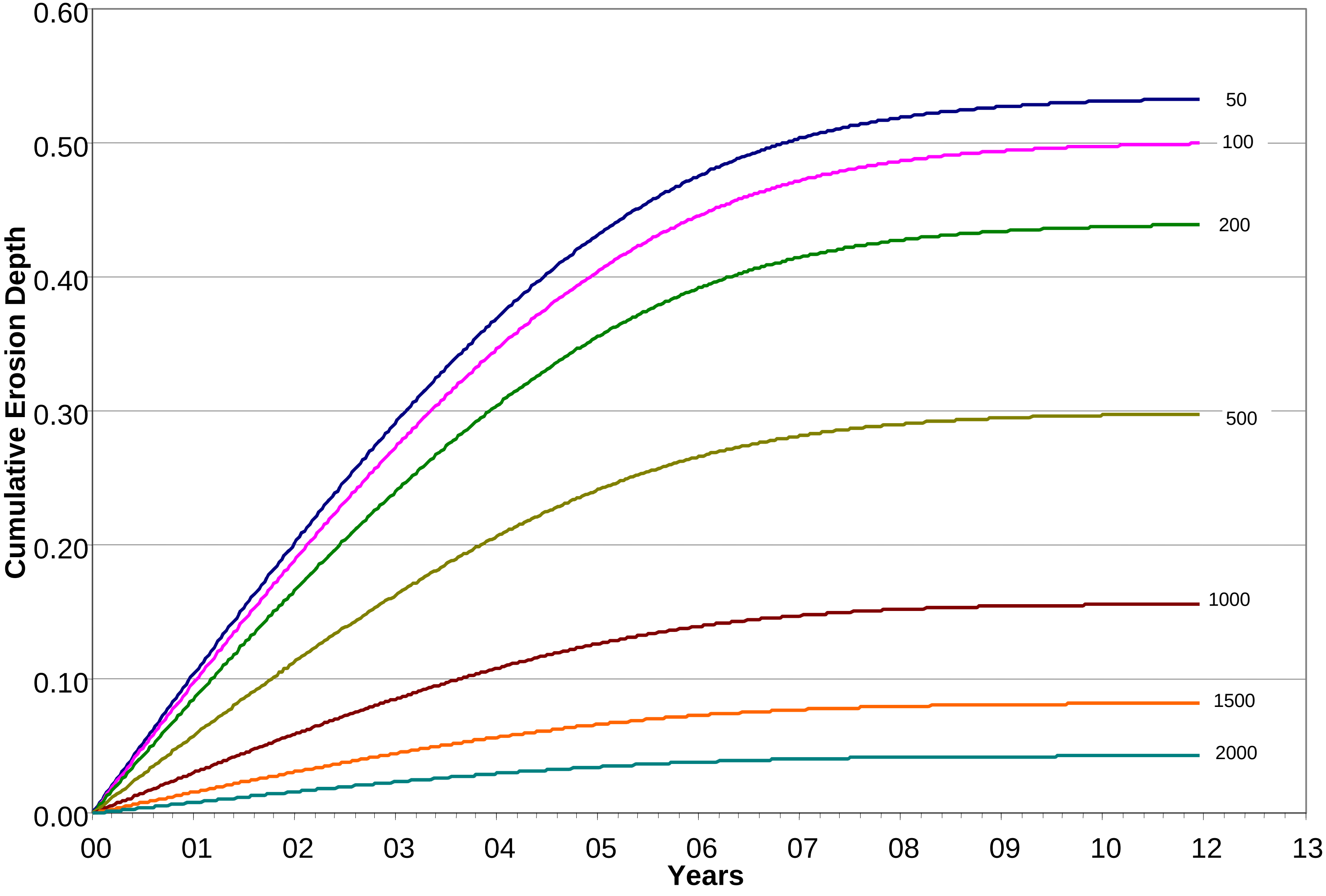


FIGURE 3.35.b.Sandy Point – Sandy Point (with 75 ft total water depth in pit) – Predicted pit margin erosion with time at several distances from the edge of the pit for the EW flow condition using the 1D analytical approach.

Again, these predictions were carried out under the assumptions that the flow pattern is in an east-west direction all the time or in a north-south direction all of the time. In reality the flow would only occur in either of these direction for some fraction of time during the year and the predicted erosion would be reduced. There is insufficient site information to determine the fraction of time flows in a north-south or east-west direction, or whether there is a southerly bias to the north-south flow. The conclusions were also found to be sensitive to suspended sediment concentration, another unknown at the site. The numerical model results showed that a reduction in contribution from external sources such as the Mississippi River discharge plume would increase erosion. The assumed background base concentration may be high as it predicts net deposition at the site at levels which seem unlikely.

Despite the lack of information on flow conditions at the proposed Sandy Point Dredge Pits some conclusions on estimates of erosion can be made that neither EW noR NS flow will occur all the time and assuming a background concentration in the range of 70 to 100 mg/l. For a 55 ft deep pit (the current design depth) it is likely that there would be less than 0.9 m of vertical erosion at distances greater than 100 to 150 m from the pit edge. For a 75 ft deep pit (the suggested ultimate pit depth) less than 0.9 m of vertical erosion would occur at distances greater than 200 to 300 m from the edge of the pit. Therefore, a 150 m buffer may be appropriate for the 55 ft deep pit and a 300 m buffer for the 75 ft deep pit (providing temporary erosion over pipelines of 0.9 m (3 ft) or less is acceptable). These estimates compare to the approximate results from the 1D analytical analysis of 100 and 200 m buffers for the 55 ft and 75 ft deep pits, respectively. It must be emphasized that these estimates are approximate. To increase the confidence level in these recommended buffers, site-specific current measurements and suspended sediment concentrations are required for a period of at least one year.

3.2.3 Summary of the Proposed Sandy Point Borrow Pit Investigations

The analysis of the proposed Sandy Point borrow area resulted in several key findings related to the evolution of muddy-capped pits and the required buffer to protect pipelines from being exposed during the temporary pit margin erosion around these borrow pits. These are summarized below:

- Pit margin erosion is very sensitive to the flow direction when the pit has different width and length dimensions. The reason for this is that erosion is predicted to extend over longer distances as the pit width or length increases, provided there is flow in that direction.

- Pit margin erosion increases with pit depth below the adjacent sea floor. The reason for this is that, in the absence of an external source of sedimentation (see next point), total pit margin erosion (in quantity) matches the pit volume.

- An external source of suspended sediment concentration such as plumes from the Mississippi River (i.e. not from local re-suspension by waves and currents) reduces the pit margin erosion by contributing to pit infilling (meaning the pit margin erosion quantity can be less than the pit volume).

- There is insufficient information on currents and suspended sediment concentration (on an annual basis) to make definitive estimates of buffer requirements for the Sandy Point borrow site. Nevertheless, approximate buffers of 100 to 150 m for the 55 ft pit (proposed design) and 200 to 300 m for the 75 ft pit (ultimate pit depth) were determined with the available information. These buffers assume that 0.9 m or less of temporary erosion over pipelines is acceptable.

3.3 Block 88 Dredge Pit for Whiskey Island West Flank Restoration (Proposed)

Block 88 on Ship Shoal has been identified as a borrow area for several nearby barrier island restoration projects. The Block 88 seabed is sandy with a median grain size of 0.2 mm. Sand from a proposed pit in Block 88 will be used for the restoration of the west flank of Whiskey Island. The regional location of the pit and a close up view of the pit, the surrounding bathymetry, and pipelines are shown in Figures 3.40 and 3.41 respectively. The proposed borrow area has a width that ranges from 365 m (at either end) to 640 m (in the middle section), a length of 1,635 m and a depth of 5.2 m (15 ft) for a total water depth of 10 m (33 ft) in the pit.

As explained in Section 2.8 the morphologic evolution of sandy pits is a significantly different process from the evolution of muddy-capped pits. For sandy pits bed load is a dominant form of sediment transport at least of the same order if not greater than suspended load. The 1D analytical approach developed in Section 3.1, which addressed suspended transport of fine sediments is not applicable here. The 1D analytical approach developed by Ribberink et. al. (2005) for sandy pit evolution is instead applied. The equations were derived by describing a pit as a migrating wave, linking the damping factor and migration speed of the bed wave with bed load and suspended load (see Section 2.3.4 for more details). This approach was used to estimate the migration and infilling rate for the proposed Block 88 pit. The Bailard (1981) sediment transport formulation is used by Ribberink et. al. (2005) and therefore, wave and current parameters must be defined.

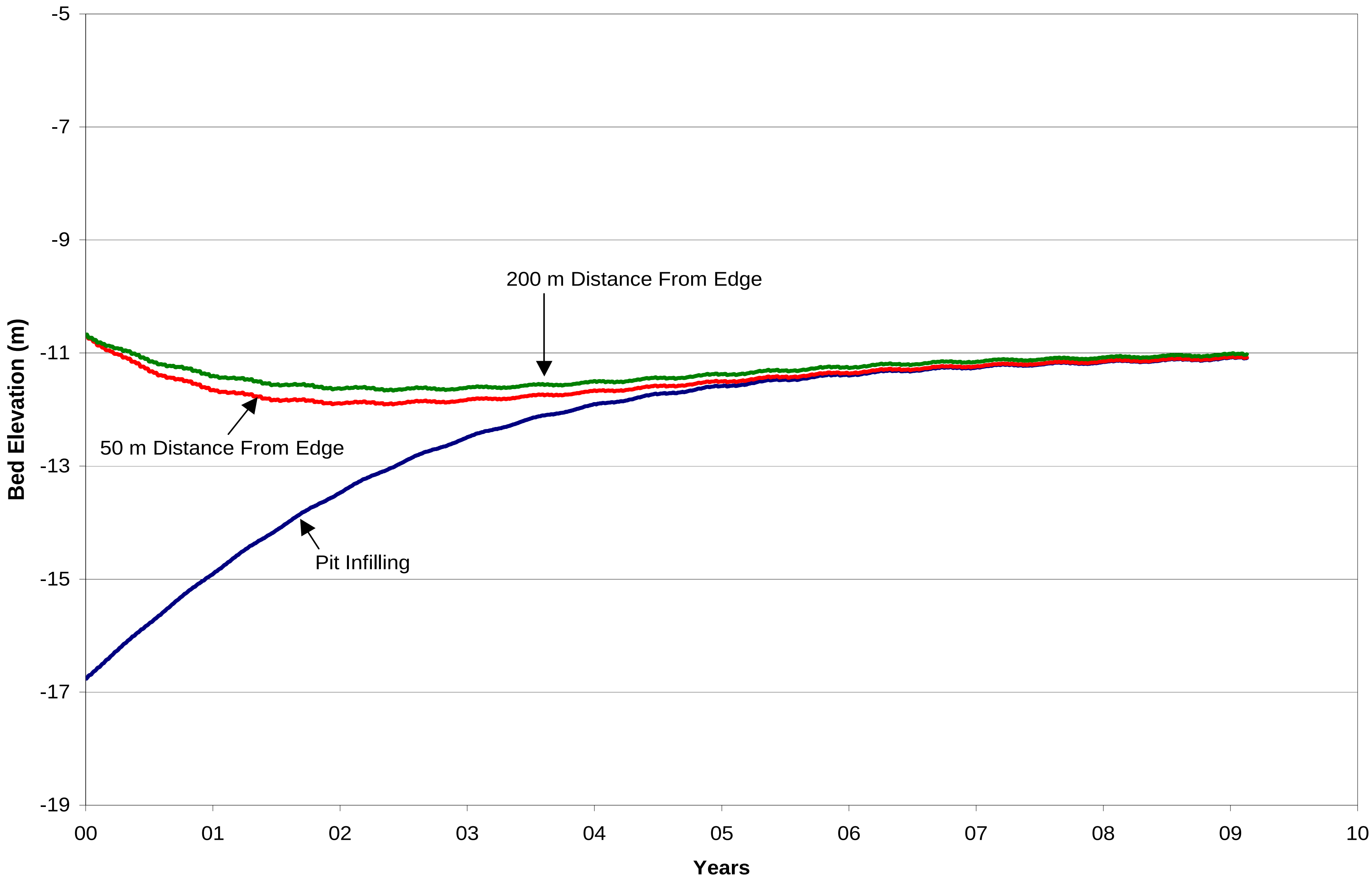


FIGURE 3.36.a. Sandy Point Dredge Pit (55 ft pt) – Change in total depth in the pit and for two locations on the pit margin for the NS flow direction (with 100 mg/l background suspended sediment concentration).

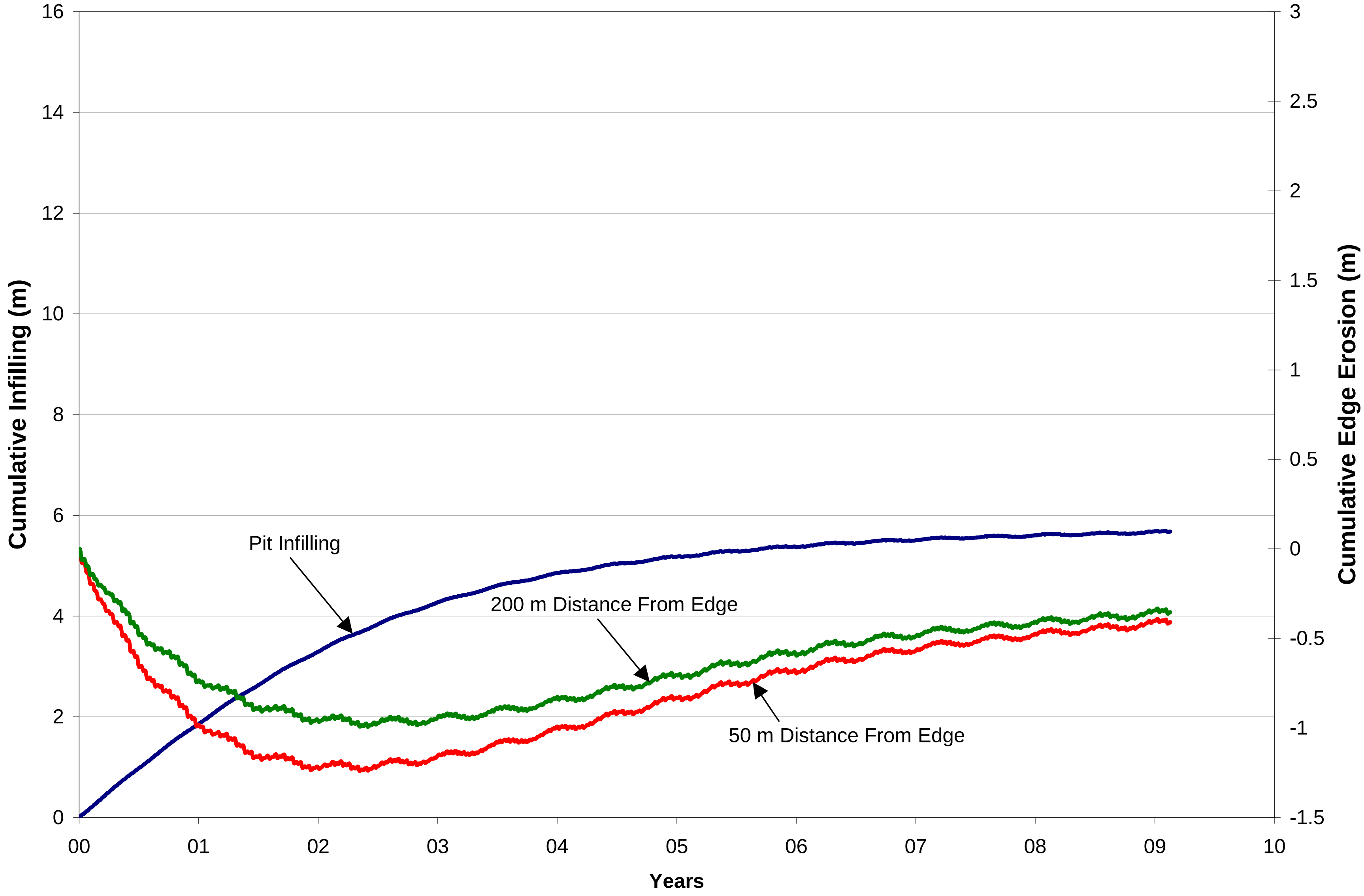


FIGURE 3.36.b.Sandy Point Dredge Pit (55 ft pit) – Change in bed elevation in the pit and at two locations in the pit margin for the NS flow direction (with 100 mg/l background suspended sediment concentration).

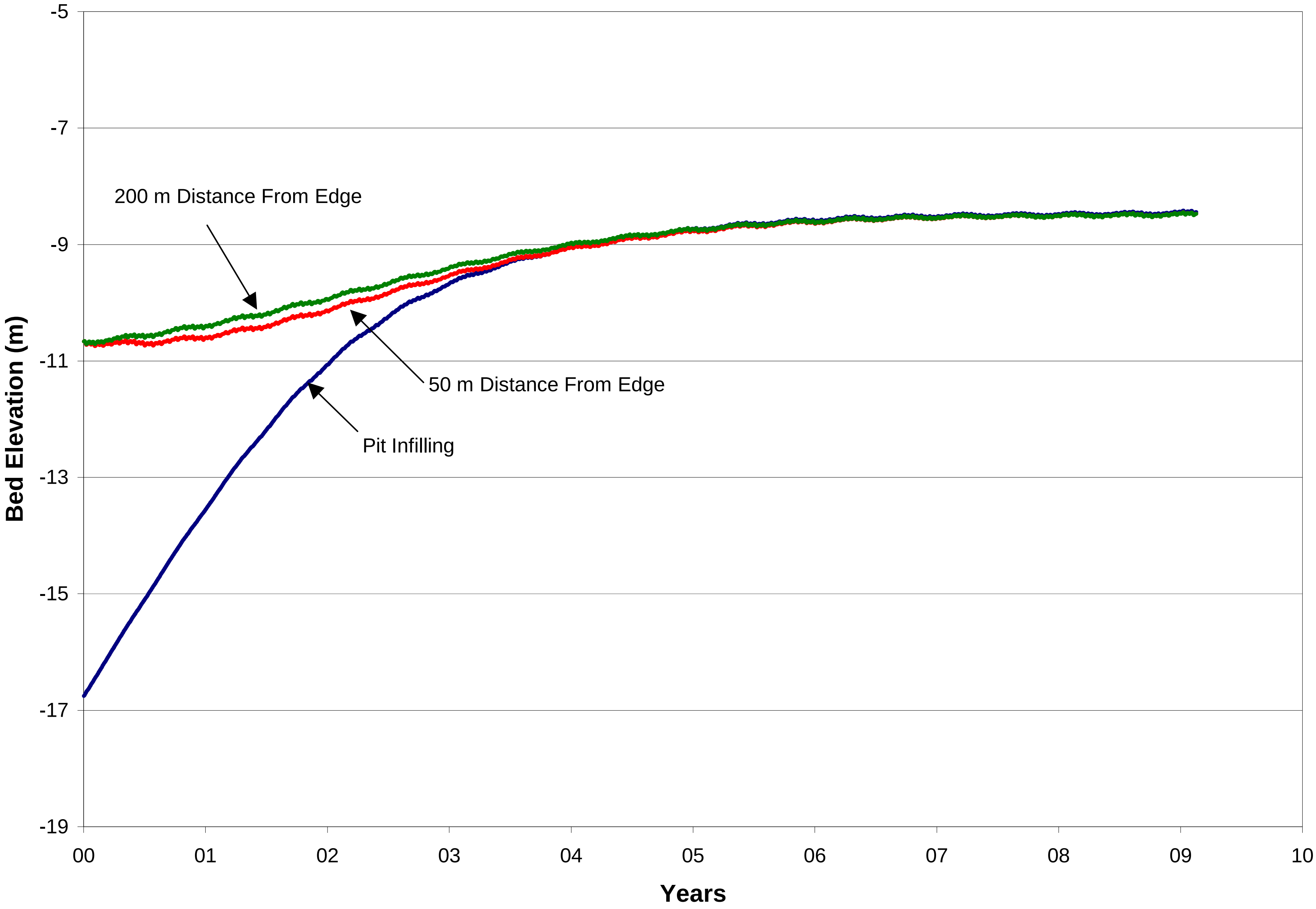


FIGURE 3.37.a. Sandy Point Dredge Pit (55 ft pt) – Change in total depth in the pit and for two locations on the pit margin for the EW flow direction (with 100 mg/l background suspended sediment concentration).

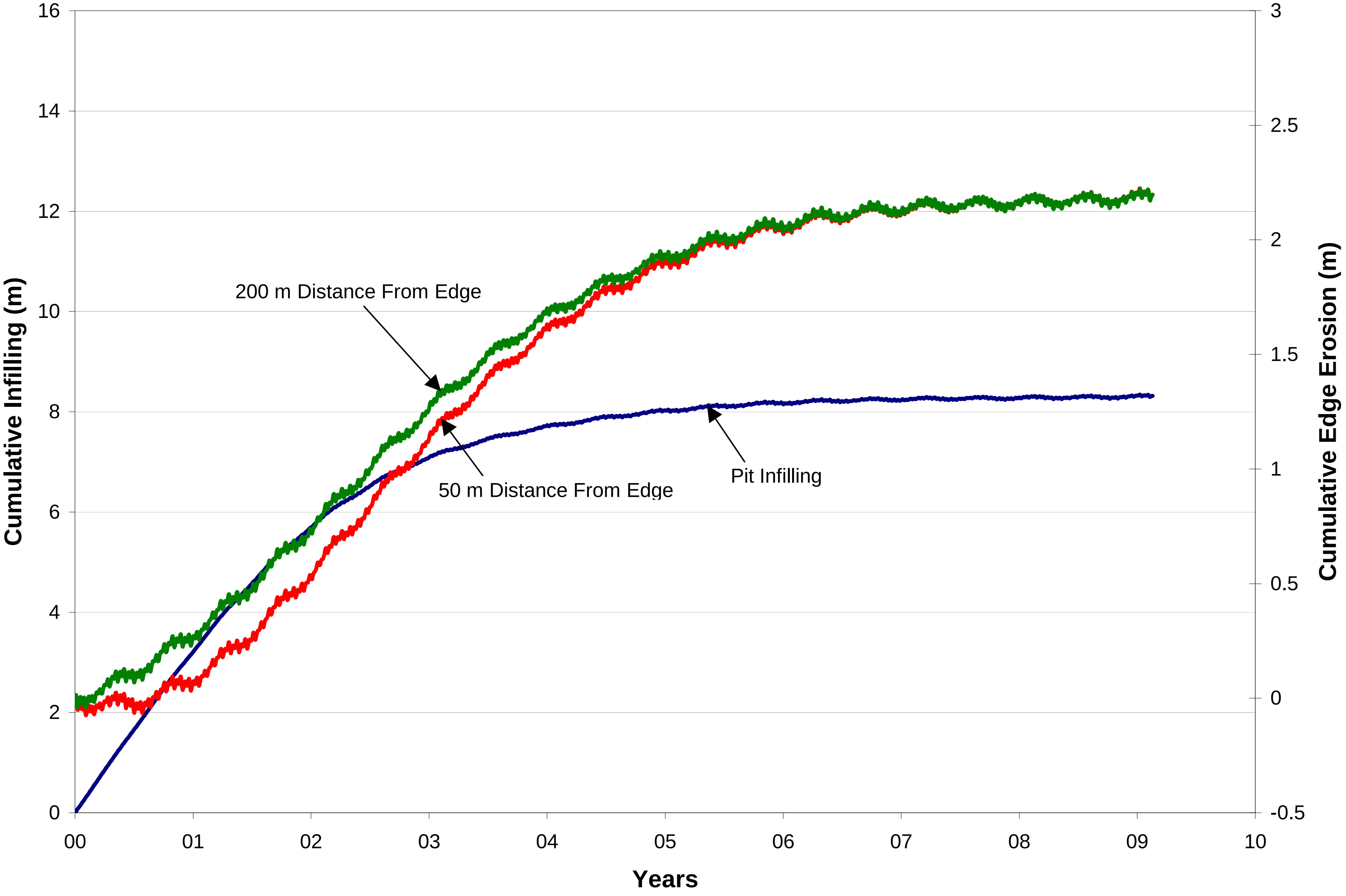


FIGURE 3.37.b.Sandy Point Dredge Pit (55 ft pit) – Change in bed elevation in the pit and at two locations in the pit margin for the EW flow direction (with 100 mg/l background suspended sediment concentration).

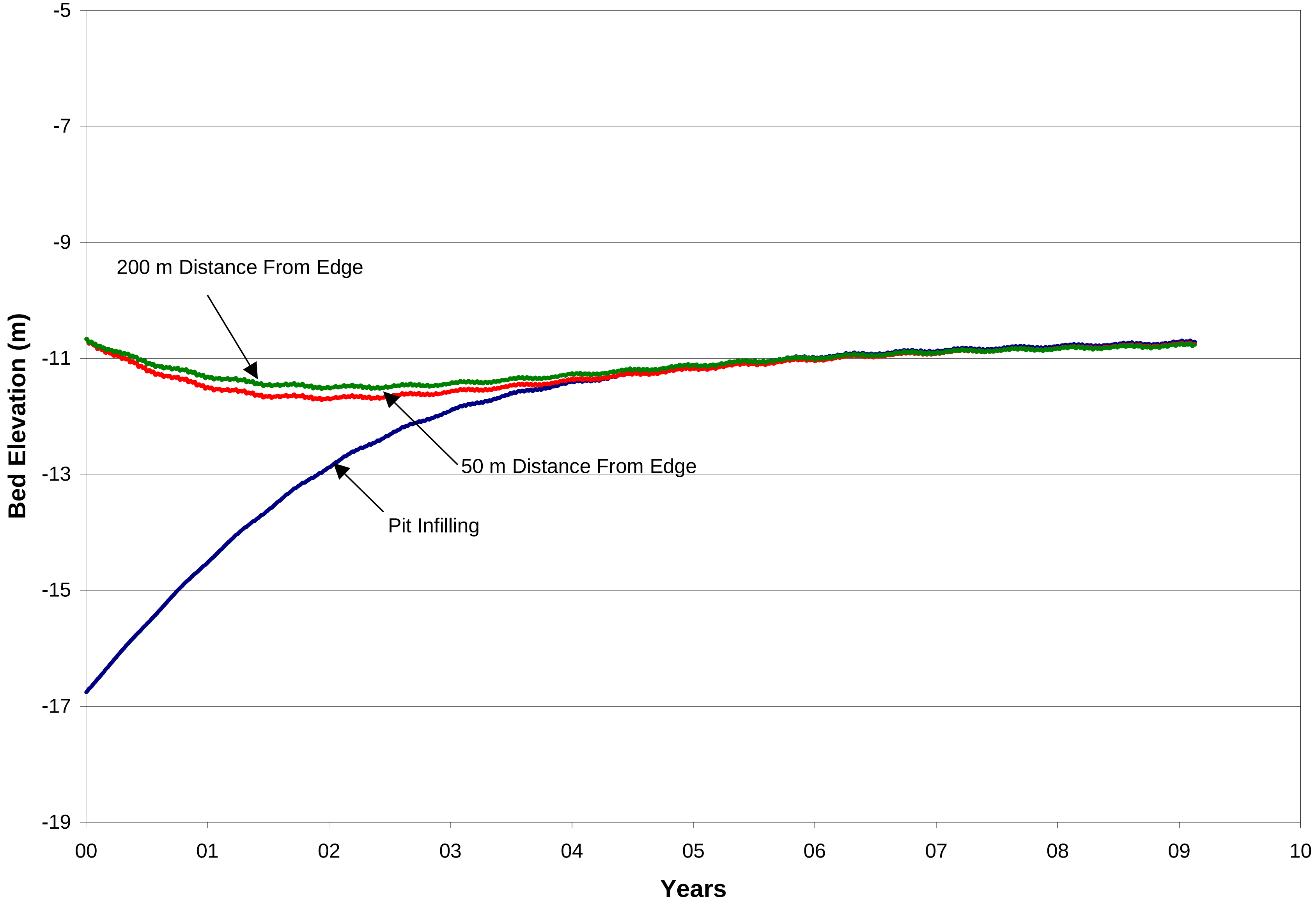


FIGURE 3.37.c. Sandy Point Dredge Pit (55 ft pt) – Change in total depth in the pit and for two locations on the pit margin for the EW flow direction (with 70 mg/l background suspended sediment concentration).

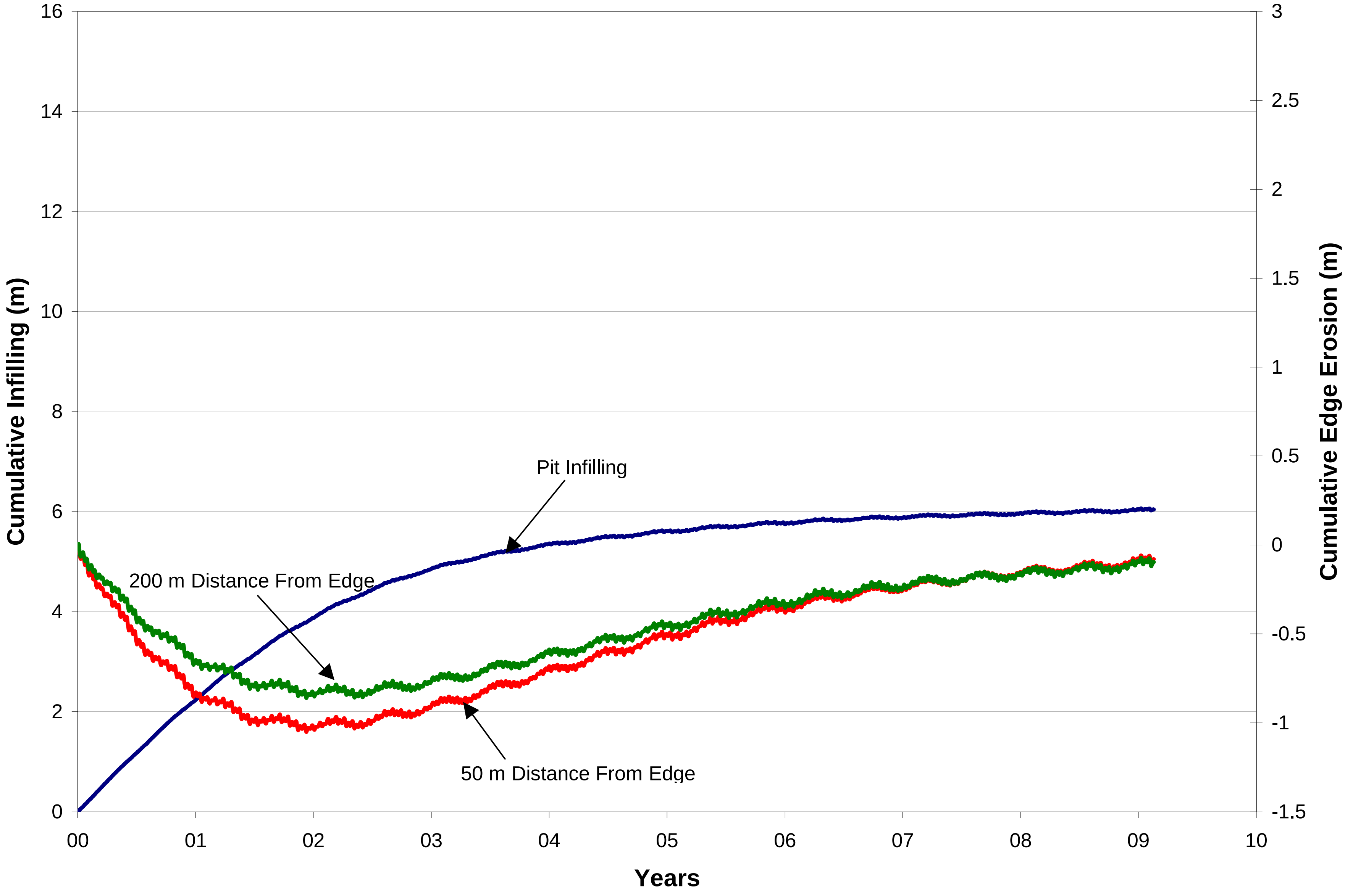


FIGURE 3.37.d.Sandy Point Dredge Pit (55 ft pit) – Change in bed elevation in the pit and at two locations in the pit margin for the EW flow direction (with 70 mg/l background suspended sediment concentration).

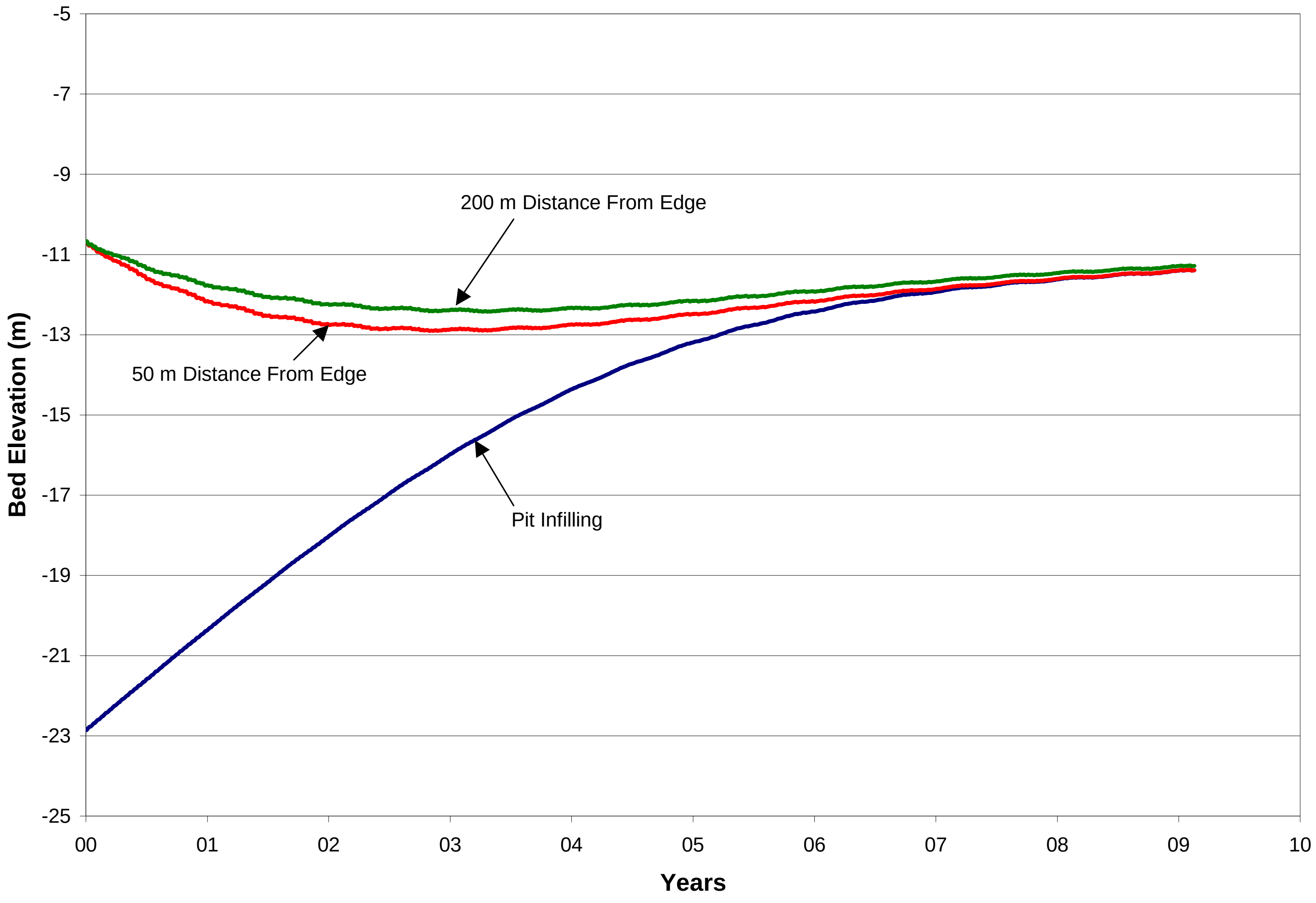


FIGURE 3.38.a. Sandy Point Dredge Pit (75 ft pt) – Change in total depth in the pit and for two locations on the pit margin for the NS flow direction (with 100 mg/l background suspended sediment concentration).

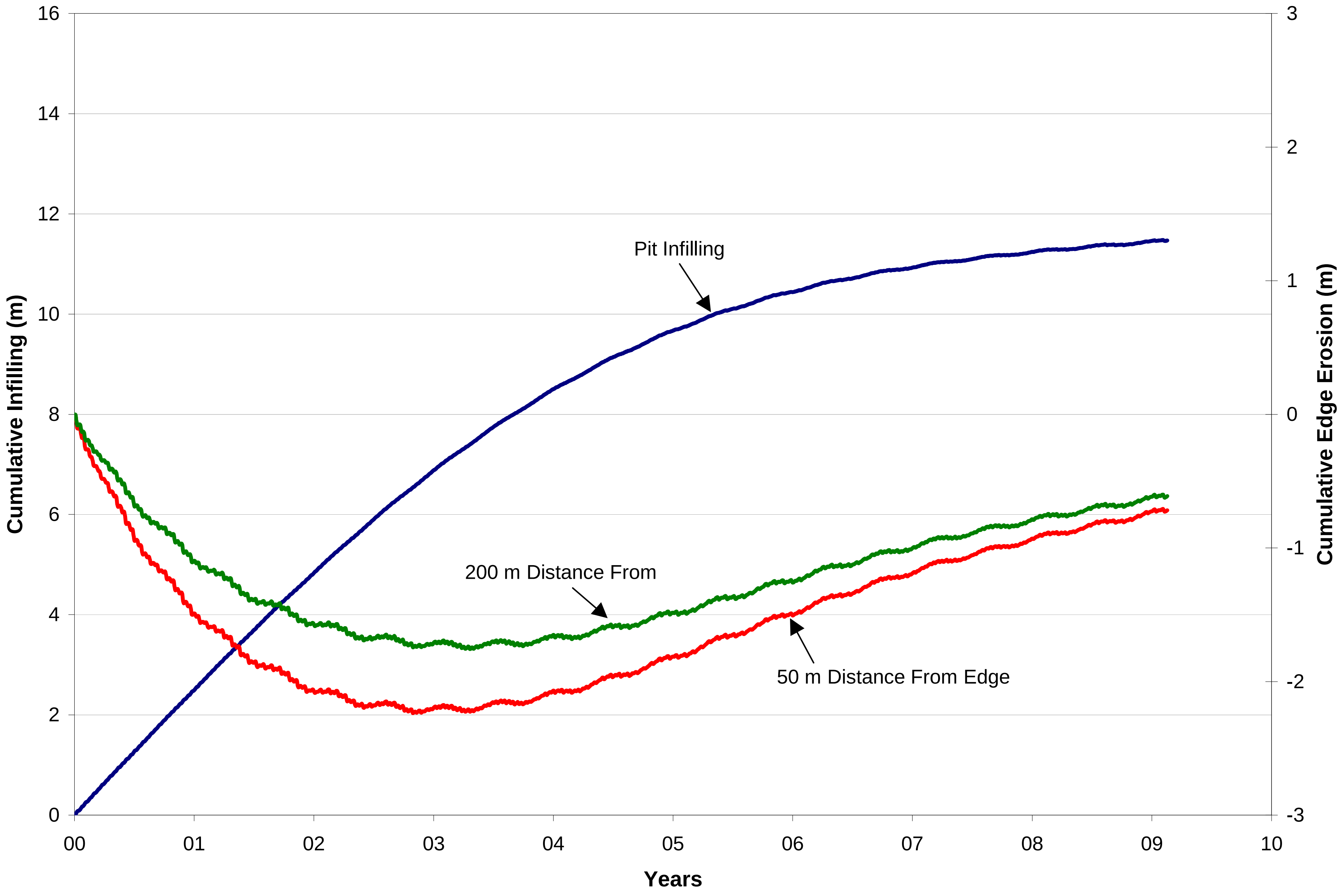


FIGURE 3.38.b.Sandy Point Dredge Pit (75 ft pit) – Change in bed elevation in the pit and at two locations in the pit margin for the NS flow direction (with 100 mg/l background suspended sediment concentration).

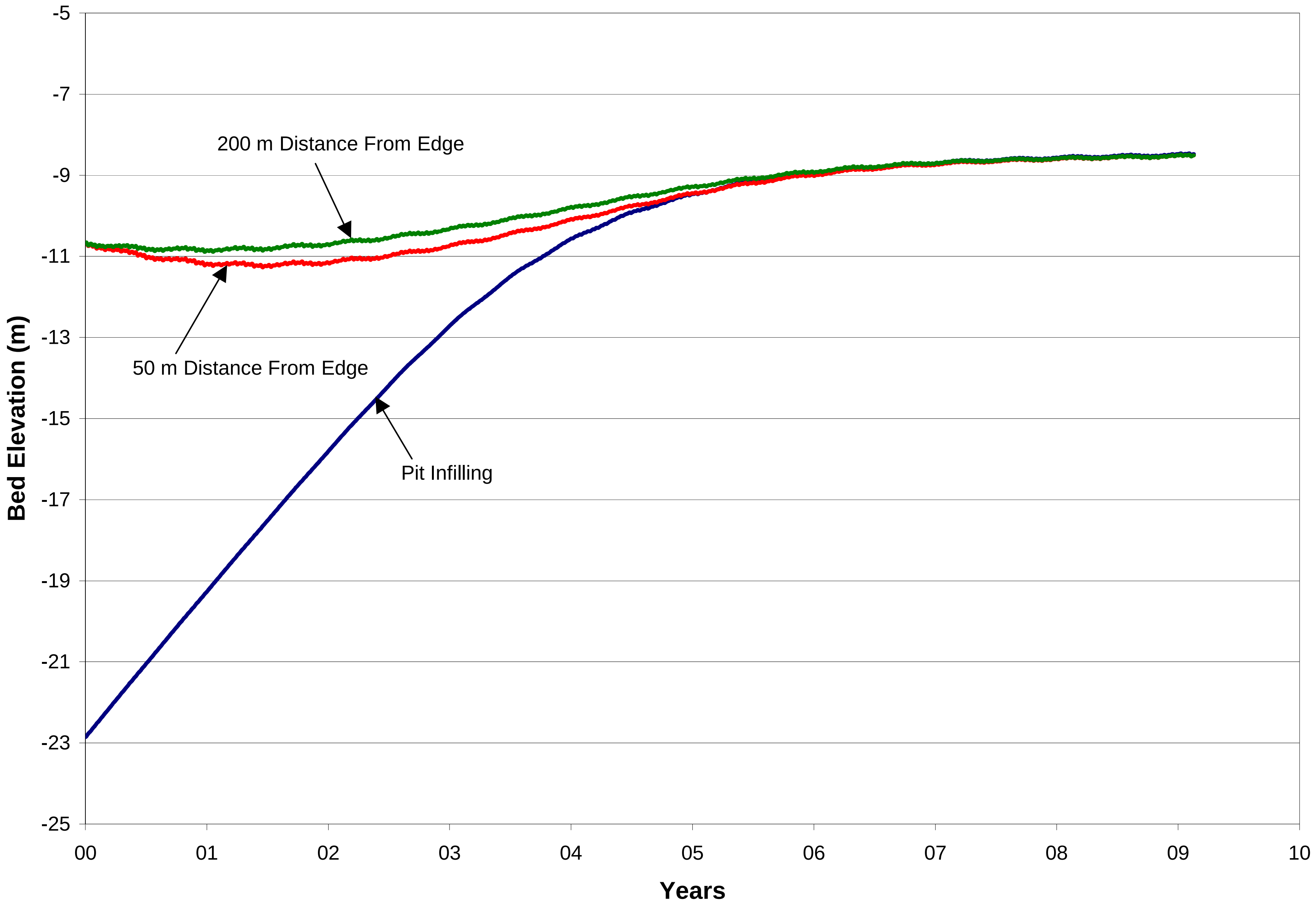


FIGURE 3.39.a. Sandy Point Dredge Pit (75 ft pt) – Change in total depth in the pit and for two locations on the pit margin for the EW flow direction (with 100 mg/l background suspended sediment concentration).

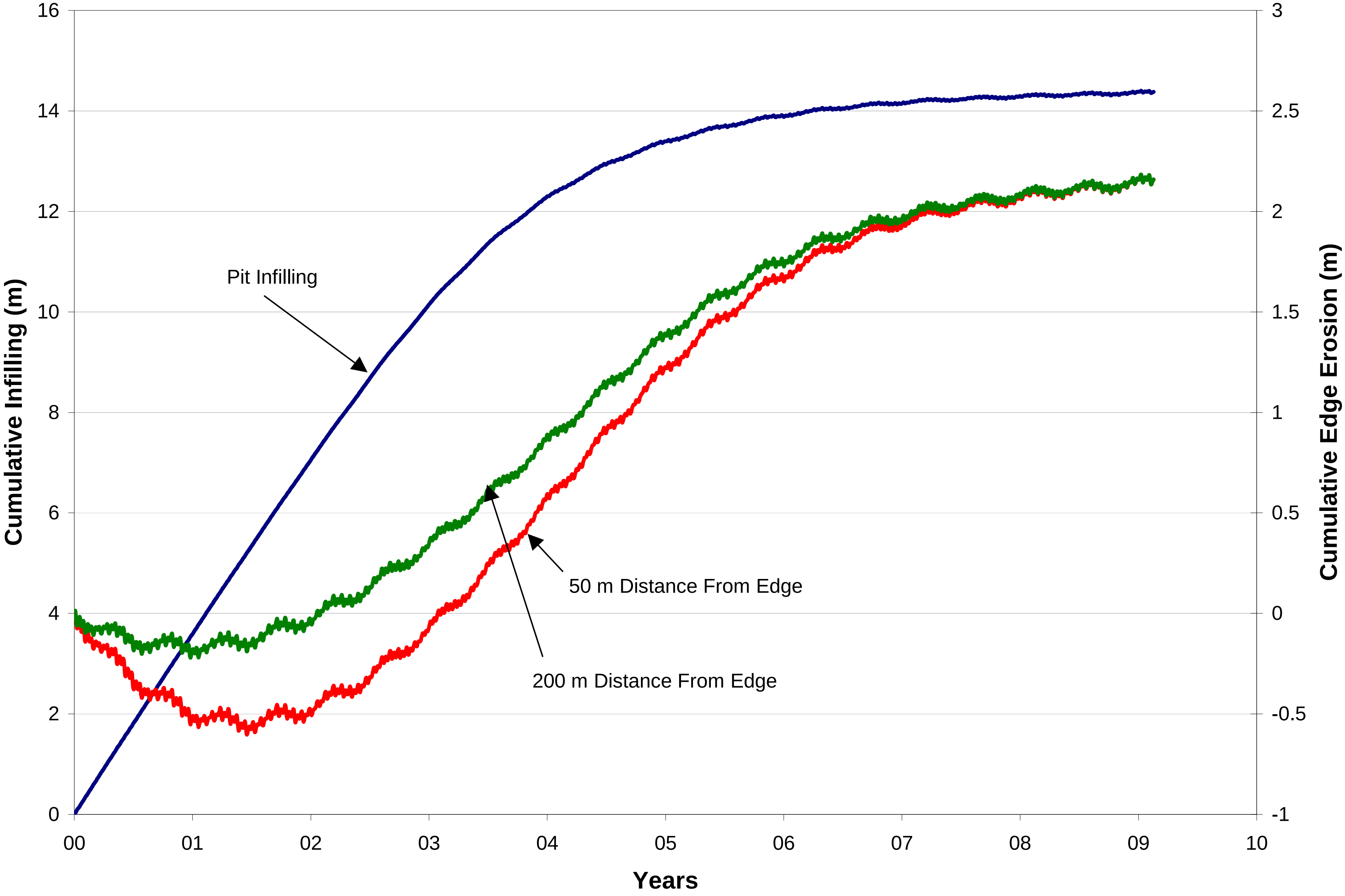


FIGURE 3.39.b.Sandy Point Dredge Pit (75 ft pit) – Change in bed elevation in the pit and at two locations in the pit margin for the EW flow direction (with 100 mg/l background suspended sediment concentration).

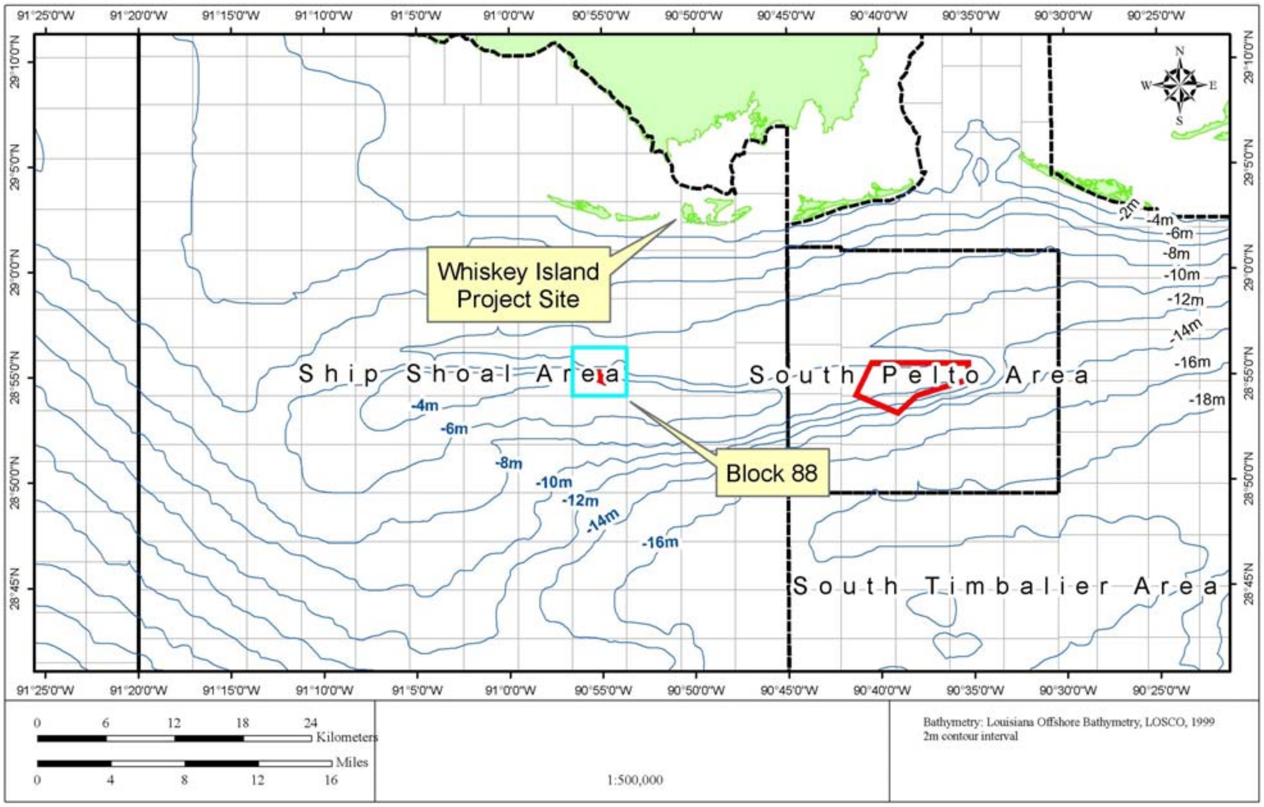


FIGURE 3.40. Regional location map for the Block 88 borrow area.

3.3.1 Tidal Currents

A depth-averaged tidal current of 0.3 m/s was used for the calculations based on a review of the Ship Shoal measurements presented in Pepper and Stone (2000) and a consideration of the measurements at WAVCIS CSI-03.

3.3.2 Waves

Wave information from WIS Station 125 together with measurements of waves at three locations on Ship Shoal by Pepper and Stone (2000) were used to define an average wave condition. An average annual significant wave height of 1.1 m and peak wave period of 5 seconds were selected for this analysis. Sensitivity tests were completed for average wave heights in the range of 0.3 to 2 m.

3.3.3 Bed Roughness

Bed roughness is a key parameter in the calculation of bed shear stresses for currents, waves, and combined waves and currents. The parameter has a significant impact on the

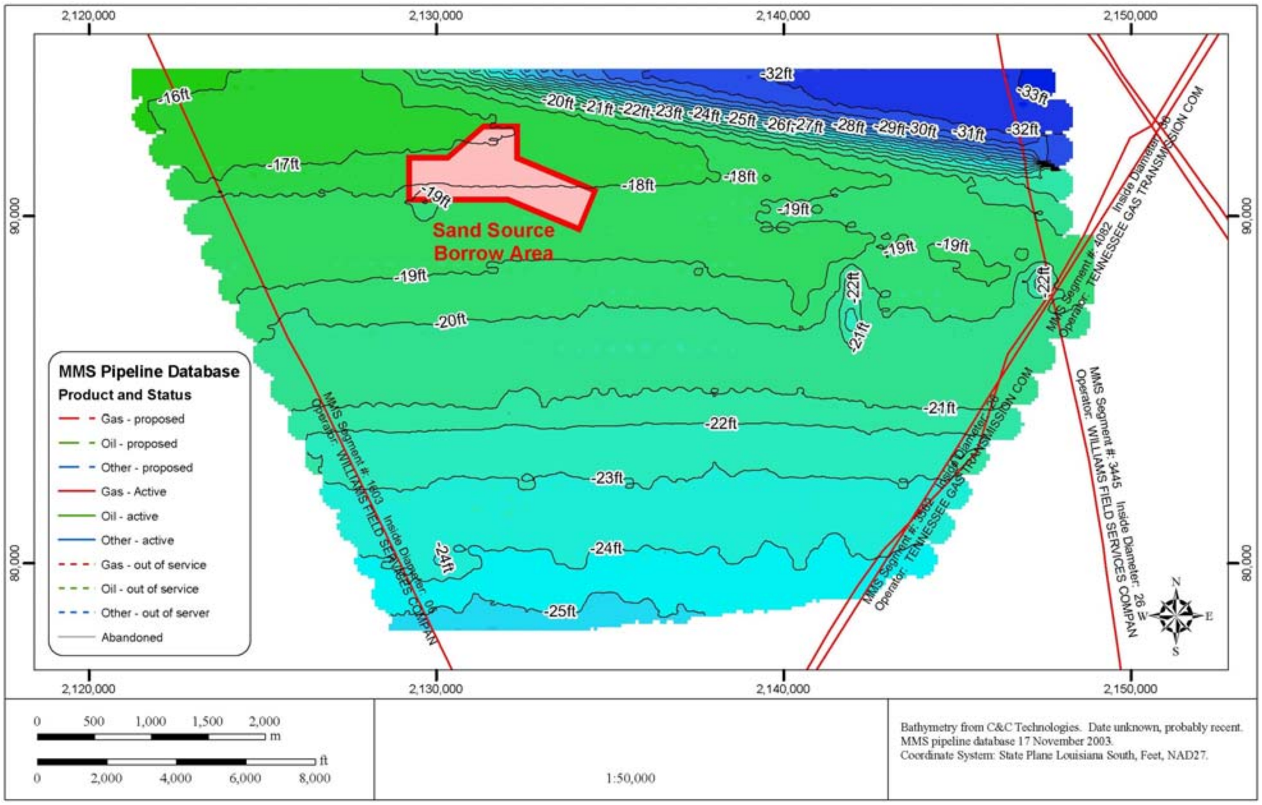


FIGURE 3.41. Map of the Block 88 borrow area for the Whiskey Island West Flank Restoration Project with oil and gas infrastructure and local bathymetry (the latter provided by LA DNR).

infilling rate and migration speed due to its strong influence on bed load and suspended load. The initial definition of bed roughness by Nikuradse (1933) is equal to the median grain size (d_{50}) for flat bed with uniform sediment and equal to d_{65}, d_{75}, or d_{90} for flat bed with non-uniform sediment. For a bed with ripples, the roughness could be up to four times d_{90} or half of ripple height. Considering this range of possible conditions, the bed roughness at Block 88 could range from 0.2 mm to 2 mm. This range of roughness was investigated in sensitivity tests. For the base case tests, an average roughness of 1 mm was used. However, Wright et. al. (1997) estimated a bottom roughness of 0.1 to 0.15 mm in the Ship Shoal area, but this was for depths of 15 to 20 m (compared to 5 to 6 m at the Block 88 site. Therefore, a roughness of approximately 1 mm should be appropriate for the shallower Block 88 site.

3.3.4 Other Parameters

A number of other parameters were defined in the equations of Ribberink et. al. (2005). Table 3.3 lists all parameters and values assigned for this analysis. The Ribberink approach is valid for estimating migration of pits due to a net or residual current direction. It is not applicable in its current form for estimating cross-shore migration rates and particularly onshore migration which may occur at this site due to wave asymmetry (this is addressed later in Section 3.3.6). Therefore, in Table 3.3 both the depth and time averaged flow velocity u_0 and the residual velocity (towards the west) are presented. The residual velocity averaged over 10 years was determined by using the local tidal constituents in a hydrodynamic model. It must be noted that this does not include the possible contribution of wind-driven currents to the net residual flow towards the west (due to the dominant SE winds). Therefore, sensitivity tests have been completed with residual currents of 0.15 (likely upper bound) and 0.3 m/s.

3.3.5 Estimates of Pit Migration Speed and Infilling Rates

Figures 3.42a and b show the pit migration with time for pit widths of 365 and 640 m, respectively, as predicted by the Ribberink et. al. (2005) approach with a residual current speed of 0.06 m/s and an average current speed of 0.3 m/s. Figures 3.43a and b show the pit evolution for the two pit widths and a residual current speed of 0.15 m/s and an average current speed of 0.3 m/s. The bed roughness (n) for the shear stress calculation was assumed to be 1 mm. The figures indicate that the pit will be filled in about 5 to 6 years after initial dredging if it is 640 m wide and 3 to 4 years for a 365 m wide pit, both in the longshore direction. These results do not apply to evolution of the pit in the cross-shore direction, as this is likely a result of wave asymmetry and not a residual current. Using the Van Rijn (2004) formulation, the gross transport rate at the Block 88 site on Ship Shoal was found to be approximately 150 m^3/m/year. This is relatively high and due to a moderate wave climate combined with the relatively shallow water at this site. This rate is towards the high end of the range of SANDPIT study sites and is almost two orders of magnitude higher than the gross transport rates at Delray Beach where the pits in depths of 10 to 20 m of water have changed very little with time (refer to Section 2.4.3). The high gross transport rate at this site explains the relatively fast morphologic (and pit infilling) time scale.

The pit migration speed was determined using the Ribberink et. al. (2005) approach and the parameters in Table 3.3 to be 1.4 m/year for a 640 m wide pit and 1 m/year for a 365 m wide pit, both in the longshore direction towards the west. As an example of the sensitivity to residual current velocity the migration speed increases to 4.5 to 7.2 m/year and 17 to 29 m/year for residual speeds of 0.15 m/s and 0.3 m/s, respectively for the 365 and 640 m wide pits (the 7.2 and 29 m/year migration rates corresponding to the wider 640 m pit). A review of Figure 3.42a and b and Figure 3.43a shows that the infilling of the pit outpaces any pit edge erosion from migration; therefore in these cases there is no erosion beyond the original edge of pit location. Only the case of the 640 m wide pit with a residual current speed of 0.15 m/s shows minor erosion on the west (right hand) edge of the pit (see Figure 3.43b). Even in this case the vertical erosion is small (less than 0.2 m) and there is no erosion beyond about 50 m from the edge of the pit on the west side.

TABLE 3.3. Parameters used for the Ribberink et. al. (2005) analysis of the Block 88 infilling and migration rates.

Depth averaged flow velocity (u_0)	**0.3 m/s**
Residual longshore flow velocity (to the west)	**0.06 m/s**
Velocity profile coefficient (α_b)	**0.1**
Velocity profile coefficient (α_s)	**0.5**
Concentration profile coefficient (L)	**0.5**
Settling velocity of sediment (ω_s)	**0.01 m/s**
Relative density of sediment (Δ, Rho_r)	**1.65**
Coefficient of the Bailard formula for bed load (ε_b)	**0.1**
Coefficient of the Bailard formula for suspended load (ε_s)	**0.02**

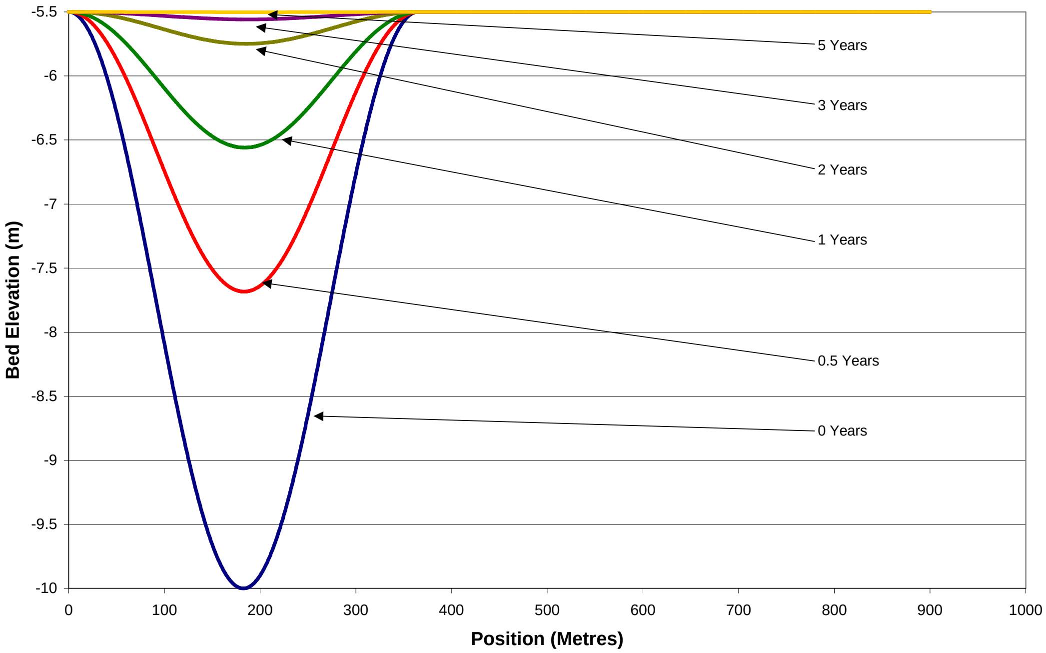


FIGURE 3.42.a. Predicted pit evolution for an initial width at 365 m and a residual westward (to the right) current speed of 0.06 m/s.

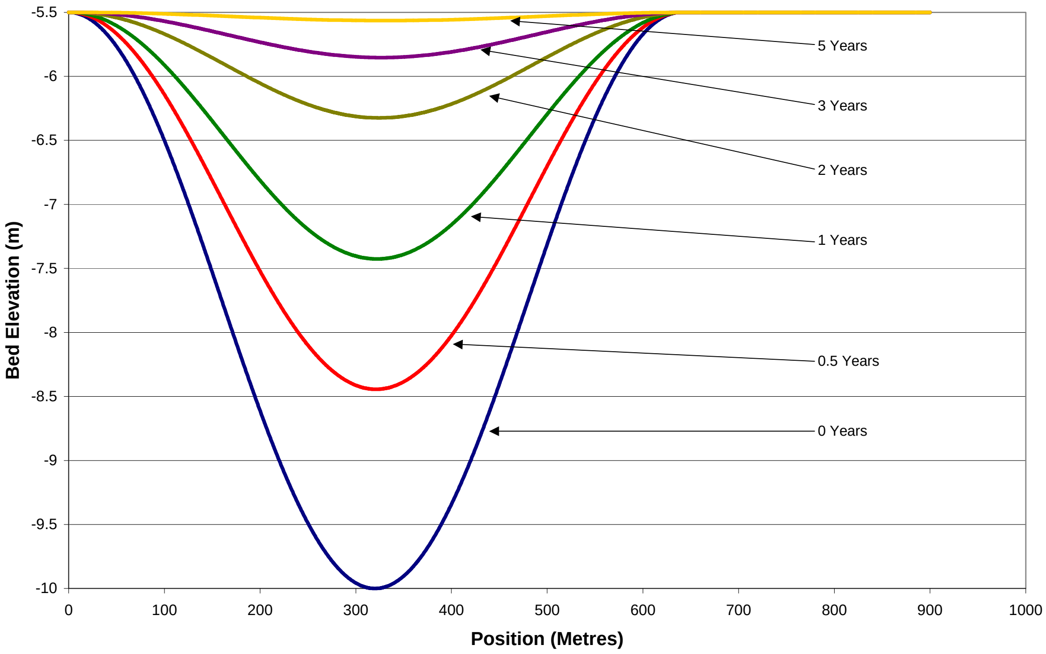


FIGURE 3.42.b. Predicted pit evolution for an initial width at 640 m and a residual westward (to the right) current speed of 0.06 m/s.

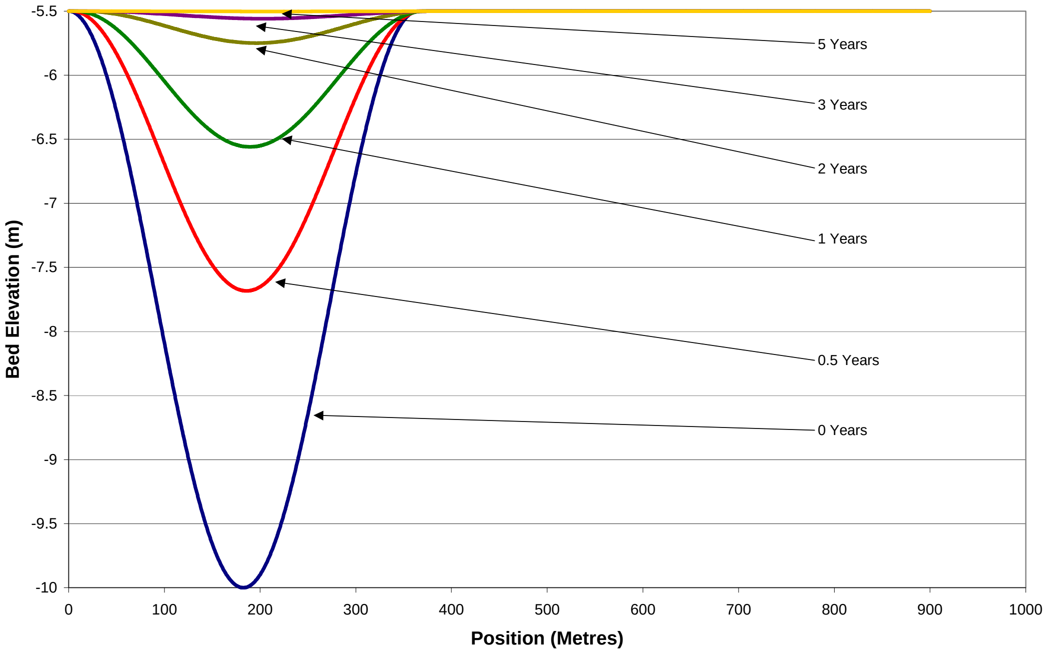


FIGURE 3.43.a. Predicted pit evolution for an initial width at 365 m and a residual westward (to the right) current speed of 0.15 m/s.

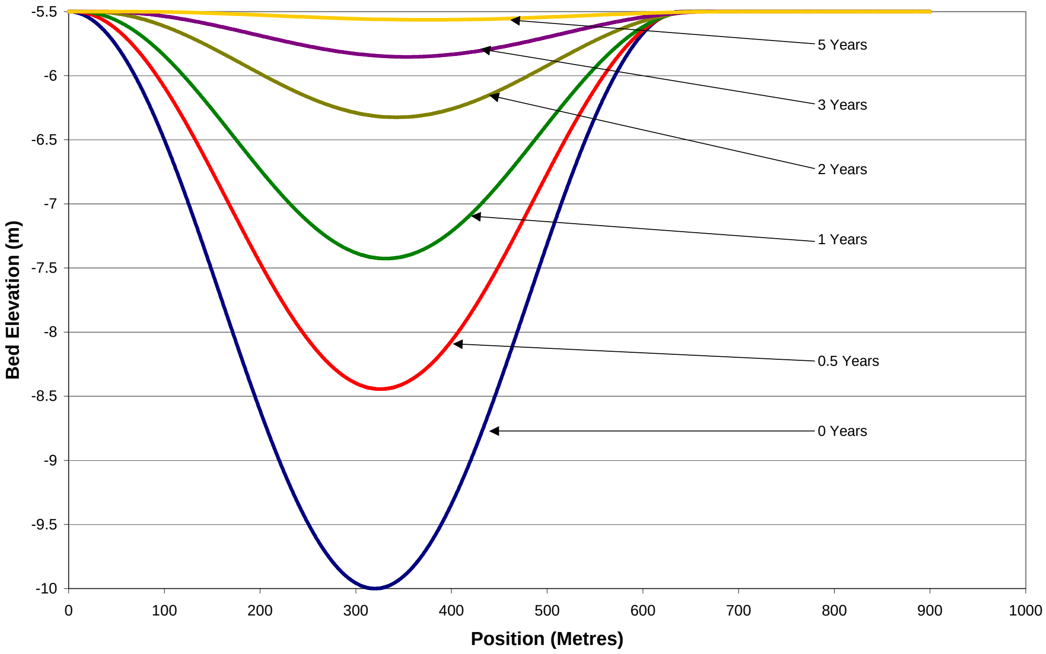


FIGURE 3.43.b. Predicted pit evolution for an initial width at 640 m and a residual westward (to the right) current speed of 0.15 m/s.

Figure 3.44 shows the number of years for a pit with a width of 365 m to reach a condition of 95% filled and the pit migration distance for a range of different bed roughness assumptions. The variation in maximum pit migration with bed roughness is also shown in this figure (it should be noted that this is the total migration rate for the sand wave, or pit feature and not necessarily the pit slope migration rate). The results indicate that the pit fills and migrates faster as the roughness increases, which in turn results in higher bottom bed shear and more sediment load. Figure 3.45 shows the number of years for the 365 m wide pit to reach 95% filled and the pit migration distance for a range of different wave conditions. Higher sediment load under the larger wave condition increases the rate of pit filling and migration. The pit-infilling rate is very sensitive to the assumption of annual average wave heights in the range of 0.5 to 1 m.

As noted above, the Ribberink et. al. (2005) approach is not currently formulated to consider the wave asymmetry influence on sediment transport that occurs under shoaling waves in depths that exist in the Block 88 area. Nevertheless, using the relative migration speed of the wave like Ship Shoal feature and the proposed dredge pit in Block 88 on Ship Shoal, an estimate of the possible shoreward migration of the proposed Block 88 pit can be made. Based on the evaluation of repeated bathymetric surveys, Penland et. al. (1988) suggest that Ship Shoal is migrating landward at a rate of 7 m/year (in the east) to 15 m/year (in the west). Figures 3.46 and 3.47 show the 2002 and 1936 bathymetry for the Block 88 site. The proposed Block 88 dredge pit is located close to the steep shoreward slope of Ship Shoal. The top and toe of the steep shoreward slope from the 2002 survey have been superimposed on the 1936 survey. The slope in the 1936 survey is not as well defined owing to the lower density of survey points. Nevertheless, this slope has clearly translated shoreward for a distance of approximately 150 to 230 m over the 66-year period for a migration rate in the range of 2.3 to 3.5 m/year. This observation is compatible with the asymmetric form of the shoal, which has steeper slopes on the inshore flank (see Figure 3.41). The processes that are causing the landward migration of this feature (at least in part due to the contribution from wave asymmetry to cross-shore sand transport) will also act on any pit dredged on Ship Shoal.

Ribberink et. al. (2005) also provide a relationship describing the migration rate of large-scale sand wave features (whether pits or shoals – see Section 2.3.4 for further discussion). The migration rate is a function of the ratio of feature length to local water depth for the undisturbed bed (L/h) and u^*/W_s (the ratio of shear to fall velocity). From the relationships presented by Ribberink et. al. (2005) and considering L/h for the shoal itself is approximately 6000 m/6 m or 1000, and the L/h for a typical pit would be 500 m/5 m or 100, and for a typical u^*/W_s of 1, it may be expected that the migration rate of a

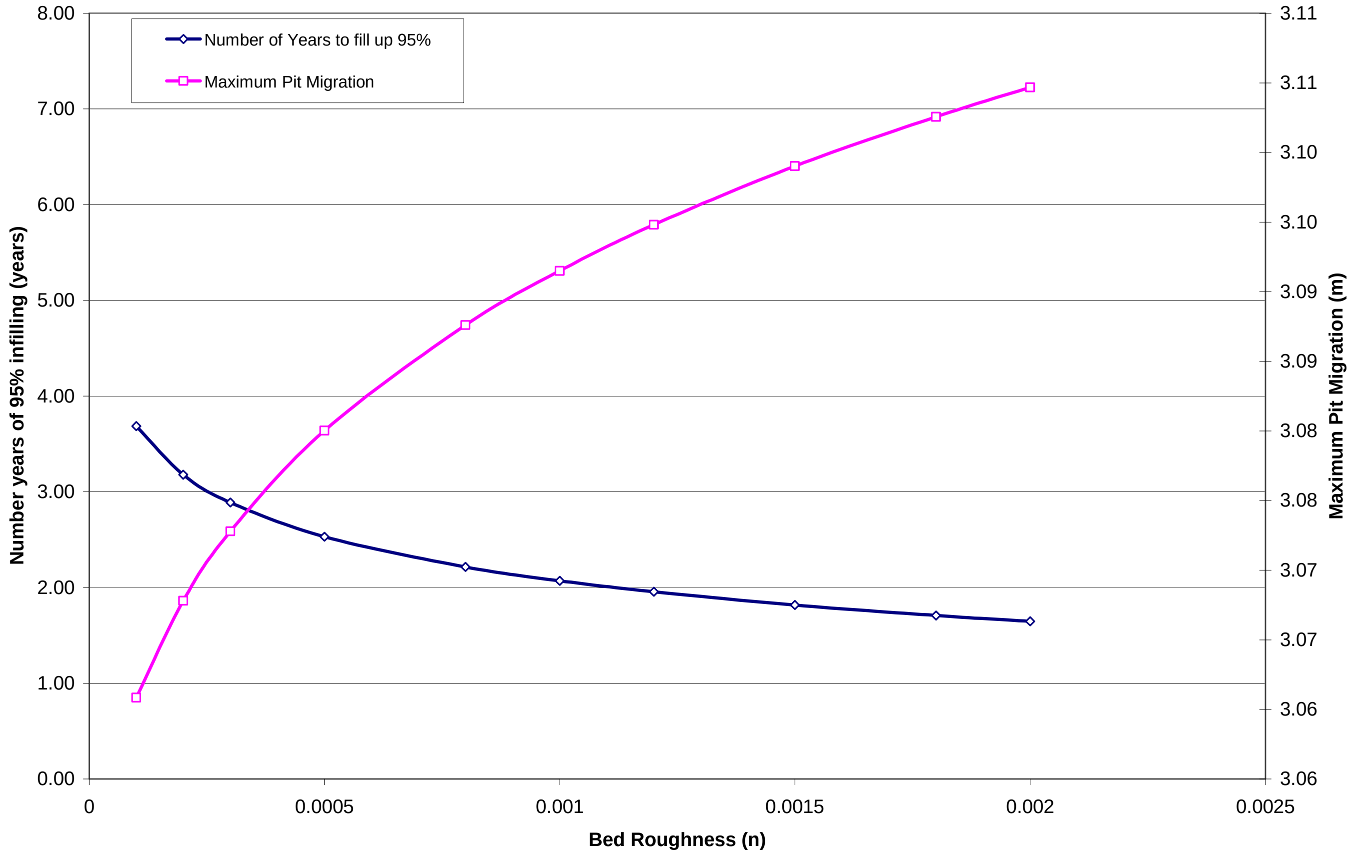


FIGURE 3.44. Block 88 pit. Time for pit to fill to 95% capacity for different bed roughnesses, a pit width of 365 m, a residual current speed of 0.06 m/s and an average annual significant wave height of 1.1 m.

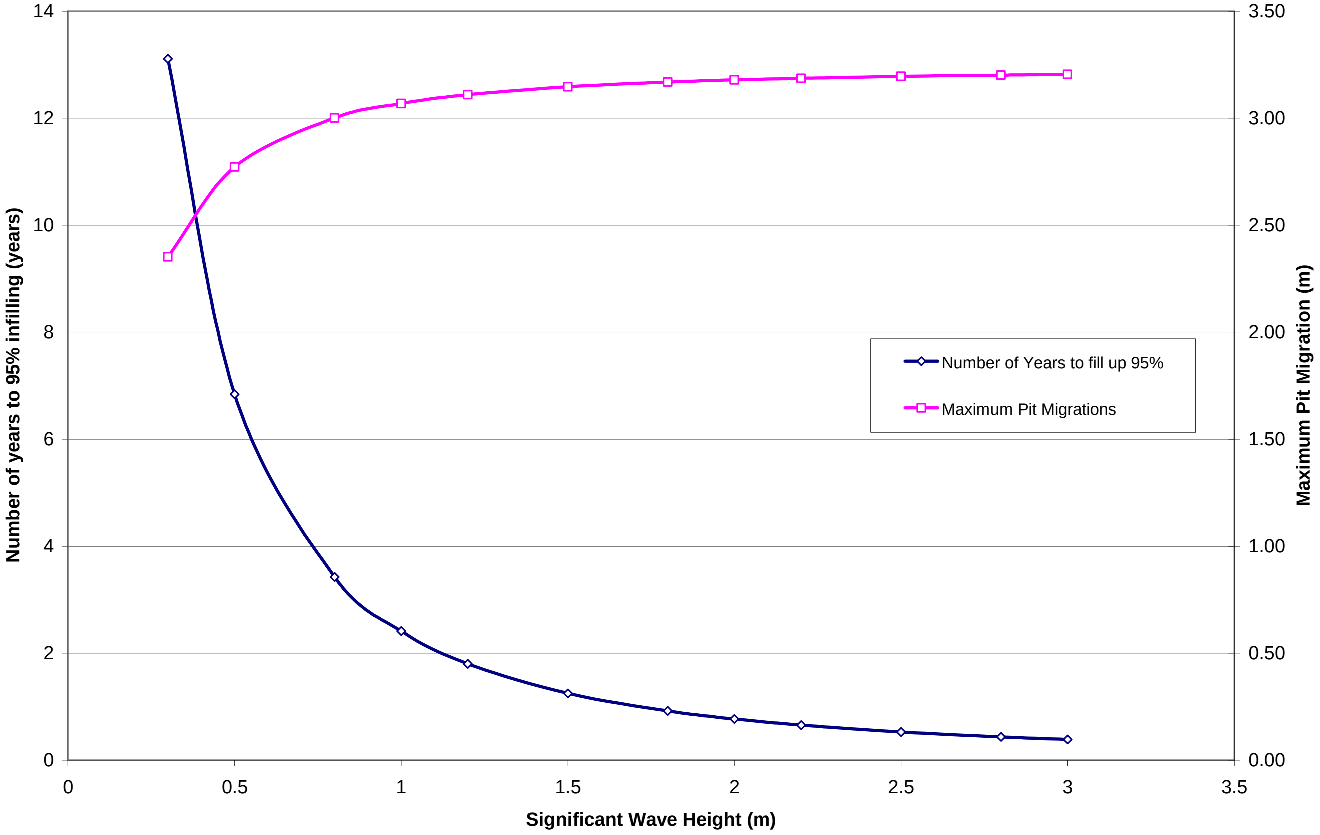


FIGURE 3.45 Block 88 pit. Time for pit to fill to 95% capacity for different average annual significant wave heights, a pit width of 365 m and a residual current speed of 0.06 m/s.

pit would be only slightly less than that of the shoal feature (within a factor of 1 to 2 less). Therefore, the pit migration rate could be in the range of 1 to 3.5 m/year based on the relationships of Ribberink et. al. (2005).

In summary, predicted migration rates both in an onshore direction and in the longshore direction (likely resulting in a net NW migration of the pit) will be small and less than about 5 m/year. These migration rates relate to the pit form overall and not the pit edge or slope. The pit is predicted to infill relatively fast (in less than five years). This rapid infilling rate outpaces any erosion of the pit edge beyond the original pit edge in most cases (i.e. only for the 640 m wide pit and the larger residual current speed of 0.15 m/s was there erosion beyond the edge of the pit). As a result, pit edge erosion is likely to be less than 25 to 50 m. These predictions are for the east-west migration direction, they would be less in the north-south direction due to the lower migration speed in this direction. Pit slope flattening mostly occurs within the existing limits of the pit, with erosion outside mostly due to the residual current and therefore the noted erosion is likely only to influence the north and west sides of the pit, and then only under the wide pit and higher residual current speed scenario. Based on these estimates and the available limited data, buffers for pipelines at this site could be relatively small and in the range of 25 to 50 m.

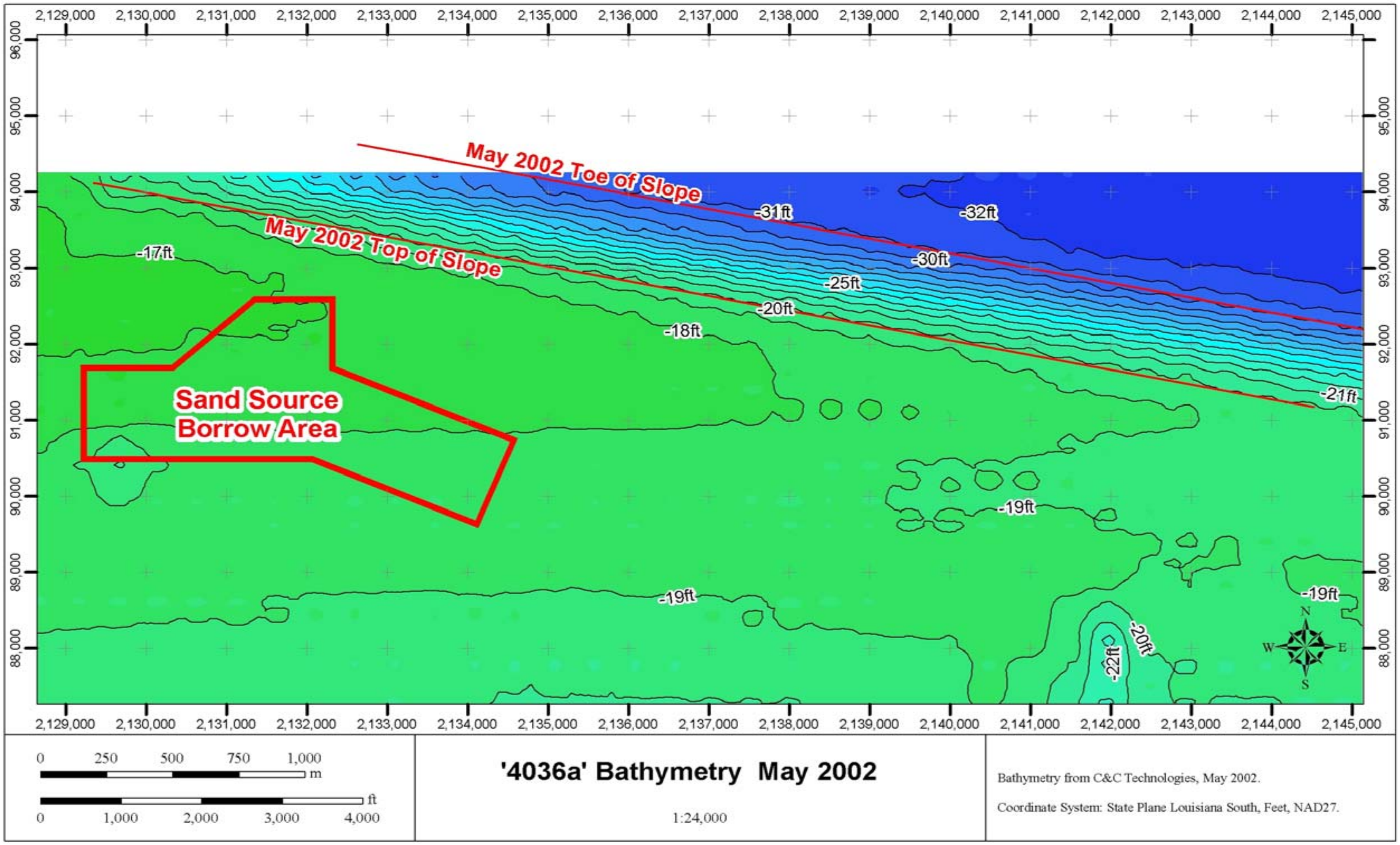
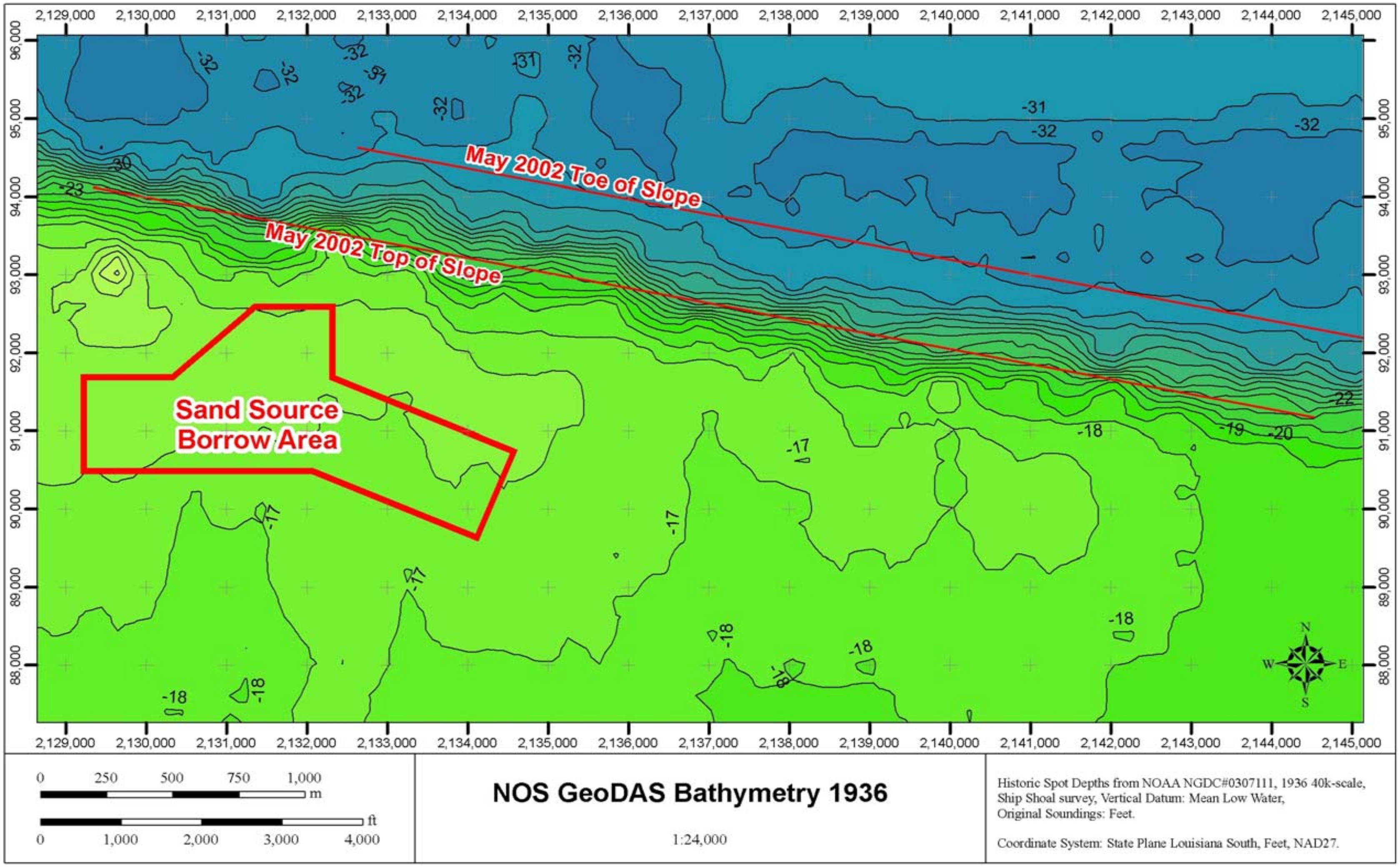


Figure 3.46 2002 Bathymetry around the Block 88 Whiskey Island West Flank Restoration Project area showing 2002 toe and crest position for the inshore slope of Ship Shoal.



NOS GeoDAS Bathymetry 1936

1:24,000

Historic Spot Depths from NOAA NGDC#0307111, 1936 40k-scale, Ship Shoal survey, Vertical Datum: Mean Low Water, Original Soundings: Feet.

Coordinate System: State Plane Louisiana South, Feet, NAD27.

Figure 3.47 1936 Bathymetry around the Block 88 Whiskey Island West Flank Restoration Project area showing 2002 toe and crest position for the inshore slope of Ship Shoal

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3.3.6 Summary of the Proposed Block 88 Borrow Pit Investigations

Sandy pits evolve in a distinctly different manner than muddy-capped pits. The change in pit slope position is driven primarily by bed load and infilling is driven by both bed and suspended load. Therefore, the infilling and pit slope change are closely coupled. In contrast to muddy-capped pits the range of erosion influence around the pit is limited, as long as the potential migration speed is low. In deeper water or for less energetic wave and current conditions there can be little or no pit evolution. However, for the crest of Ship Shoal at the Block 88 proposed borrow area the gross transport rate is relatively high and morphologic response (i.e. pit infilling) should be fast. The pit will migrate a small distance towards the west and north. The westward migration is caused by the net residual current towards the west and the northward migration is driven by the process that is causing Ship Shoal to migrate shoreward (likely due to the wave asymmetry component of sediment transport caused by shoal waves). Buffer widths in the range of no more than 25 to 50 m would be appropriate at the Block 88 site. These distances may or may not be reduced for locations in deeper water on Ship Shoal (depending on whether the total migration increases due to longer infilling periods – this will depend on the strength of residual sediment transport in deeper water). It should be noted that these proposed distances are approximate as they have been derived from estimates of the residual current at Ship Shoal and from the inference that the shoal migration rate can be used to predict the pit migration rate in the cross-shore direction (based on the work of Ribberink et. al. 2005). More information on these two key processes is required and should be obtained through long-term (at least one year) current measurements at proposed borrow sites. The Pepper and Stone (2000) data provides an excellent initial understanding but should be extended to cover a full year to assess year-to-year variability.

3.4 Summary of Pit Evolution and Possible Interaction with Pipelines

Conceptual models for the evolution of muddy-capped and sandy pits have been developed and described using three test cases. Analytical techniques and numerical models have been developed and tested to describe the evolution of pits in these two settings.

3.4.1 Muddy-Capped Pits

Muddy-capped pits experience infilling and pit margin erosion with little pit slope change where the muddy cap is left in place beyond the edge of the pit. The pit infilling and migration rates are determined by the pit dimensions (width and depth), the average wave height and tidal current speed, and external sediment load sources, such as rivers. In areas where river plumes have no influence, pit margin erosion will occur and the total eroded sediment will balance the quantity of sediment required to fill the pit. However, late in the infilling process the pit margin erosion will be reversed, as it effectively becomes part of what remains of the pit depression. Therefore, ultimately any erosion associated with a muddy-capped pit will be erased as the bed returns to its equilibrium level. In areas where suspended sediment inputs from nearby rivers contribute to net sedimentation, pit margin erosion will be reduced or altogether eliminated. In cases where the muddy cap is completely eroded exposing underlying sand, the erosion process will revert to those associated with sandy pits.

Two methods of evaluating muddy-capped pit evolution were tested: a 1D analytical approach and a 3D numerical modeling approach (applied here in 2DV form). The application of both approaches to the existing Holly Beach dredge pit and the proposed Sandy Point dredge pit showed the importance of knowledge of the local data on waves, currents, and suspended sediment load characteristics. For greater confidence in these predictive approaches, more data on pit evolution and local environmental conditions for muddy-capped pits are required, both to test the techniques and to provide input to future predictions of pit evolution. As noted in the SANDPIT study, the ability to numerically model these complex processes is limited owing primarily to insufficient understanding of sediment transport processes in these depths, although this is more of an issue in sandy setting since the complexities of sediment transport over rippled beds is not an issue in muddy settings.

The Holly Beach borrow pit immediately following dredging in April 2003 had pit dimensions of 400 m (east-west) by 600 m (north south) and a total volume of 2.2 million m^3. The post-dredge pit depth was 9 to 11.5 m and the initial water depth was about 8 m. After 20 months this pit was approximately 45% full and, based on the 1D analytical and 3D hydrodynamic and sediment transport model analyses presented in Sections 3.1.2 and 3.1.3, the pit is estimated to be completely filled by 2008 to 2010. A maximum vertical erosion of 0.9 m (i.e. the total pit cover) is likely to be limited to a distance of less than 100 to 200 m from the edge of the original pit. Providing that 0.9 m of erosion over a pipeline (just exposing the top of the pipe) was acceptable, a reasonable buffer at this site would be something in the range of 100 to 200 m. If no erosion over the pipe is a requirement, the buffer width may extend much further, possibly to 500 m from the edge of the original pit. This pit should be closely monitored in the future to provide an improved understanding of muddy-capped pit evolution and the buffer requirements for these settings.

The proposed southeast Sandy Point borrow pit has a length in the north-south direction of 1800 to 1980 m and a width in the east-west direction of 350 to 450 m. The local water depth is about 10.5 m and the pit depths of 6.3 m (proposed design) and 12.4 m (suggested ultimate depth) for total water depths of 16.8 m (55 ft) and 22.9 m (75 ft). The pit volumes for the 55 ft and 75 ft pits are 2.8 and 5.7 million m^3, respectively. Again, both the 1D analytical approach and the 2DV version of the 3D hydrodynamic and sediment transport model were applied. The results indicated that the pit would be filled in 5 to 10 years after dredging, depending on the size and assumptions on flow direction. The required buffer distance for less than 0.9 m of vertical erosion was in the range of 100 to 150 m for the 55 ft deep pit and 200 to 300 m for the 75 ft deep pit. The buffers would likely be smaller in the east-west direction due to the smaller pit width in this direction. This test case revealed that the pit margin erosion expands as pit width increases and also highlighted the importance of understanding the average flow velocity along the axis of the different pit directions where the width and length are significantly different. This site also highlighted the importance of an external source of sedimentation (such as input from the discharge of the Mississippi River) in reducing the extent of pit margin erosion. More site information is required at Sandy Point on currents and suspended sediment concentration over the period of at least at year to better refine the estimates of required buffer distances.

3.4.2 Sandy Pits

The investigation of the proposed Block 88 dredge pit provided valuable insight into the evolution of sandy pits on the Louisiana coast and particularly for Ship Shoal. The proposed pit dimensions at Block 88 for the Whiskey Island West Flank Restoration Project are: 365 m (each end) to 640 m (in the middle section) wide, 1635 m long and 5.2 m (15 ft) deep for a total water depth of 10 m (33 ft). The associated pit volume is about 3.2 million m^3.

Sandy pits generally fill in response to the gross rate of bed and suspended load (i.e. in all directions) and migrate due to any residual sediment transport rate. Block 88 is located on the crest of Ship Shoal in only 5 m of water and therefore has a relatively high gross transport rate (150 m^3/m/year based on Van Rijn, 2004) and as a result it will have a short morphologic time scale and will infill in 3 to 6 years depending on the width (the range corresponds to a range of pit widths from 365 to 640 m in the longshore direction). This filling rate may be slightly faster when cross-shore transport is considered. The predicted pit migration rates are very low (less than 5 m/year) due to low residual current in the longshore (east-west) direction and the low wave asymmetry contribution to onshore transport in the north-south direction. Furthermore, the high rate of morphologic response (due to high gross transport rate) results in the infilling outpacing the migration so that there is little or no predicted pit edge erosion in most of the scenarios investigated. Therefore, the predicted buffers at this site are low and in the range of 25 to 50 m. The morphologic response time will decrease for deeper water and this will result in slower filling. However, extent of migration could increase with slower filling if the residual currents do not reduce that much in deeper water. The Block 88 pit should be closely monitored (bathymetry change and long term wave and tide/wind-induced currents) to improve the understanding of sandy pit response on Ship Shoal.

4.0 GUIDELINES FOR BUFFERS TO PREVENT DIRECT AND INDIRECT IMPACTS OF DREDGING AND FINAL RECOMMENDATIONS

This section provides recommendations on buffers to protect oil and gas infrastructure from direct and indirect damage associated with offshore dredging operations. Section 4.1 provides recommendations on avoidance of direct impacts and a summary of buffers for other jurisdictions. Sections 4.2 and 4.3 provide recommendations for the avoidance of indirect impacts for pits in muddy and sandy settings, respectively.

4.1 Avoidance of Direct Impacts and Buffers from other Jurisdictions

Direct impacts are associated with potential vessel (including dredging equipment and anchors) collision with pipelines and other oil and gas infrastructure either submerged or above water. Direct impacts to the infrastructure would result in damage or breakage of the infrastructure. Indirect impacts, which have been the focus of this investigation, are associated with the potential for pit evolution to expose and undermine oil and gas infrastructure founded on the seabed, leading to damage to these facilities. Indirect impacts could result from anchor damage to exposed pipelines or through undermining (creation of spans) of pipelines. Exposed pipelines could also result in damage to fishing gear.

In a recent report on avoidance of dredging impacts on archeological resources (Research Planning, Inc., 2004), a minimum buffer zone in the range of 50 to 100 m was proposed, based on the following considerations with respect to avoiding direct impacts:

- To address the possibility of position inaccuracies by the dredge vessels and the drag arm or cutter head (although these usually are low at +/- 5 m). It is noted however, that improper GPS setup can result in much greater positioning errors;
- To allow for the possibility of power loss, influence of storms, or human error in the navigation and operation of the dredge vessel;
- Possible inconsistencies related to common geographic coordinates for the infrastructure and the dredge vessel position.

It is highly recommended that the geographic position of the pipeline be mapped prior to designing the borrow pit and its location. Providing this is performed, a minimum buffer distance of 50 m may be appropriate to address direct impact described by the first and second bullet points above. It may be advisable that MMS recommends the requirement of surface buoys to mark pipelines when buffers of less than 100 m are implemented. It is noted that this simply represents a minimum buffer distance and is not additive to the buffer distances recommended to address possible indirect impacts as described in Sections 4.2 and 4.3 below.

It is also noted that in the case of above water oil and gas infrastructure, any navigational constraints on approaching these structures must be followed. This includes both vessel navigation and anchoring restrictions. In many cases, these regulations will require a much larger buffer than that recommended above for direct impacts. For example, MMS requires a 400 m (1,320 ft) buffer around platforms to accommodate site clearance operations for future platform removal.

The only jurisdictions with clear stipulations on buffers around seabed pipelines and cables were in the UK (250 m on either side of the pipeline) and the Netherlands (500 m on either side of the pipeline). In neither case was any scientific justification for these buffer distances provided. There is a 500 m avoidance zone for navigation in the vicinity of platforms in the UK and Europe (Royal Haskoning, 2004).

In summary, a recommended minimum buffer distance for pipelines and other submerged oil and gas infrastructure founded on the seabed is 50 to 100 m. The lower limit would be appropriate where the location of the nearby infrastructure is accurately surveyed prior to final design of the dredge pit. For above water structures such as platforms, a minimum recommended buffer distance would be 500 m based primarily on navigational considerations.

Sections 4.2 and 4.3 will address the need for larger buffers than the minimums proposed here to protect infrastructure from indirect impacts.

4.2 Buffers to Avoid Indirect Impacts in Muddy Settings

As explained in Section 3.4.1, muddy-capped pits evolve in a distinct manner that primarily consists of two partially decoupled processes of pit infilling and pit margin erosion. Pit margin erosion has the potential to influence the existing cover over pipelines located beyond the edge of the pit immediately after dredging. Pits in muddy settings will eventually fill in, so any erosion beyond the edge of the pit will be temporary. In the absence of an external source of suspended sediment, such as a river plume, the pit margin erosion volume will approximately balance the initial pit volume. Eventually though, as both the pit and the pit margin zone are filled, this balance will be lost or spread out over a very large distance. Pit margin erosion will be reduced in direct proportion to the quantity of sedimentation in the pit related to external sources.

The MMS requires that all cables, umbilical, and pipelines inshore of the 200 ft depth contour be buried by at least 3 ft (0.9 m) below the seabed surface (measured to the top of the pipe). Based on discussions with MMS (Barry Drucker, personal communication) there are no regulations regarding the maintenance of this minimum cover and corrective action is only generally undertaken when pipelines are exposed or undermined. Therefore, in the development of these guidelines for indirect impact, it has been assumed that a maximum temporary vertical erosion of 0.9 m would be allowable; in some instances recommendations for smaller allowable vertical erosion are also provided. Reduced allowable vertical erosion may be appropriate at locations where the 3 ft (0.9 m) cover has been eroded naturally prior to initiation of the dredging project. Therefore, it is strongly recommended that the existing cover over pipelines near proposed dredged pits be surveyed to determine the actual cover. The results of this survey will in part determine the acceptable or allowable maximum temporary erosion in the pit margin zone.

The following sub-sections provide an assessment of the influence of various key parameters associated with dredged pit evolution in muddy settings on the extent of pit margin erosion. The extent of erosion is expressed as the distance from the original pit edge to the location where maximum erosion is 0.9, 0.5, or 0.1 m, depending on the scenarios considered. Effectively, these distances could represent buffers to prevent any more than 0.9, 0.5, or 0.1 m of erosion occurring over an adjacent pipeline.

Pit edge erosion is a function of many variables. The key variables consist of pre-existing water depth at the site, pit depth, pit length, and the equilibrium suspended sediment concentration. The equilibrium suspended sediment concentration in itself considers many factors including bed sediment mobility (grain size and other factors) and bed shear stress (due to the combined effect of waves and currents). Due to the number of parameters, it is not possible to provide guidance for all situations.

Two scenarios have been selected both associated with a pit having a total volume of approximately 2.5 million m^3 (i.e. both stripped mud and sand). For the first scenario a very long pit length of 2000 m has been selected as this results in very large buffer requirements. For this case the pit depth and water depth are 10 m, for a total water depth of 20 m unless varied. The pit width for this case would be 125 m, although this does not come into the calculation. The second scenario features a more typical case with a pit length of 650 m (and a pit width of 650 m) and a pit depth of 6 m, in a pre-existing water depth of 8 m. Water depth, length, and dredge depth are varied in three separate figures and the influence of suspended sediment concentration is considered in each case. These two test pits will be referred to as the long and average pits in the following discussion.

It is important to note that these estimates have been generated with the 1D analytical approach that was described in Section 3. This analytical approach was calibrated against the measured change at Holly Beach and then tested against the predicted response from the 3D numerical model for Sandy Point. As noted in the SANDPIT study report (Van Rijn et. al., 2005) there remain significant limitations of all analytical approaches and numerical models to predict pit evolution accurately, so these recommendations should be considered accordingly as approximate and applied with caution.

4.2.1 Influence of Water Depth

The pre-existing water depth in the absence of the pit has a significant influence on the extent of pit margin erosion. Figures 4.1a and b present the distance from the original pit edge to the location where erosion is always less than or equal to 0.9 and 0.5 m, respectively for the long pit. The depth of the pit below the pre-existing seabed surface is assumed to be 10 m and the pit length is assumed to be 2 km. For water depths less than

10 m for the 0.9 m limit and 8 m for the 0.5 m limit, the predictions are not available owing to the resolution of the analytical approach. The distance from the edge of the pit to the point where there is less than 0.9 m of vertical erosion increases from 100 to 200 m (the range is a function of the influence of equilibrium suspended sediment concentration) for a 10 m water depth to a maximum of 350 to 650 m for pre-existing water depths of 15 to 17 m (see Figure 4.1a). For 0.5 m of maximum allowable erosion these distances vary from 600 to 700 m for a 10 m water depth to 1,200 to 1,500 m for water depths of 15 to 17 m (see Figure 4.1b). It should be recalled that the total pit margin erosion volume will be equal to the pit volume in the absence of external sources (which is the assumption here). Effectively the pit edge erosion becomes more spread out from the edge of the pit for depths in the range of 15 to 17 m. The reason for this is that the diffusion process is weaker in deeper water. Figures 4.1a and b show that lower background suspended sediment concentration results in reduced distances to the 0.5 or 0.9 m limits.

For the average size pit and the base conditions (width of 650 m, pre-existing water depth of 8 m and dredge depth of 6 m) there is no location where the total vertical erosion is greater than 0.9 m beyond the edge of the pit. Figure 4.2 shows the maximum erosion measured at the edge of the original pit for a range of pre-existing water depths. The maximum erosion measured at the pit edge is 0.85 m for a water depth of 8 m. There is only minor difference in the results for different equilibrium suspended sediment concentrations. Figure 4.3a shows how the distance to the limit of 0.5 m erosion varies with pre-existing water depth. The distances vary from 50 to 350 m with the maximum occurring in the 9 to 10 m water depth range. There is little difference between the equilibrium concentrations of 100 and 200 mg/l and the distance to 0.5 m is lower for the 50 mg/l concentration, particularly in the deeper depths. Figure 4.3b provides the same information for an allowable maximum vertical erosion limit of 0.1 m. The required buffer distances are dramatically increased. For a pre-existing water depth of 10 m the required buffer distance is almost 1500 m, more than 4 times greater than the 350 m required for the 0.5 m limit.

4.2.2 Influence of Dredge Depth

The variation of distance from the pit edge with erosion greater than 0.9 and 0.5 m for the long pit for different dredge depths (i.e. depth of pit below seafloor level) is shown in Figures 4.4a and b, respectively. For the 0.9 m limit the distances vary from a little over 100 m for the 7 m dredge depth to almost 700 m for the 15 m deep pit. The erosion increases for deeper pits due to the volume required to fill the pit. For the 0.5 m limit the distance increases from 400 m for a 5 m dredge depth to almost 1,200 m for a 15 m dredge depth.

Figures 4.5a, b and c show the results of distance from pit edge for erosion greater than 0.9, 0.5, or 0.1 m (respectively) as it varies with dredge depth for the average pit. The distances vary from 75 m for a pit depth of 7 m to almost 400 m for a pit depth of 12 m with the 0.9 m erosion limit. For the 0.5 m limit the distances vary from 100 to 700 m for dredge depths from 4 to 12 m. In comparison, with the 0.1 m limit, the distances vary from 1,000 to 1,600 m for depths of 4 to 12 m. In all cases the distances are virtually the same for the 100 and 200 mg/l equilibrium suspended sediment concentrations and slightly less for the 50 mg/l condition.

4.2.3 Influence of Pit Length

It is important to note that pit length is defined as the dimension coincident with the direction of dominant flow. In fact, in the analytical solutions used to develop these buffer distances it has been assumed that the flow is always in a direction coincident with the axis of the pit along the pit length. Therefore, for locations where the flow direction is not dominant in the direction of the longest pit dimension the buffer distances will be over-estimated. The influence of pit length on the distance to less than 0.9 and 0.5 m of vertical erosion for the long pit is shown in Figures 4.6a and b. For the 0.9 m limit, the distance varies from 100 to 550 m for pit lengths of 1,500 and 2,500 m, respectively. With the 0.5 m limit the distance varies from 200 to 1,000 m for pit lengths of 800 to 2,500 m, respectively. The results for the 50 mg/l equilibrium concentration are the only results that show an influence of this parameter and the predicted distances are slightly less.

The results of pit length influence on distances to 0.9 and 0.5 m of erosion for the average pit are shown in Figures 4.7a and b. For the 0.9 m limit the distances vary from 100 to 750 m for pit lengths from 800 to 2,500 m, respectively. For the 0.5 m limit the distances vary from 200 to 1,100 m for pit lengths of 500 to 2,500 m, respectively.

4.2.4 Summary of Buffer Requirements for Pits in Muddy Settings

The distance from the edge of the pit to a location beyond which there is less than 0.9, 0.5, or 0.1 m of vertical erosion varies widely depending on pit width or length, dredge depth, pre-existing water depth, and equilibrium concentration. These distances effectively represent buffer requirements to avoid more than 0.9, 0.5, or 0.1 m of vertical erosion over a pipeline adjacent to a dredged pit. For 0.5 or 0.9 m of allowable vertical erosion, the buffers were about a factor of 2 (but sometimes as high as 5 or 6) times greater for the 0.5 m limit than the 0.9 m limit. The required buffers range from 100 m to 1,500 m for the long pit and 50 to 1,200 m for the average pit. For the average pit the 1,200 m buffer corresponded to a very deep 15 m dredge depth and the 0.5 m erosion limit. For the average pit with typical pre-existing water depth (5 to 10 m) and dredge depths (5 to 10 m) the required buffer distance was generally less than about 200 m.

Some tests were completed to evaluate the influence of requiring no more than 0.1 m of allowable vertical erosion over a pipeline adjacent to a dredged pit. Compared to the tests with a 0.5 m erosion limit, the required buffers with a 0.1 m limit were generally 3 to 10 times greater. It is not possible to give a single buffer distance for all conditions in muddy settings, as it would either be overly conservative or insufficient in most cases. The most important parameter influencing buffer width is the pit length in the direction of dominant flow; buffer width increases with increasing pit length. For locations where the flow is not always in the direction of the longest pit dimension, the buffer distances will be over-estimated. The second most important influence is pit depth; buffer distances increase with increasing pit depth. Finally, an increase in pre-existing water depth sometimes increases and sometimes decreases buffer requirements; it depends on the geometry of the pit (and specifically the depth of the dredge pit versus the pre-existing water depth). It is important to recognize that when the muddy cap is fully eroded, exposing sand below, the pit evolution process may change to that associated with a sandy setting and the buffer requirements may revert to the sandy setting recommendations (i.e. a reduced buffer width). The extent to which buffer requirements are reduced in this situation will be site specific and depend on the uniformity of the muddy cap thickness and areas of sandy sediment exposure. Where sand becomes fully exposed for more than 50 to 100 m beyond the edge of the pit, the sandy buffer requirements described in Section 4.3 will become effective.

In areas where there is a need to maximize the useable size of a borrow deposit located close to pipelines, a site-specific study of future pit evolution is recommended based on data collection and numerical modeling.

4.3 Buffers to Avoid Indirect Impacts in Sandy Settings

Sandy pits differ in their morphologic response compared to muddy-capped pits. The morphologic changes are more localized to the pit slope due to the stronger influence of bed load and the more rapid adaptation of sediment transport to the change in water depth caused by the presence of the pit. The other primary difference is that sandy pits have the potential to migrate where there is a residual or net sediment transport direction. Therefore, on the one hand, if residual currents are small, then the influence zone of sandy pits will likely be smaller than those of muddy pits. However, if the residual or net transport is strong, then the pit influence will be greater, although it will only occur on the downdrift slope of the pit.

The analytical approach of Ribberink et. al. (2005) developed as part of the SANDPIT study is used to evaluate buffer requirements for a range of conditions and scenarios. As with the muddy pit analysis, the key parameter that is determined is the distance from the edge of the pit to the location where erosion is 0.9 or 0.5 m or less. This effectively defines the required buffer distance providing that 0.9 or 0.5 m of erosion is acceptable over an existing pipeline.

The Ribberink analytical approach was applied to both the long pit (2,000 m by 125 m by 10 m deep in 10 m of water) and the average pit (650 m by 650 m by 6 m deep in 8 m of water) assuming sandy conditions. The results indicated that in no case for the range of conditions considered (water depths up to 20 m, pit lengths up to 2,000 m and pit depths up to 26 m) was either 0.5 m or 0.9 m exceeded at any distance from the edge of the pit. The reason for this is that the pit infilling rates are fast enough to cancel out the slope erosion caused by migration rates. Average annual residual current speeds up to 0.3 m/s were considered, which is believed to be more than what exists along the Louisiana coast.

It is important to note that these recommendations only apply to single pits. Where multiple pits are dredged on either side of pipeline corridors leaving a berm in between, erosion will be much greater for two reasons. First, bed load will be intercepted by the updrift pit, which will lead to much more erosion to the downdrift berm. Secondly, the berm slopes will erode from both directions. Such conditions should be analyzed on a site specific basis to develop appropriate buffer plans.

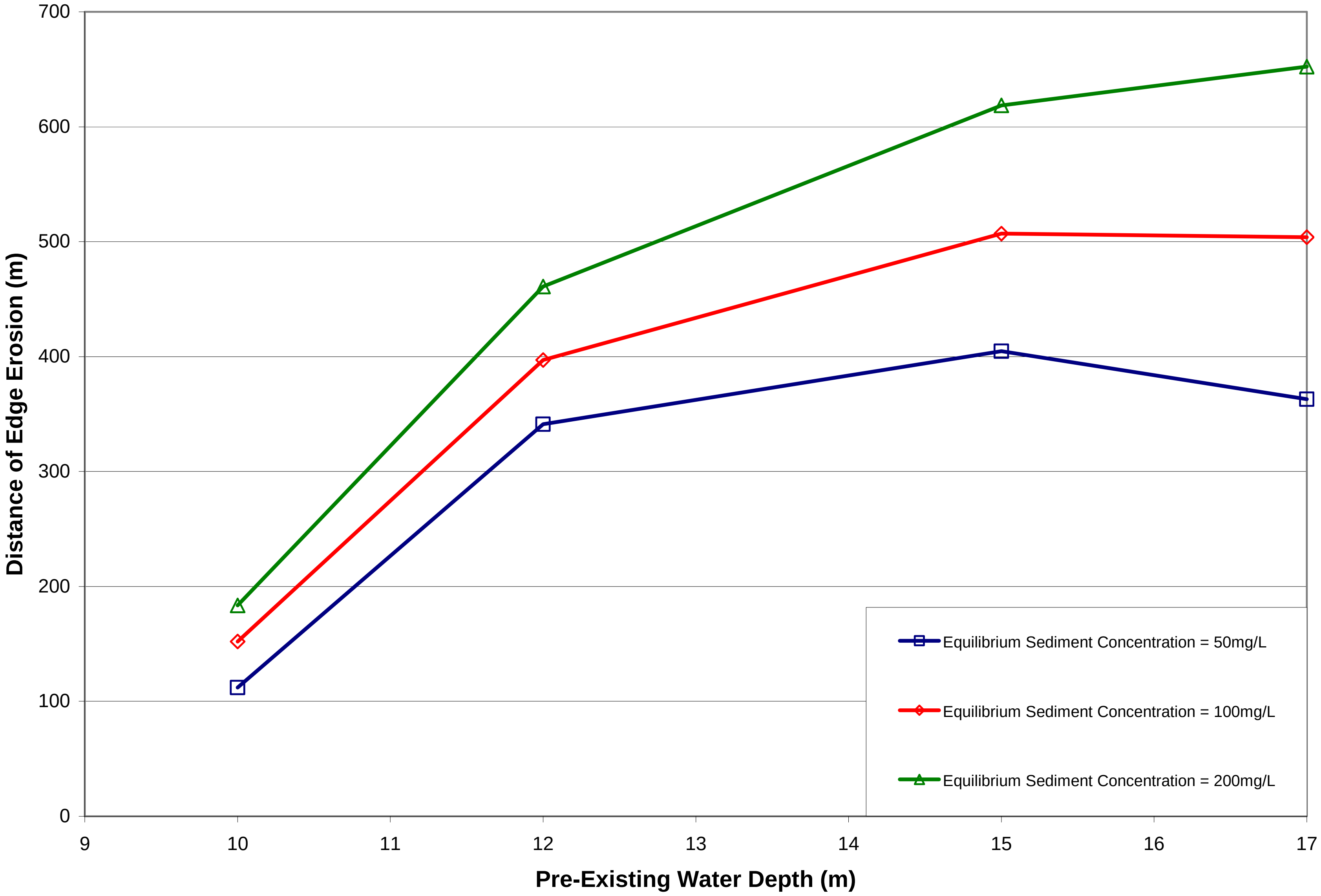

FIGURE 4.1.a. Long Pit in Muddy Setting. Distance from edge with erosion greater than 0.9 m as a function of pre-existing water depth (based on estimates from an analytical approach)

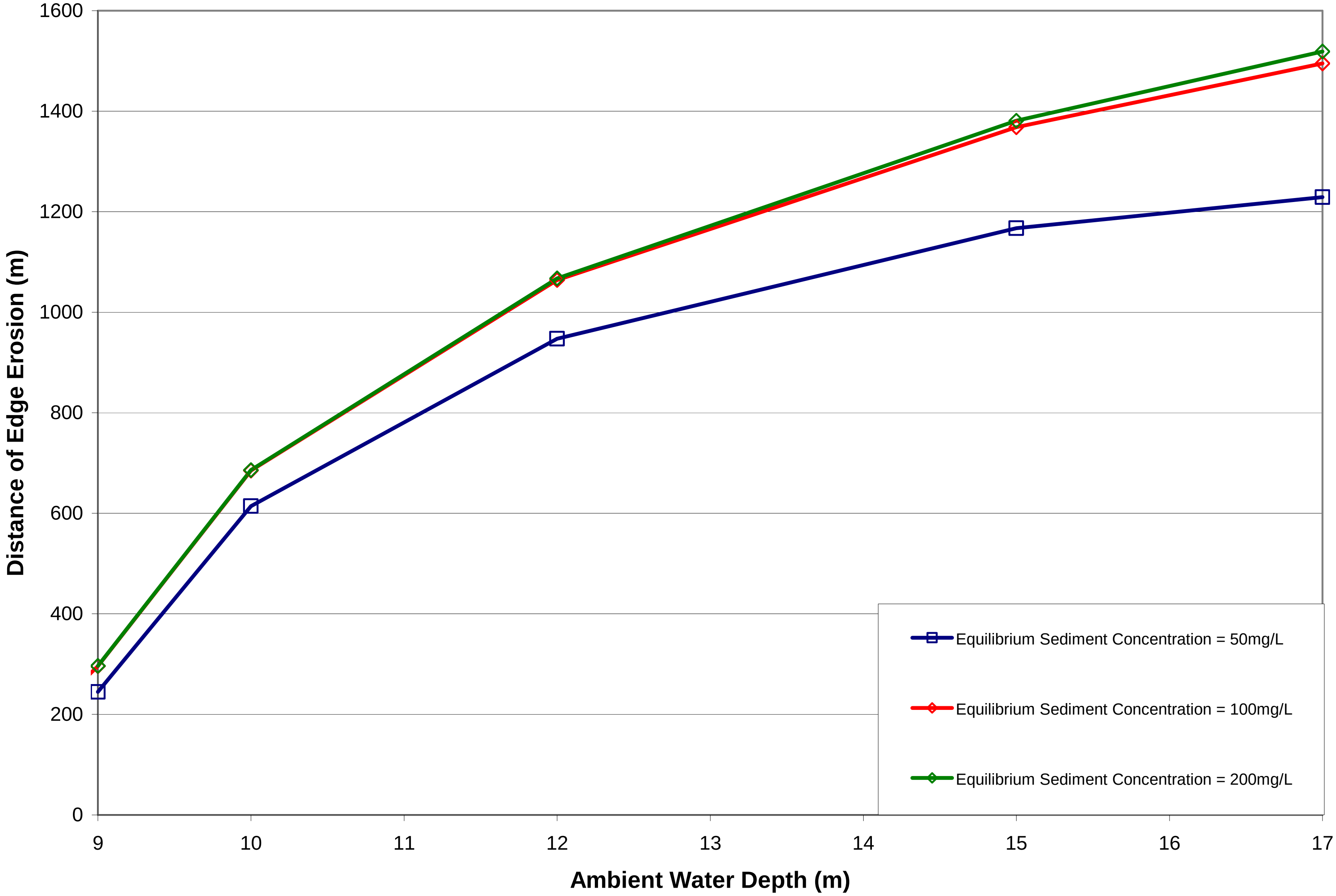

FIGURE 4.1.b. Long Pit in Muddy Setting. Distance from edge with erosion greater than 0.5 m as a function of pre-existing water depth (based on estimates from an analytical approach).

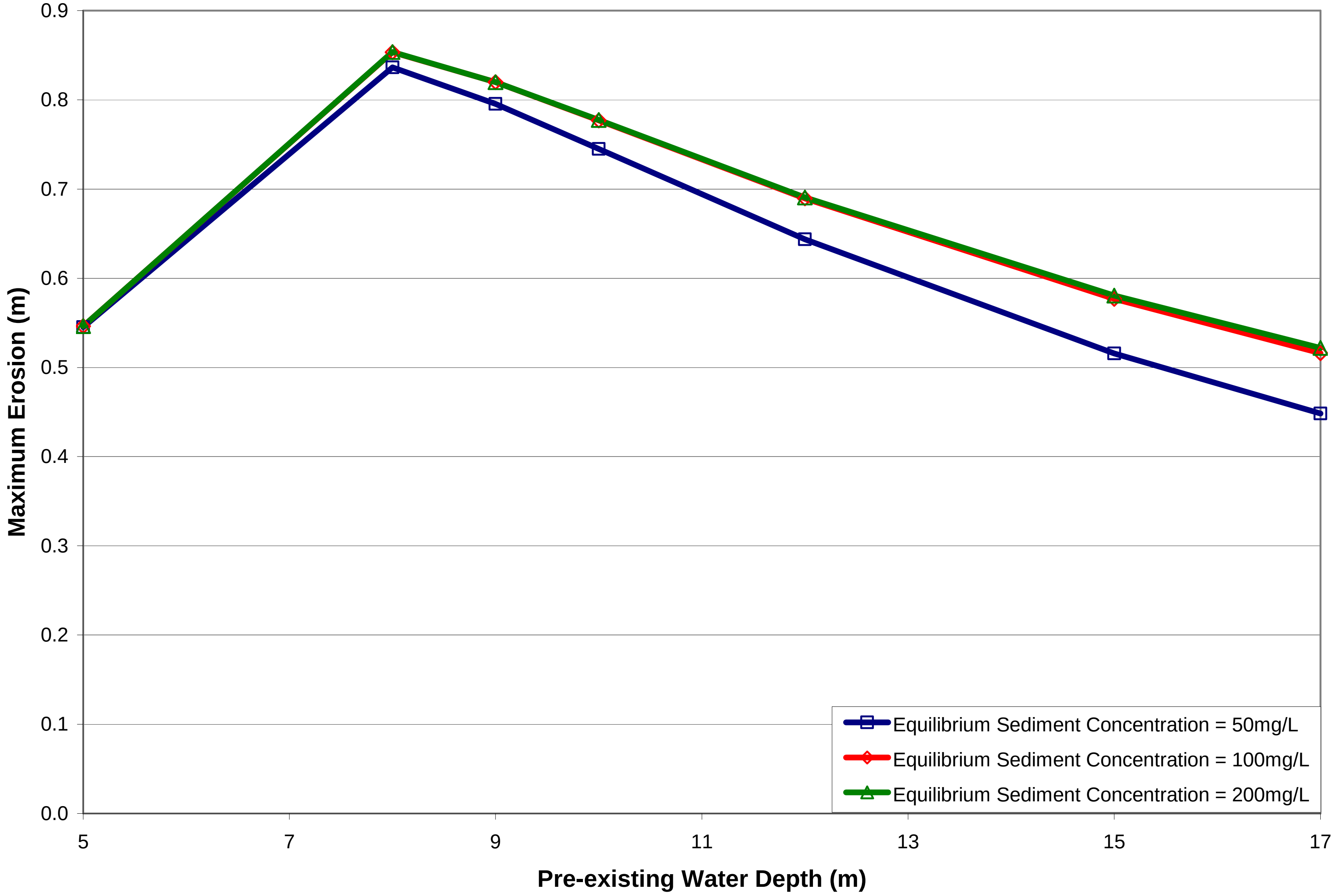

FIGURE 4.2. Average Pit in Muddy Setting. Maximum vertical erosion measured at the edge of the pit as a function of pre-existing water depth - always less than 0.9 m (based on estimates from an analytical approach).

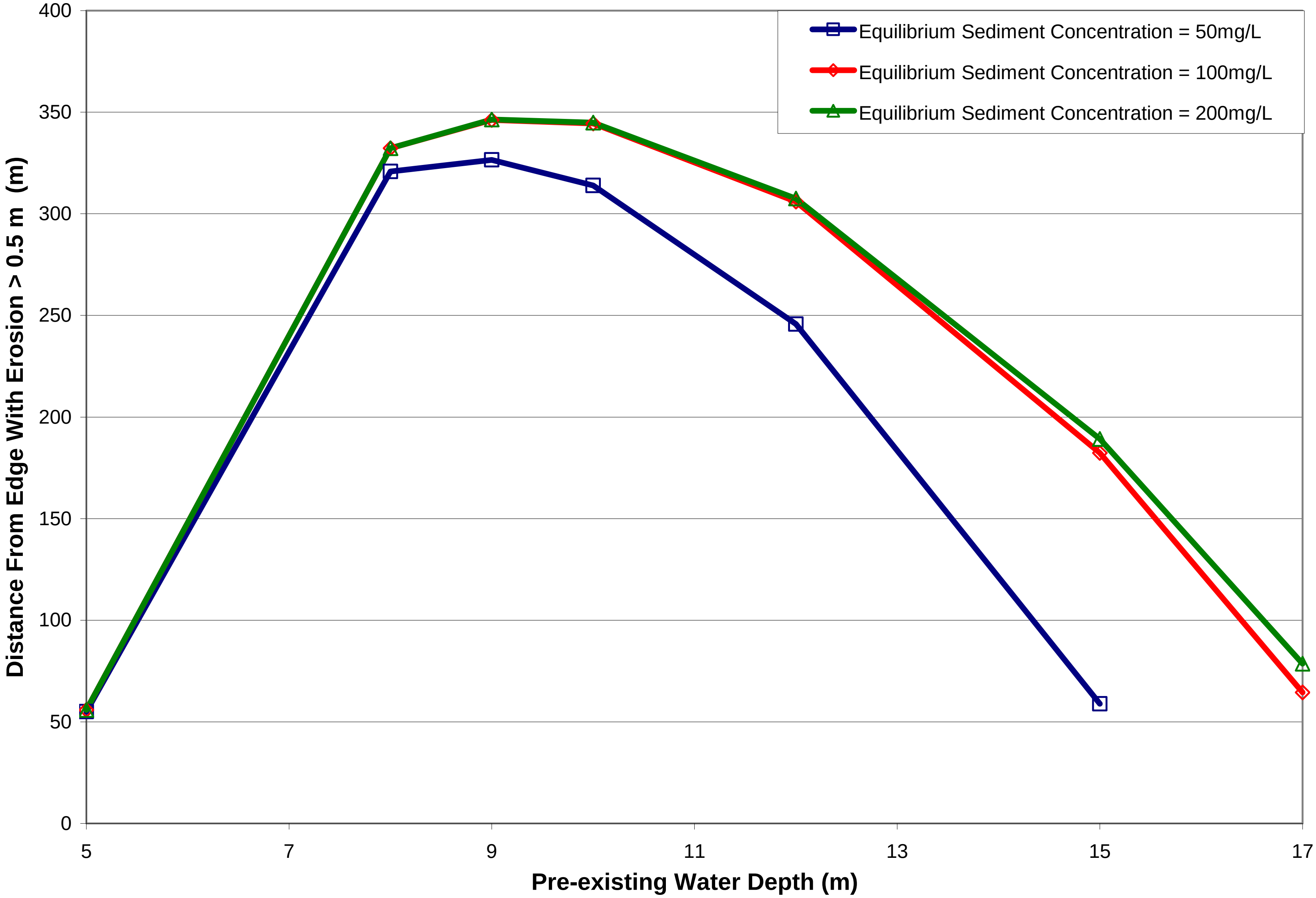

FIGURE 4.3.a. Average Pit in Muddy Setting. Distance from edge with erosion greater than 0.5 m as a function of pre-existing water depth (based on estimates from an analytical approach).

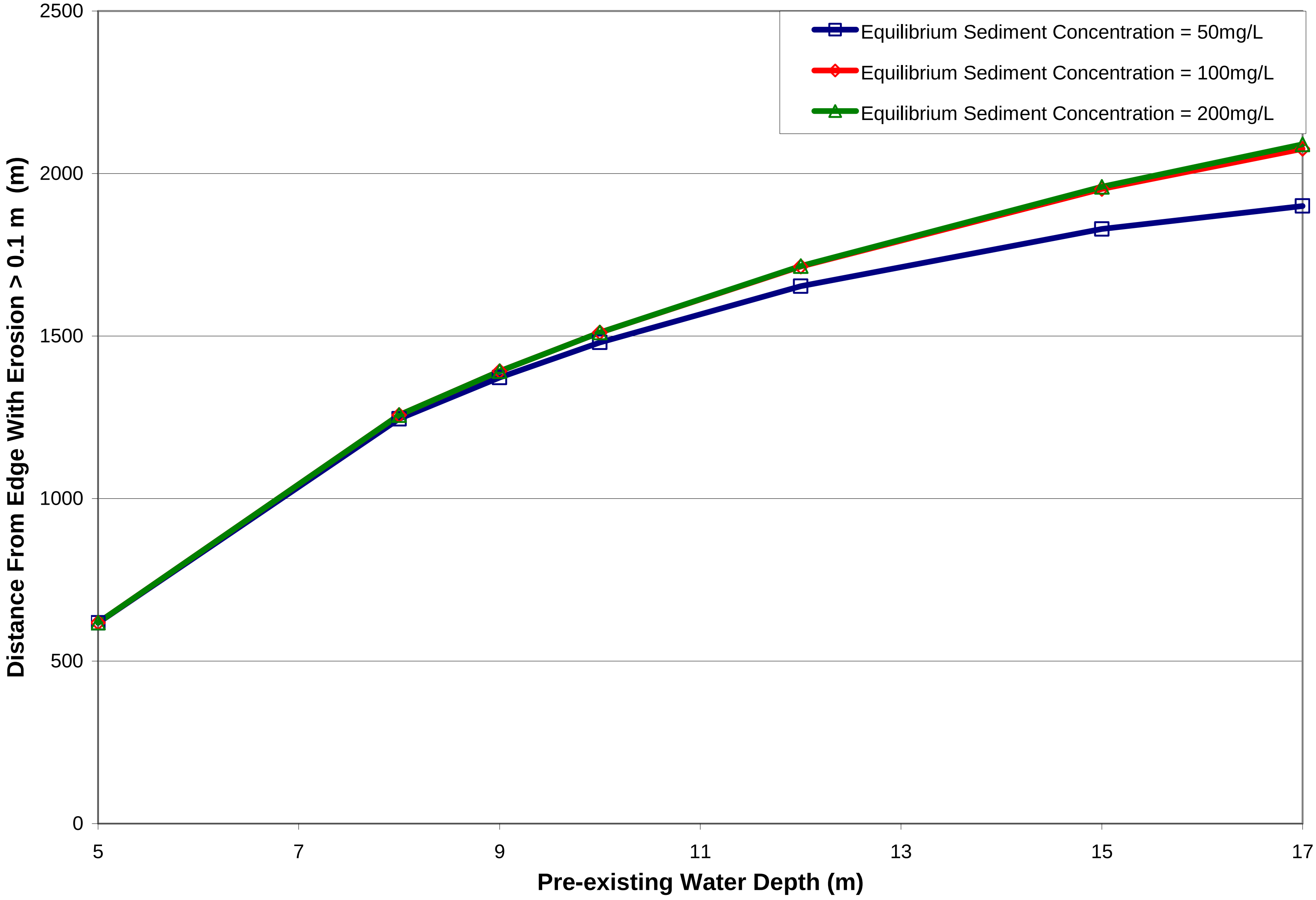

FIGURE 4.3.b. Average Pit in Muddy Setting. **Distance from edge with erosion greater than 0.1 m as a function of pre-existing water depth (based on estimates from an analytical approach).**

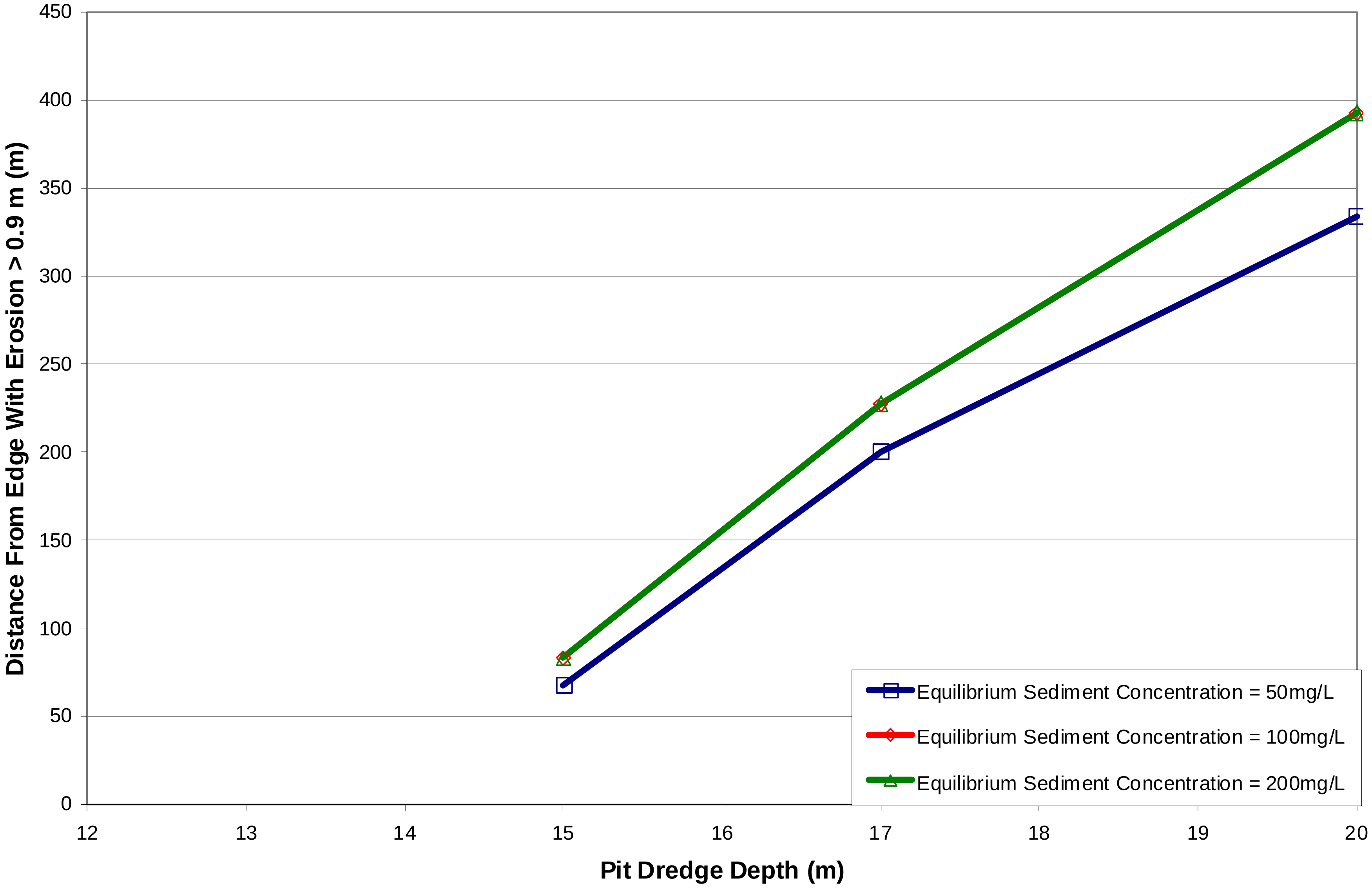

FIGURE 4.4.a. Long Pit in Muddy Setting. Distance from edge with erosion greater than 0.9 m as a function of pit dredge depth (based on estimates from an analytical approach).

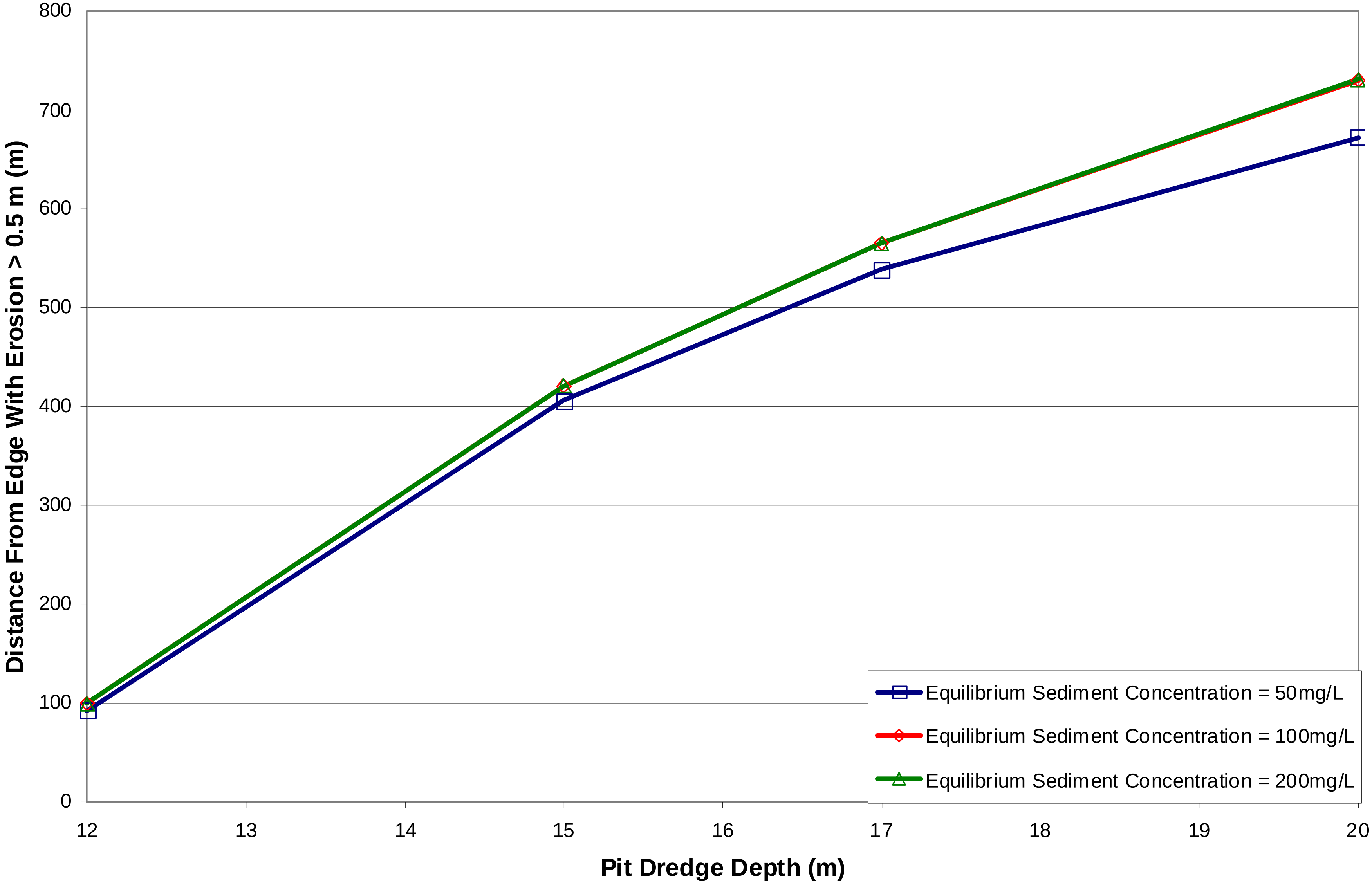

FIGURE 4.4.b. Long Pit in Muddy Setting. Distance from edge with erosion greater than 0.5 m as a function of pit dredge depth (based on estimates from an analytical approach).

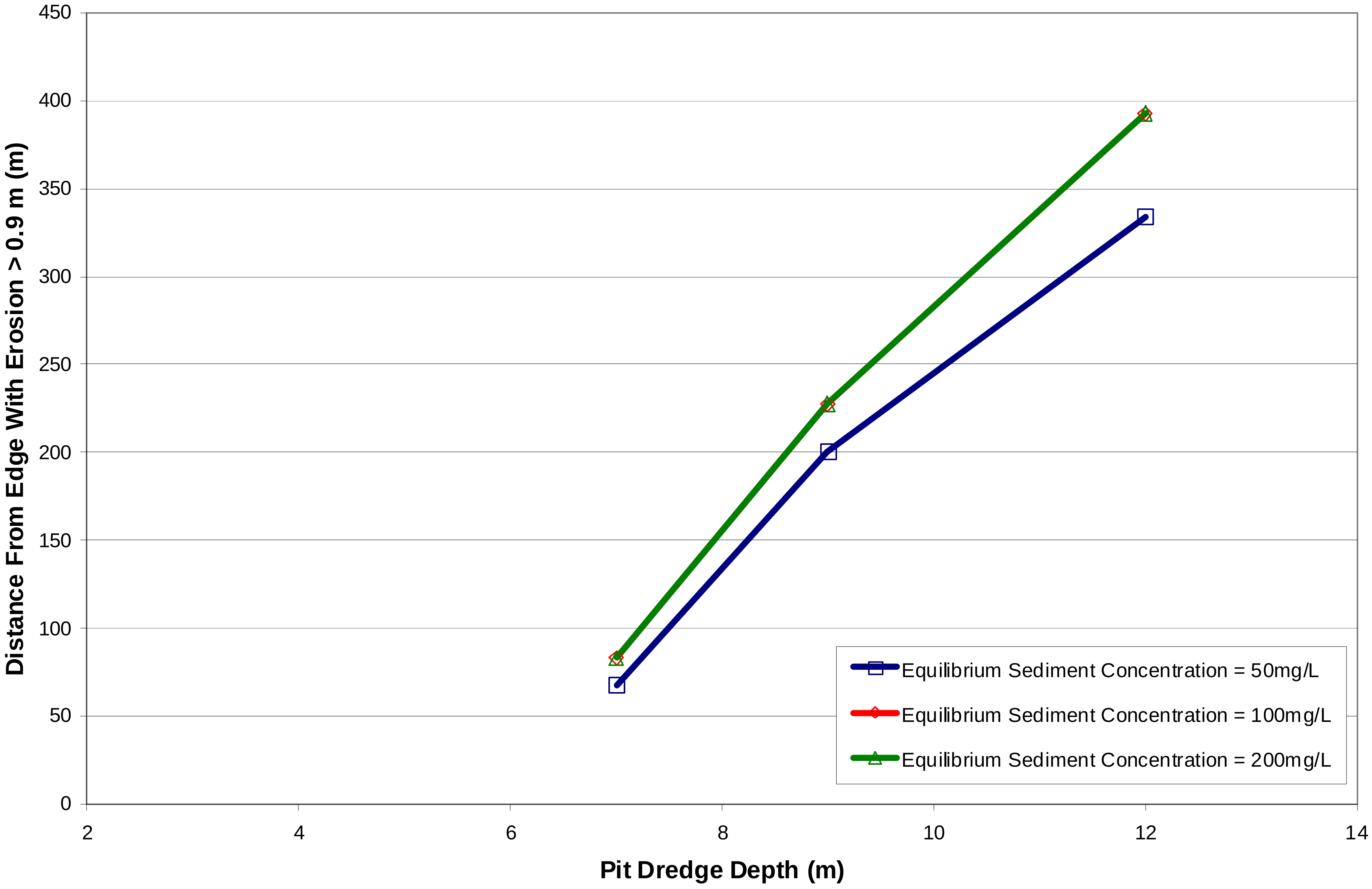

FIGURE 4.5.a. **Average Pit in Muddy Setting. Distance from edge with erosion greater than 0.9 m as a function of pit dredge depth (based on estimates from an analytical approach).**

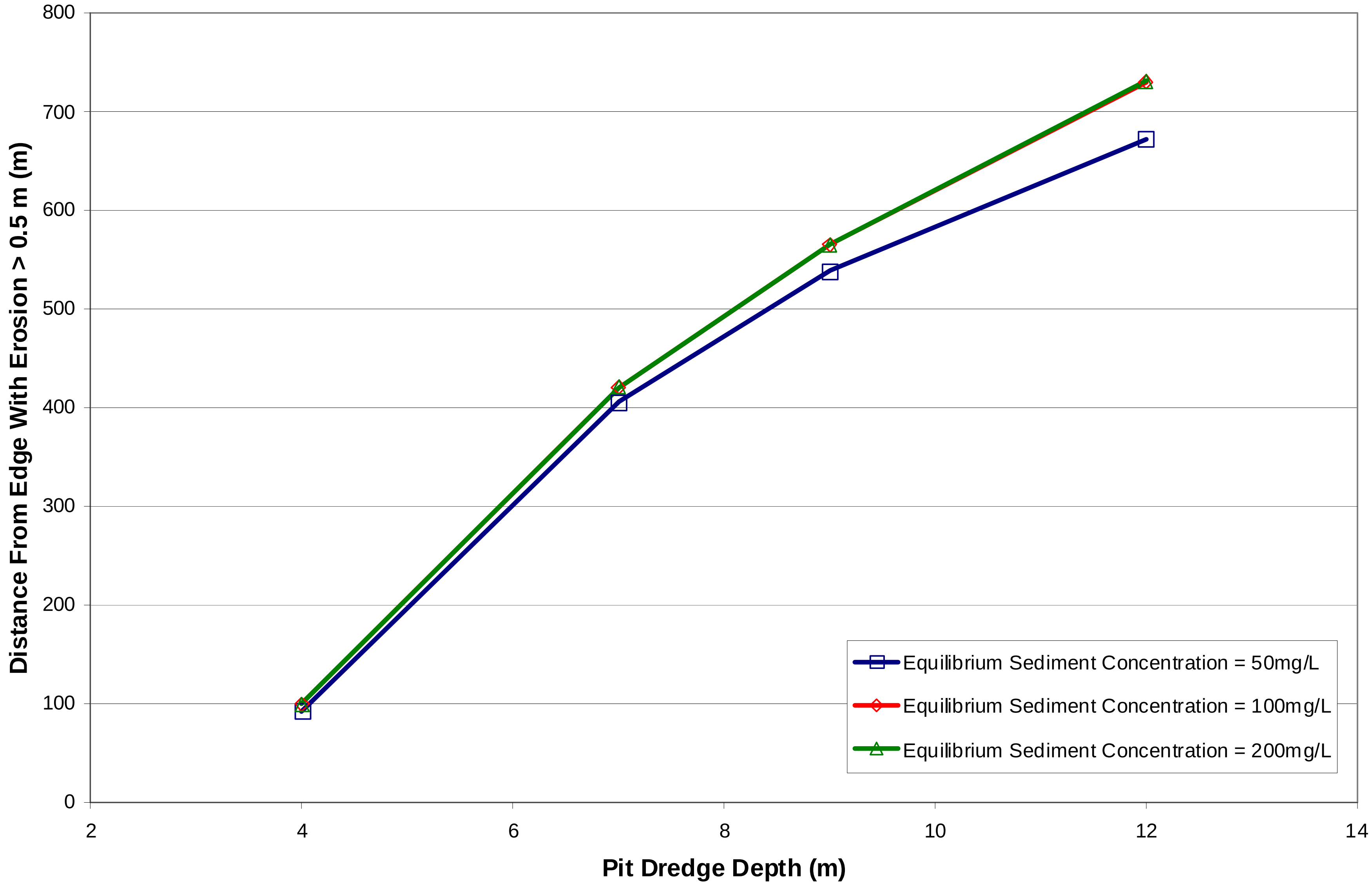

FIGURE 4.5.b. Average Pit in Muddy Setting. Distance from edge with erosion greater than 0.5 m as a function of pit dredge depth (based on estimates from an analytical approach).

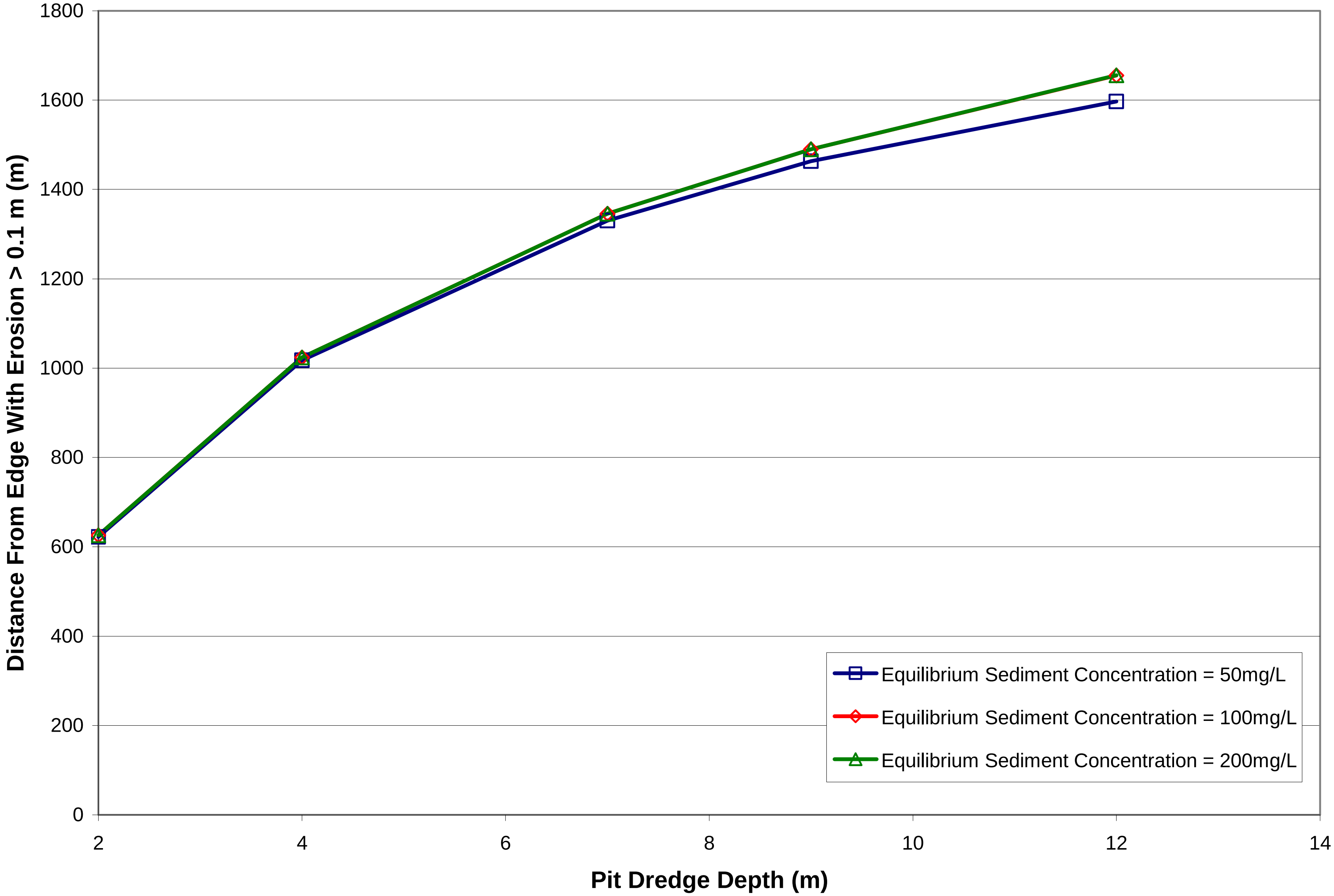

FIGURE 4.5.c. Average Pit in Muddy Setting. Distance from edge with erosion greater than 0.1 m as a function of pre-existing water depth (based on estimates from an analytical approach).

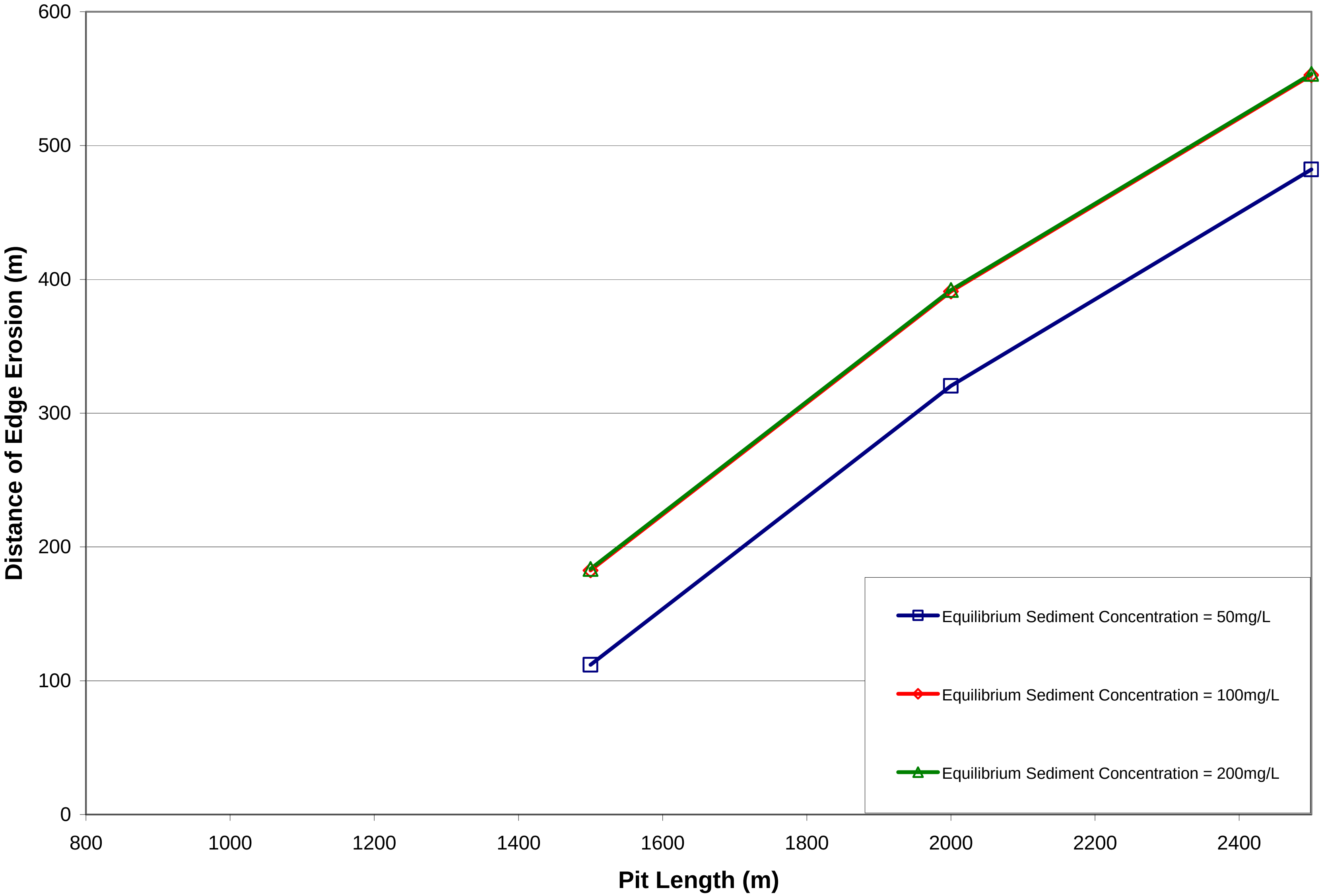

FIGURE 4.6.a. Long Pit in Muddy Setting. Distance from edge with erosion greater than 0.9 m as a function of pit length (based on estimates from an analytical approach).

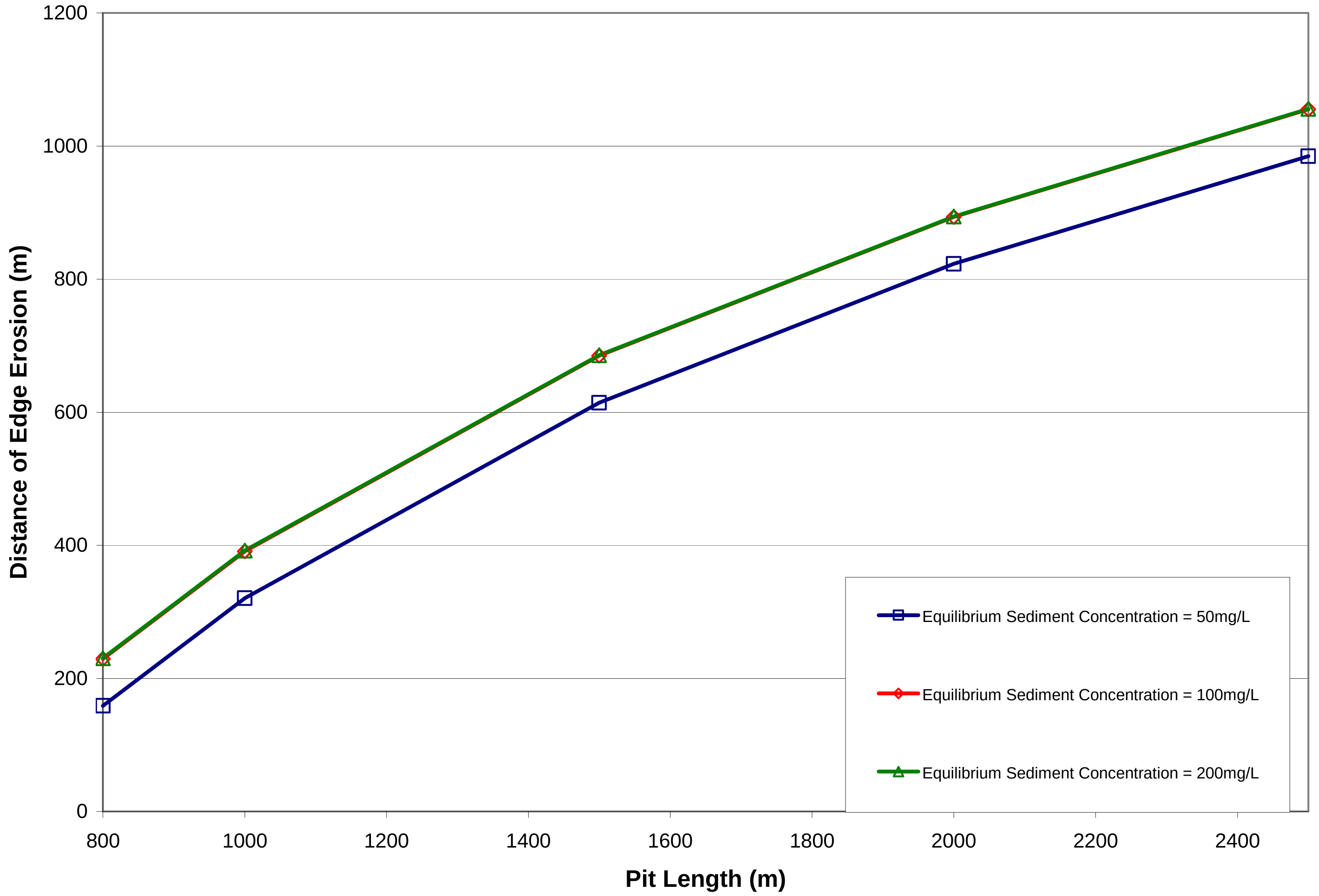

FIGURE 4.6.b. Long Pit in Muddy Setting. Distance from edge with erosion greater than 0.5 m as a function of pit length (based on estimates from an analytical approach).

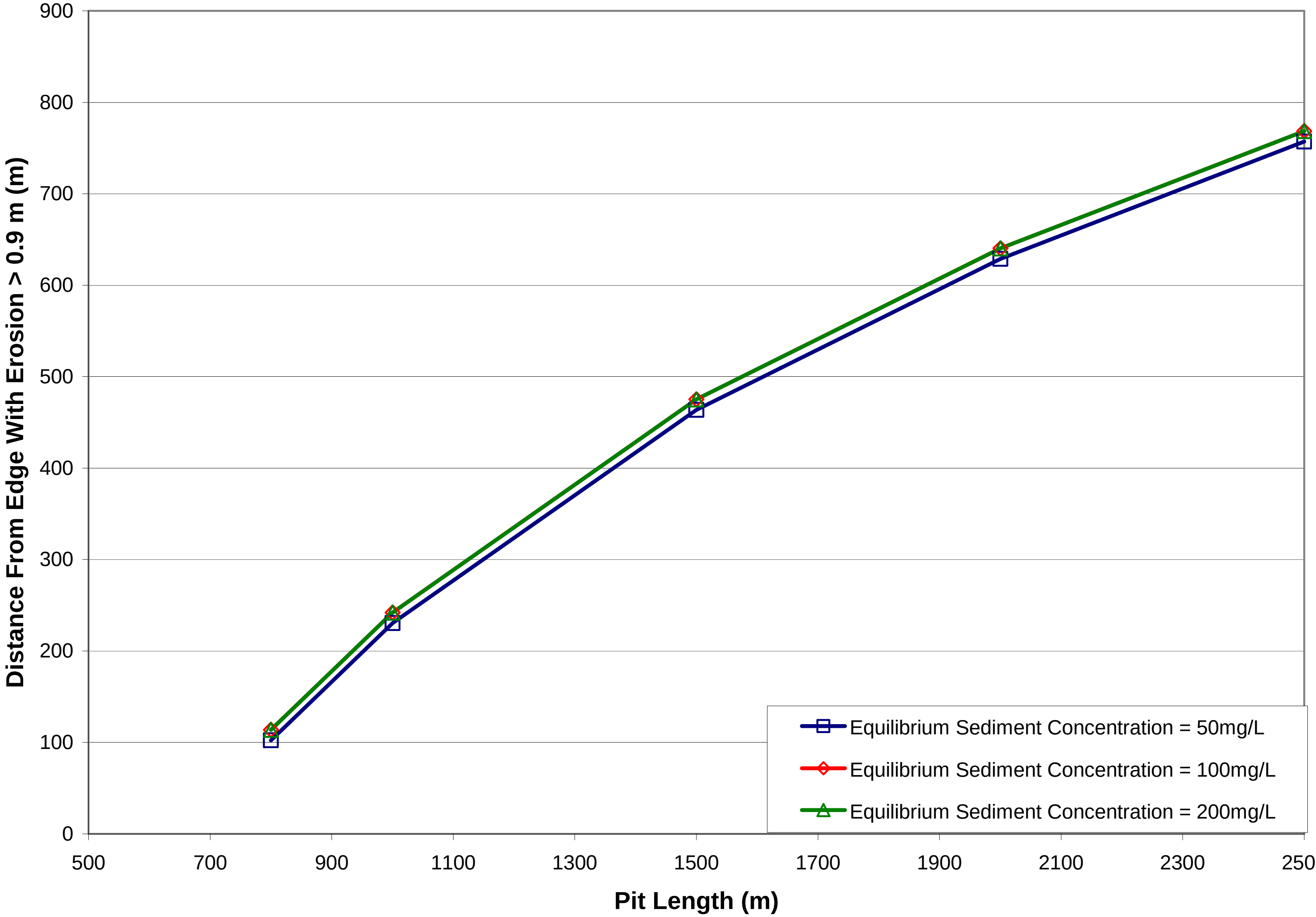

FIGURE 4.7.a. Average Pit in Muddy Setting. Distance from edge with erosion greater than 0.9 m as a function of pit length (based on estimates from an analytical approach).

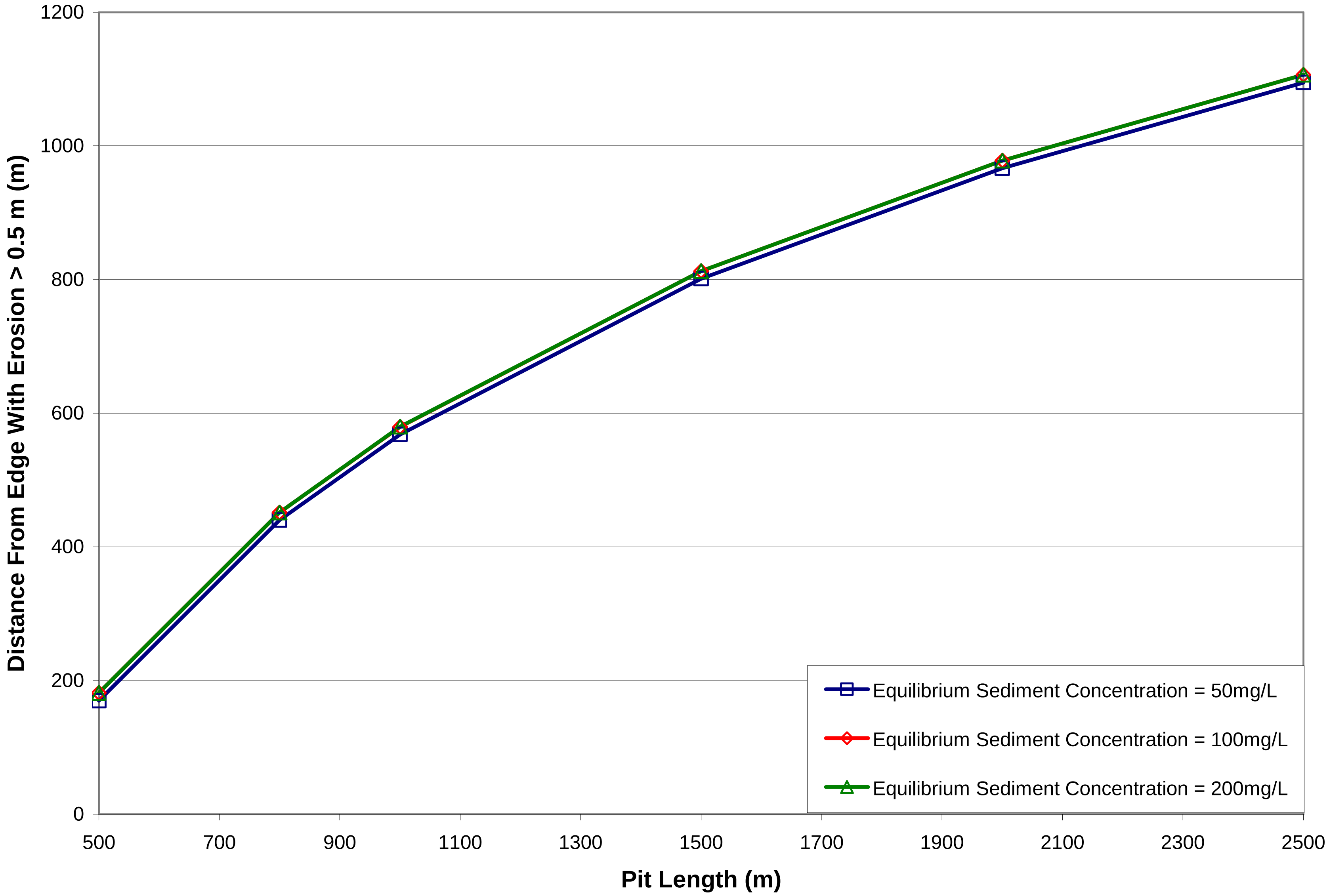

FIGURE 4.7.b. Average Pit in Muddy Setting. Distance from edge with erosion greater than 0.5 m as a function of pit length (based on estimates from an analytical approach).

5.0 CONCLUSIONS AND RECOMMENDATIONS

Buffers are required around oil and gas infrastructure on the seafloor offshore Louisiana to protect these facilities from direct or indirect damage due to offshore dredging operations.

Minimum buffer requirements are defined by navigational considerations. For submerged infrastructure (e.g., pipelines, cables, etc.) the minimum recommended buffer distance to avoid direct impact from dredging operations is 50 m. This buffer distance assumes that the pipeline position is accurately surveyed prior to final design of the borrow pit. For above water infrastructure such as platforms, a minimum buffer distance of 500 m is recommended.

The specification of buffers to avoid indirect impacts requires a decision on the acceptable level of erosion over a pipeline. Pipelines are required to have 0.9 m (3 ft) of cover over the top of the pipe when installed. There is no policy or regulation on the long-term maintenance of a minimum cover. However, if pipelines become exposed or worse, undermined, they must be immediately repaired and recovered to a depth of 0.9 m. A key recommendation is to complete a survey of the actual cover over pipelines near proposed borrow areas. This survey should be completed prior to final design of the borrow pit and will assist in defining an allowable maximum erosion over the pipeline.

Indirect impacts are associated with the potential interaction of a pit slope (for sandy pits) or pit margin zone (for muddy pits) with the cover over a pipeline, and specifically the potential for erosion. Exposure or undermining of a pipeline can lead to breakage or damage to the pipeline itself or to commercial or recreational fishing operations. Pits in sandy and muddy settings evolve in different ways and, as such, have different buffer requirements. Targeted borrow areas in federal waters offshore of Louisiana comprise both muddy and sandy settings.

Pit evolution is influenced by a wide range of variables including setting (muddy or sandy), pre-existing water depth, dredge depth, maximum pit dimension, grain size, wave climate, current conditions, and external sources of sediment load, if any.

It was found that for sandy settings and conditions with a net residual current of less than 0.3 m/s (which is believed to cover most if not all locations offshore Louisiana) erosion at the edge of sandy pits of greater than 0.5 m (or 0.9 m) will never exceed 50 m. Therefore, a 50 m buffer should be sufficient for individual pits in sandy settings offshore Louisiana. These buffers were developed using an analytical approach for sandy pits developed by Ribberink et. al. (2005) for the SANDPIT study. Although the Ribberink approach was tested against morphologic change for several pits in Europe, it has not been directly tested for the conditions of the Louisiana coast. Further testing of this approach or others that may be available is recommended. As another cautionary note, where multiple pits are dredged on either side of pipelines in sandy settings, the buffer requirements could be much larger as the updrift pit will intercept the bed load, leaving downstream pits to migrate without infilling. Buffers for these conditions should be developed on a site-specific basis with appropriate analysis.

Buffers from 50 m to 1,500 m were determined for the range of possible conditions for muddy settings offshore the Louisiana coast assuming allowable vertical erosion over a pipeline adjacent to the dredged pit in the range of 0.5 to 0.9 m. Therefore, buffers of greater than 50 m are almost always required for muddy-capped pits. For average sized pits with dimensions of 650 by 650 m (or less) and a dredged depth of 6 m (or less) in less than 10 m of water, the required buffer is generally less than 200 m and always less than 350 m for an allowable erosion over the pipe of 0.5 m. The required buffers were found to increase by 3 to 10 times (and sometimes much more) for typical conditions and 0.1 m of allowable vertical erosion limit. Therefore, if 0.5 m of temporary erosion over a pipeline is acceptable, a buffer of 350 m would be conservative for the conditions listed above. In order to avoid being overly conservative (too large a buffer) or insufficiently conservative (too small a buffer), ideally the buffer should be estimated for each site-specific situation. The allowable vertical erosion over a pipeline should be determined based on surveys of actual cover over pipelines adjacent to a proposed borrow pit. Buffers will vary in width around a pit, particularly where there is a dominant flow direction and/or a much longer pit direction in one direction. In situations where the muddy cap is completely removed by erosion, exposing the underlying sand, the buffer requirements may be reduced reverting to the sand setting recommendations.

Section 4 provided some recommendations for buffers for a range of possible conditions associated with muddy-capped pits in federal waters offshore Louisiana. These buffers were developed using an analytical approach developed specifically for this study. The muddy-capped pit approach developed in this study was tested against the limited data available for the Holly Beach dredge pit located offshore western Louisiana and against the results from a 3D numerical model for the proposed Sandy Point pit offshore the west flank of the Mississippi River delta. The $5 million SANDPIT study completed in 2005 (Van Rijn et. al., 2005) was the most comprehensive of its kind. Although this study significantly advanced the science of sediment transport and pit evolution in depths of 10 to 20 m, it recognized that existing models and formulae do not produce accurate predictions of pit evolution. Therefore, the recommendations presented in Section 4 should be applied with caution, and perhaps with some form of factor of safety.

It order to improve the understanding of pit evolution for muddy and sandy settings offshore Louisiana, it is recommended that pit evolution be monitored to provide better information to test the types of approaches used in this study to develop the recommendations for buffers to protect pipelines from indirect damage.

In areas where there is a need to maximize the useable size of a borrow deposit located close to pipelines, a site-specific study of future pit evolution is recommended based on data collection and numerical modeling.

Although not a mandate of this investigation, it is noted that mitigation measures, involving the implementation of erosion protection over buried pipelines, may be an alternative for reducing buffer requirements.

In summary, the following steps are recommended to determine required buffer distances to protect oil and gas infrastructure from indirect impacts associated with erosion beyond the post-construction edge of a dredged pit:

1. Define and suitably locate the infrastructure requiring protection within the vicinity of the proposed dredged pit.

2. Determine whether the proposed pit conditions are defined as sandy or muddy-capped.

3. For above water infrastructure such as platforms, a minimum buffer distance of 500 m is recommended.

4. Complete a survey to define the existing cover (or extent of burial) for all pipelines within 2,000 m of the edge of the proposed dredge pit for muddy-capped settings and 200 m from the edge of the proposed pit for sandy settings. This survey will provide information to assist in determining the limit for allowable vertical erosion over pipelines.

5. For a single pit in a sandy setting, a minimum buffer distance of 50 m is recommended.

6. The pipeline location should be buoyed for any cases where the buffer distance is less than 150 m.

7. Where multiple sandy pits are dredged (or planned to be dredged) in close proximity, a site-specific evaluation of the required buffer distance should be completed. Larger buffers will likely be required.

8. Section 4 of this report provides guidance for determining the required buffers around muddy-capped pits. Providing a single buffer width for all muddy-capped pits would lead to overly conservative requirements in many cases and undersized buffers in many other cases. The recommendations of Section 4 should be applied with caution and with some factor of safety as they are based on evolving science related to the morphodynamic development of dredged pits.

9. If the mud cap around the margin of a muddy-capped pit is removed through erosion processes associated with the indirect impacts of the presence of the pit, the buffer width requirements revert to those of a sandy pit setting. Where this circumstance arises a site-specific assessment of buffer requirements should be completed, as it will likely reduce the buffer width requirements.

10. Erosion protection measures to prevent removal of any cover over a pipeline may be considered to reduce the buffer width requirements.

6.0 REFERENCES CITED

Applied Coastal Research and Engineering, Inc., Continental Shelf Associates, Inc., Barry A. Vittor & Associates Inc., and Aubrey Consulting, 1999. Environmental Survey of Identified Sand Resource Areas Offshore Alabama. U.S. Department of the Interior, Minerals Management Service, Sand and Gravel Unit, Leasing Division, Herndon, VA. OCS Report MMS 1999-0051.

Bailard, J.A., 1981. An Energetics Total Load Sediment Transport Model for a Plane Sloping Beach. J. of Geophys. Res. Vol 86, No. C3. p. 2035-2043.

Baird & Associates Ltd. and Research Planning Inc., 2004. Preliminary Infrastructure Study Offshore Louisiana. U.S. Department of the Interior, Minerals Management Service, Sand and Gravel Program, Leasing Division, Herndon, VA. OCS Report MMS 2004-019, 30 pp.

Blake, N.J., Doyle, L.J. and Culter, J.J., 1995. Impacts and Direct Effects of Sand Dredging for Beach Nourishment on the Benthic Organisms and Geology of the West Florida Shelf. U.S. Department of the Interior, Minerals Management Service, Sand and Gravel Program, Leasing Division, Herndon, VA. OCS Report MMS 1995-005, 109 pp. + Appendices.

Coastal Planning & Engineering, 2002. Holly Beach Breakwater Enhancement and Sand Management Plan. Evaluation of Offshore Sand Sources Near Holly Beach, Louisiana. Report to Louisiana Dept. of Natural Resources. 27 pp. + appendices.

Galappatti, R. and Vreugdenhill, C.B., 1985. A Depth-Integrated Model for Suspended Sediment Transport. J. Hydraulic Res. Vol. 23, No. 4, p. 359-377.

Gomi, P. and Sergent, P., 2004. Presentation of the CNEXO pit dedicated to the modelers of European SANDPIT program. Report CETMEF, France.

Havinga, F.J., 1992. Sediment concentrations and sediment transport in case of irregular non-breaking waves with current. Report H480. Delft Hydraulics, Delft, The Netherlands.

HR Wallingford, 2004. Egypt LNG Review of Sediment Infill. Technical Note EBR3635-1. 28 pp.

HR Wallingford, 2002. Egypt LNG Metocean Investigation. Initial Investigation Report (Release 2.1). Report EX4442, August 2002. xiv+49 pp.

Louisiana DNR, 2004. Rejoinder for “Preliminary Infrastructure Stability Study, Offshore Louisiana (OCS Study MMS 2004-019) by Baird & Associates”. 18 pp.

Lu, Q. and Wai, O.W.H., 1998. An Efficient Operator Splitting Scheme for Three-dimensional Hydrodynamic Computations, International Journal of Numerical Methods in Fluid, 26, 771-789.

Migniot, C. and Viguier, J., 1980. Influence de l'extraction des granulats en mer sur l'equilibre du littoral. La Houille Blanche, Vol. 35, p. 177-194.

Minerals Management Service, 2004a. Environmental Assessment: Issuance of Non-competitive lease for the use of Outer Continental Shelf Sand Resources from the Ship Shoal, Offshore Central Louisiana for Coastal and Barrier Island Nourishment and Hurricane Levee Construction. U.S. Department of the Interior, Minerals Management Service, Washington, DC. 105 p. + appendices (no publication number).

MMS 2003a. Draft Stipulations for Whiskey Island Restoration Lease Agreement.

MMS 2003b. Draft Stipulations for New Cut Lease Agreement.

MMS 2004. Draft Stipulations for Pelican Island Restoration Lease Agreement.

MMS, 2004b. Damage caused by Hurricane Ivan. Notice to Lessees (NTL) and Pipeline Right-of-Way Holders in the Outer Continental Shelf, Gulf of Mexico OCS Region, New Orleans, LA.MTL.No.2004-G18.

Nikuradse, J. (1933), Stromungsgesetze in Rauhen Rohren, Forschung Arb. Ing. Wesen No. 361, West Germany

Penland, S., Boyd, R. and Suter, J.R., 1988. Transgressive depositional systems of the Mississippi Delta Plain: a model for barrier shoreline and shelf sand development. Journal of Sedimentary Petrology, 58(6): 932-949.

Pepper, D. and Stone, G.W., 2000. Part 2. Wave Climate and Bottom Boundary Layer Dynamics with Implications for Offshore Sand Mining and Barrier Island Replenishment, South-Central Louisiana. U.S. Department of the Interior, Minerals Management Service, Sand and Gravel Unit, Leasing Division, Herndon, VA. OCS Study MS 2000-053. 219 pp.

Research Planning, Inc., Tidewater Atlantic Research, Inc., and Baird & Associates Ltd., 2004. Archaeological Damage from Offshore Dredging: Recommendations for Pre-Operational Surveys and Mitigation During Dredging to Avoid Adverse Impacts. U.S. Department of the Interior, Minerals Management Service, Sand and Gravel Unit, Leasing Division, Herndon, VA. OCS Report MMS 2004-005, 75 pp. + appendices.

Ribberink, J.S., Roos, P.C. and Hulscher, J.H.M., 2005. Morphodynamics of Trenches and Pits Under the Influence of Currents and Waves – Simple Engineering Formulas. Proc. of Coastal Dynamics '05. ASCE. (in press).

Rijkswaterstaat, 2004. "Regionaal Ontgrondingenplan Noordzee 2" (=Regional Extraction Plan North Sea 2). [Ministerie van Verkeer en Waterstaat (in Dutch). Rijkswaterstaat, Directie Noordzee.].

Royal Haskoning, 2004. Marine Aggregate Extraction: Approaching Good Practice in Environmental Impact Assessment. A report prepared for the Mineral Industry Research Organization (MIRO) and the UK Office of the Deputy Prime Minister. 261 p. + appendices.

Schapery & Dunlap, 1978, "Prediction of Storm Induced Sea Bottom Movement and Platform Forces, Proceedings, Offshore Technology Conference, Houston.

Soloviev, A, Luther, M.E. and Weisberg, R.H., 2003. Energetic baroclinic super-tidal oscillations on the shelf off Southeast Florida. Geophysical Research Letters, 30, No. 9, 1463, doi:10.1029/202GL016603.

Sumer, B.M. and Fredsoe, J. 2002. The Mechanics of Scour in the Marine Environment. Advanced. Series in Ocean Engineering – Vol. 17. World Scientific.

Svasek, J.N., 2001. PUTMOR, Field Measurements at a temporary sand pit. Parts 1, 2, 3. Rotterdam.

Svasek, J.N., 1964. Behaviour of trial dredge trench in the sea bed of the North Sea near Scheveningen (in Dutch). Report Deltadienst, the Hague, The Netherlands.

Van Dolah, R.F., Digre, B.J., Gayes, P.T. Donovan-Ealy, P. and Dowd, M.W., 1998. An Evaluation of Physical Recovery Rates in Sand Borrow Sites Used for Beach Nourishment Projects in South Carolina. Final Report submitted to The South Carolina Task Force on Offshore Resources and the Minerals Management Service, Office of International Activities and Marine Minerals. 77 pp. + Appendices.

Van Rijn, L.C., Soulsby, R.L., Hoekstra, P. and Davies, A.G., (editors). 2005. SANDPIT, Sand Transport and Morphology of Offshore Sand Mining Pits. Process knowledge and guidelines for coastal management. End Document, May 2005. Part 1. EC Framework V Project No. EVK3-2001-00056. Aqua Publications, The Netherlands.

Van Rijn, L.C., 2004. Principles of Sedimentation and Erosion Engineering in Rivers, Estuaries and Coastal Seas. Aqua Publications. ISBN:90-800356-6-1.

Van Rijn, L.C., 1986. Sedimentation of dredged channels by currents and waves. J. Waterway, Port, Coastal and Ocean Engineering, Vol. 112, No. 5, p. 541-559.

Walstra, D.J.R., Van Rijn, L.C., Boers, M. and Roelvink, D., 2003. Offshore Sand Pits: Verification and Application of a Hydrodynamic and Morphodynamic Model. Proc. of Coastal Sediments 2003, ASCE.

Walstra, D.J.R., Van Rijn, L.C., Hoogewoning, S.E. Aarninkhof, S.G.J., 1999. Modelling of Sedimentation of Dredged Trenches and Channels Under the Combined Action of Tidal Currents and Waves. Proc. of Coastal Sediments 1999, ASCE. p. 2355-2370.

Wright, L.D., Sherwood, C.R. and Sternberg, R.W., 1997. Field measurements of fairweather bottom boundary layer processes and sediment suspension on the Louisiana continental shelf. Marine Geology, 140: 329-345.

APPENDIX A:
REPORT BY PEGASUS INTERNATIONAL ON PIPELINE CONDITIONS AND CHARACTERISTICS

BAIRD & ASSOCIATES

FEDERAL WATER
DREDGING PROJECT

GENERAL REVIEW OF PIPELINE CONDITIONS AND CHARACTERISTICS

A	Issued for Comments	01/21/05	O. Mauvoisin	J. Hines	J. Hines		
Rev	**Description**	**Date**	**Originator**	**Checker**	**Project Approval**	**Pegasus Approval**	**Client Approval**

DOCUMENT NO.: 3406-197-ST-001

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1.0 INTRODUCTION

1.1 General

The Minerals Management Service (MMS) requested an assessment of the potential impact of proposed sand dredging projects on the Outer Continental Shelf in water depths of 10 to 20 m (for land reclamation and beach nourishment) on existing oil and gas infrastructure in the Gulf of Mexico. Over the next couple of years it is expected that 10 to 20,000,000 m3 will be dredged. Baird & Associates is performing analyses through the application of numerical models that look at stability of the sea bed once the sediment has been removed.

Pegasus International Inc has been contracted by Baird and Associates to provide its expertise in understanding general conditions and the extent to which pipelines can or cannot withstand scour.

1.2 Scope

The scope of this report is to review the following factors and questions based on Pegasus extensive experience with oil and gas infrastructure design and maintenance projects in the Gulf of Mexico:

- What types of oil and gas infrastructure may be susceptible to damage related to direct or indirect impacts of dredging and in what ways (this study is restricted to impacts in Federal Waters)?
- What is the precision of pipeline mapping for planned, as-builts, and resurveyed locations (there have been a couple instances of dredges hitting pipelines that were not well mapped)?
- Has this changed through time with improvements in survey precision, are pipelines resurveyed to take advantage of improvements in survey accuracy?
- What is known, is it necessary to complete survey of the full extent of every borrow deposit to look for pipelines that may not be mapped?
- Condition of pipeline burial or spanning and mitigation measures.
- What is design requirement for burial in different situations;
- Is a consideration given during design to natural erosion processes (and the influence on burial)?
- To what extent can pipelines self bury when undermined?
- Is mapping available providing information on pipeline invert (as-built or periodic update)?

- Is mapping or documentation of spanning available and to what extent is this known (is there a chance there are many areas unmapped)?
- How widespread is spanning and is it prevalent and perhaps impacts of dredging may be small/local issue and/or may get blamed for existing spanning?
- In general terms when does this become an issue (there are two perspectives here:

    i) are there instances where this goes unnoticed and then must be repaired in very short order – i.e. are there instances of failure from spanning?

  ii) how much spanning can be sustained)
- What are mitigation measures (scour protection aprons?), approximate costs and how prevalent is implementation?

2.0 PIPELINE CONDITIONS AND CHARACTERISTICS

2.1 General

There are several oil and gas infrastructure types that may be susceptible to damage related to direct or indirect impacts of dredging. The first type is a structure fixed to the seabed (platforms, caissons, old wells shut off). The second type is a line. It can be a pipeline, an umbilical or a power cable.

The first is accurately located on maps. However, the second type can be more difficult to locate since its position relies on surveys.

Directional drilling is normally used for pipeline shore approaches to carry the pipeline to the shoreline. This drillings are generally less than 1 mile long.

2.2 MMS Requirements

The MMS requires that in federal shallow waters (less than 200ft), all lines (cables, umbilical, pipelines, etc…) have to be buried.

Pipeline burial is at least 3 feet below the existing mud line. Top of pipe must be a minimum of 3 feet below mud line.

Trenching of a pipeline may be achieved by laying the pipe into a pre-cut trench or trenching after lay of the pipeline. There are a number of different types of trenching equipment including ploughs and jet sleds. The trench will be naturally filled with sand to establish the required 3 feet of cover.

Since the pipeline is in a trench, there is no spanning problem, no post-installation mitigation measures are required.

It is correct to assume that all the existing pipelines laid in shallow waters in the GOM have been trenched.

In areas where pipeline cover has been lost to erosion and is exposed, the policy is to have the line reburied, however, covering the exposed line with grout bags, riprap, or similar materials can be considered on a case-by-case basis.

Operators would only consider a survey of their pipelines if the MMS specifically requires it in a corridor after a severe weather event, or if operators realize pipelines do not operate as expected. However, when additional work is performed on the pipelines after which the pipelines are still located within their rights of way (200ft wide), notification to the MMS of the new pipeline locations is not required.

In the case of a pipeline crossing, there should be a separation of 18 inches (usually 2 concrete mattresses, 9 inch high each) between the 2 pipelines. The top pipeline still requires 3 feet of cover. This can be achieved with mattresses and/or concrete bags.

2.3 Pipeline Survey and Mapping

The way pipelines in the GOM have been as-built surveyed historically has been by triangulation using land survey instruments positioning the laybarge.

For post installation surveys, a magnetometer is towed 2 to 3 boat lengths behind the survey vessel. The device is assumed at a constant position behind the vessel. The pipeline coordinates are then derived from the coordinates of the vessel.

Vessel coordinates are nowadays obtained with a GPS device. Most of the inaccuracies come from the precision of the magnetometer itself and its real position relative to the survey vessel. The inaccuracies in data, if it had to be guessed, are 10, 20m at a minimum. It should be noted that in some cases, pipelines were found 1 mile away from the position indicated on the map.

In order to determine the number of pipelines that have been surveyed using old versus new method, with the associated accuracy of it, it would require a search of MMS data..

In deeper water, accuracies have become better. However, methods to locate buried pipelines in shallow waters are pretty much the same. Operators are not required to do regular surveys. Operators would only consider a survey of their pipelines if MMS specifically requires it in a corridor after a severe event, or if operators realize pipelines do not operate as expected.

Operators are required to provide the MMS with maps of the pipelines from the post–installation surveys. All pipelines are then mapped. For dredging operations, it is not required to perform a pre-survey to look for unmapped pipelines. However, it is good practice to do it. For example, prior to pipeline installation, a route survey is required. It allows identifying any potential debris, getting an accurate seabed profile of the route and pinpointing the eventual pipeline crossings.

A complete survey of the borrow area would be useful to locate potential debris and lines.

Operators are not required to provide the MMS with as-built pipeline profiles. Only pipeline routes are required. Pipelines are assumed to have at least 3 feet of cover.

Mapping or documentation of spanning is not available. The pipelines have to be covered by law. Any discovered span has to be immediately repaired. Any exposed pipeline has to be covered.

The best recommended practice is to do a dredging site clearance survey. The full area should be surveyed using a magnetometer (provides x and y of any metallic object on seabed or buried), a side-scan (locates visible debris, exposed pipelines), a sub-bottom (depth of an buried objects) and a bathymetry. The bathymetry survey would be performed before and after the dredging to calculate accurately the quantity of borrowed sand. Buoy the pipelines found and create a local GIS for the dredge area.

2.4 Exposed Pipelines and Mitigation Measures

Natural erosion during pipeline design is not typically considered in the GOM. However, it would be a good practice, if you consider working in a sand bar area. It would be considered in a shore approach.

Pipelines can self-bury in granular soils but only in very specific conditions. The sand has to have a specific grain size and the surrounding water to be at a specific velocity. However, it is not known to occur in the GOM.

Exposed pipeline is rare in the GOM, let alone spanning. The shallow areas are very flat, spanning should not occur. The pipelines are simply assumed buried. If spanning is discovered close to an area where dredging was performed, dredging might then be blamed for the spanning. A look at the seabed slope between the dredged area and the spanning area can prove/disprove it. Therefore, it is recommended to perform a pre-survey of the pipelines to know their conditions.

The allowable span length for a given pipeline varies from a few meters to more than 30 meters. It depends on the pipeline properties (diameter, grade, wall thickness), the environmental loading (wave, current) and the seabed (type of soil, gap below pipeline, type of restraints at ends of span). The limiting factor is the bending stress that occurs at the ends of the span and in the sagbend when the pipeline is sagging (static)or when it is vibrating due to vortex shedding (dynamic). A pipeline fails from spanning when it is overstressed in bending (plastically deformed).

It is difficult to notice such failure unless the pipeline is leaking and there is a loss of pressure or a survey is performed.

If the pipeline is overstressed (can be determined by its curvature), the concerned section has to be propped using sand bags or mattresses and reburied or covered with sand bags or mattresses. In the extreme case where the pipeline has excessive yielding due to a pipe free span, the only applicable corrective action may be to cut out the yielded position and replace it. If the pipeline is spanning but not overstressed, it is to be covered again with at least 3 feet of material.

An approximate cost to prop a pipeline would $50,000.00. This includes the cost of the mattresses, the use of a diving spread and the divers, but it does not include the mobilization/demobilization of the spread. The operation should last a couple of days.

Replacing a section of a pipeline would cost much more, at least $200,000.00. This estimation does not include compensations for the pipeline shut-down (loss of production) and potential lawsuits.

3.0 CONCLUSION

It is recommended that a survey is undertaken of the proposed dredging area and the surrounding area prior to commencing operations. Typically, the survey would include magnetometer, side-scan, sub-bottom and bathymetry.

APPENDIX B:
WIS STATION DATA PROVIDING WAVE CLIMATES

SANDY POINT PIT-WIS STATION 132
BLOCK 88 PIT-WIS STATION 125
HOLLY BEACH PIT-WIS STATION 94

WIS Station #125

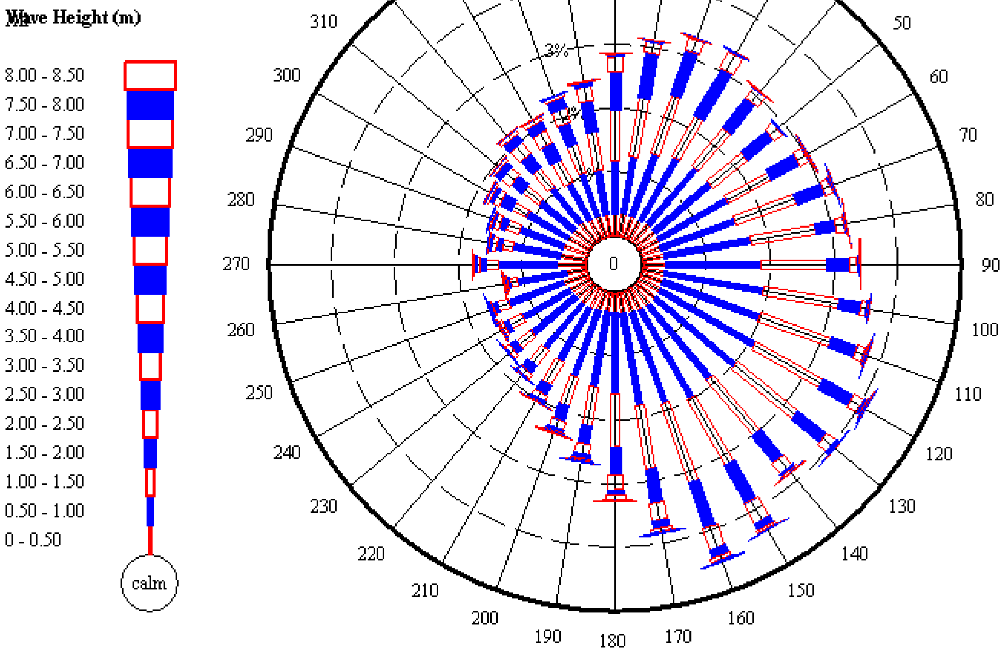
Depth =18m

Current Time Interval:

01 Jan, 1980 to 31 Dec, 1999

Season Selection:

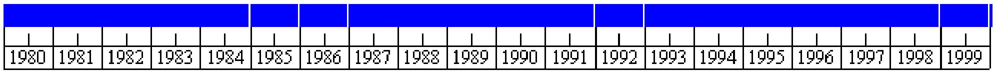
All



Time Series Legend:

Equal or < 85 % ☐ Between 85 and 95 % 🟨 Equal or > 95 % 🟦

Minimum Scale Rate: 30 days



WIS Station #125

Depth =18m

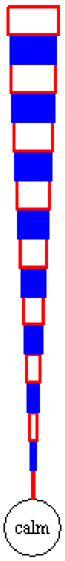
Current Time Interval:

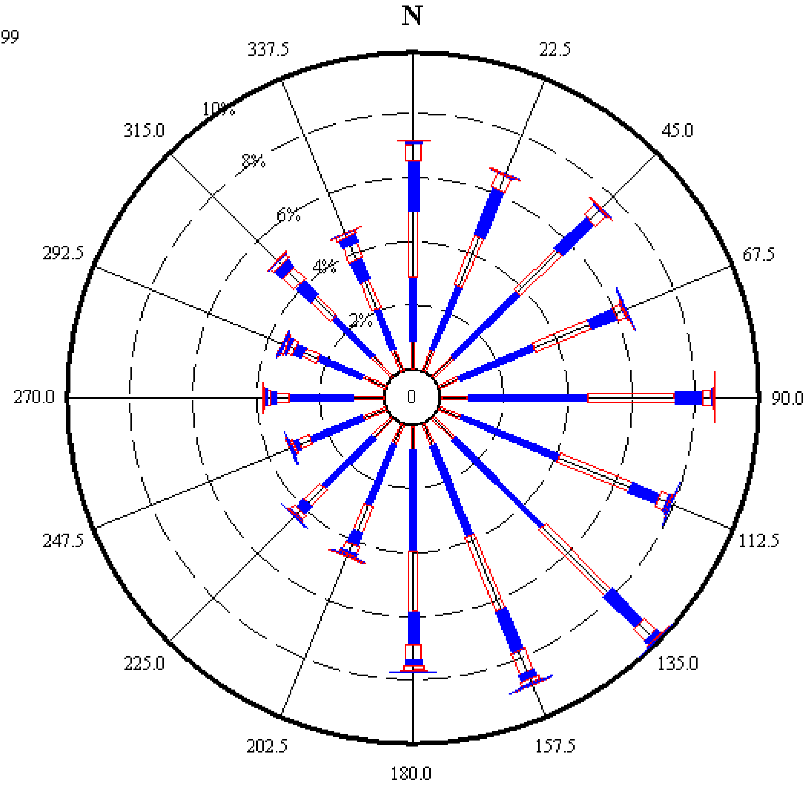
01 Jan, 1980 to 31 Dec, 1999

Season Selection:

Wave Height (m)

8.00 - 8.50
7.50 - 8.00
7.00 - 7.50
6.50 - 7.00
6.00 - 6.50
5.50 - 6.00
5.00 - 5.50
4.50 - 5.00
4.00 - 4.50
3.50 - 4.00
3.00 - 3.50
2.50 - 3.00
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0 - 0.50

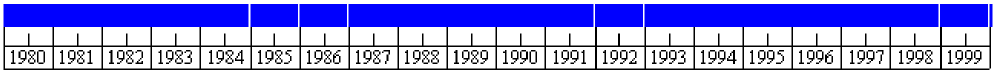




Time Series Legend:

Equal or < 85 % ☐ Between 85 and 95 % 🟨 Equal or > 95 % 🟦

Minimum Scale Rate: 30 days



WIS Station #125
Wave Height Frequency Distribution By Direction
Depth =18m
Date Range: 01 Jan 1980 01AM to 31 Dec 1999 06PM
Season: All

	Wave Height Frequency Distribution (%)																		Maximum
Direction	0.00-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	6.0-6.5	6.5-7.0	7.0-7.5	7.5-8.0	8.0-8.5	Total	Height
0.0	0.34	0.83	0.80	0.61	0.23	0.05	0.00	0.00	0.00	0.00	0.00							2.86	5.30
10.0	0.37	0.89	0.94	0.72	0.17	0.02	0.00	0.01	0.00	0.00	0.00							3.12	5.41
20.0	0.35	1.04	0.97	0.75	0.21	0.01	0.00	0.00	0.00	0.00	0.00							3.32	5.30
30.0	0.34	1.13	0.71	0.85	0.30	0.02	0.00	0.00	0.00	0.00								3.37	4.64
40.0	0.37	1.14	0.76	0.60	0.18	0.03	0.00	0.00	0.00		0.00							3.09	5.26
50.0	0.36	1.14	0.70	0.51	0.17	0.02	0.00	0.01										2.91	3.95
60.0	0.34	1.24	0.76	0.50	0.15	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			3.03	7.38
70.0	0.32	1.24	1.00	0.46	0.13	0.03	0.01	0.01	0.00	0.00	0.00					0.00		3.20	7.81
80.0	0.34	1.38	1.01	0.32	0.14	0.01	0.02	0.01								0.00	0.00	3.24	8.02
90.0	0.34	1.51	1.02	0.36	0.12	0.03	0.01	0.01	0.00	0.00							0.00	3.39	8.03
100.0	0.34	1.58	1.19	0.36	0.09	0.03	0.02	0.01	0.00	0.00								3.61	4.90
110.0	0.35	1.60	1.19	0.43	0.12	0.03	0.02	0.02	0.00		0.00	0.00				0.00		3.76	7.97
120.0	0.37	1.70	1.22	0.54	0.17	0.05	0.02	0.01	0.00			0.00	0.00			0.00		4.08	7.74
130.0	0.38	1.64	1.22	0.57	0.18	0.04	0.01	0.01	0.00					0.00		0.00		4.04	7.58
140.0	0.37	1.50	1.12	0.54	0.20	0.05	0.03	0.01	0.00			0.00	0.00					3.82	6.20
150.0	0.36	1.59	1.19	0.68	0.34	0.12	0.04	0.02				0.00	0.00	0.00		0.00		4.35	7.67
160.0	0.36	1.50	1.31	0.75	0.35	0.14	0.07	0.01	0.01	0.00	0.00	0.00		0.00		0.00		4.50	7.95
170.0	0.32	1.47	1.02	0.53	0.28	0.11	0.06	0.01	0.01	0.00		0.00		0.00		0.00		3.82	7.67
180.0	0.30	1.27	0.83	0.44	0.23	0.09	0.06	0.01	0.01	0.00	0.00	0.00		0.00	0.00			3.26	7.39
190.0	0.31	1.19	0.61	0.29	0.15	0.07	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00				2.69	6.85
200.0	0.32	1.09	0.48	0.25	0.14	0.05	0.02	0.01	0.00	0.00	0.00	0.00	0.00					2.36	6.40
210.0	0.35	0.94	0.41	0.17	0.10	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00					2.03	6.03
220.0	0.34	0.92	0.31	0.15	0.07	0.03	0.01	0.01	0.00	0.00								1.83	4.53
230.0	0.35	0.89	0.28	0.12	0.06	0.03	0.01	0.00	0.00			0.00						1.74	5.99
240.0	0.37	0.85	0.23	0.08	0.04	0.02	0.01	0.00	0.00									1.61	4.27
250.0	0.40	0.92	0.17	0.07	0.04	0.02	0.01	0.00				0.00						1.64	5.59
260.0	0.33	0.77	0.12	0.04	0.02	0.02	0.01	0.00	0.00									1.32	4.16
270.0	0.45	0.93	0.20	0.10	0.06	0.04	0.02	0.00	0.00		0.00							1.80	5.13
280.0	0.42	0.75	0.17	0.09	0.07	0.04	0.03	0.01										1.59	3.98
290.0	0.40	0.74	0.21	0.11	0.07	0.05	0.04	0.01		0.00								1.63	4.53
300.0	0.40	0.74	0.26	0.19	0.10	0.08	0.04	0.03	0.00									1.83	4.07
310.0	0.39	0.69	0.32	0.21	0.17	0.11	0.05	0.02	0.00									1.96	4.06
320.0	0.40	0.70	0.37	0.26	0.22	0.16	0.07	0.01	0.01									2.20	4.19
330.0	0.36	0.63	0.41	0.30	0.23	0.14	0.07	0.01	0.00									2.16	4.49
340.0	0.35	0.71	0.46	0.37	0.24	0.16	0.06	0.00		0.00								2.36	4.64
350.0	0.34	0.70	0.62	0.48	0.24	0.06	0.01	0.00	0.00	0.00	0.00							2.46	5.19
Totals	12.90	39.55	24.60	13.79	5.78	2.03	0.88	0.30	0.08	0.03	0.01	0.02	0.01	0.01	0.00	0.00	0.00		
Cum.	12.9	52.5	77.1	90.8	96.6	98.6	99.5	99.8	99.9	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0		

Total Calm Hours: 0 Percent: 0.00 %

Total Missing Hours: 0 Percent: 0.00 %

Frequency rounded to two decimal places (ie 0.001 shown as 0.00)

WIS Station #125
Wave Period Frequency Distribution By Direction
Depth =18m
Date Range: 01 Jan 1980 01AM to 31 Dec 1999 06PM
Season: All

	Wave Period Frequency Distribution (%)																Maximum
Direction	2.00-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	9.0-10.0	10.0-11.0	11.0-12.0	12.0-13.0	13.0-14.0	14.0-15.0	15.0-16.0	16.0-17.0	Total	Period
0.0		0.39	1.40	0.88	0.12	0.04	0.01	0.00	0.01	0.00	0.00	0.00				2.86	13.28
10.0		0.40	1.72	0.85	0.10	0.02	0.01	0.01	0.01	0.01	0.00	0.00				3.12	13.52
20.0		0.39	1.81	0.99	0.09	0.03	0.00	0.01	0.00	0.00						3.32	11.98
30.0		0.43	1.50	1.32	0.10	0.02	0.00	0.00	0.00	0.00						3.37	11.78
40.0		0.42	1.50	1.04	0.10	0.02	0.01	0.00	0.00							3.09	10.68
50.0		0.43	1.44	0.90	0.09	0.04	0.01	0.01	0.00							2.91	10.39
60.0		0.44	1.55	0.91	0.11	0.02	0.01	0.00	0.00	0.00						3.03	11.05
70.0		0.40	1.59	0.98	0.17	0.04	0.01	0.00	0.00	0.00						3.20	11.34
80.0		0.41	1.68	0.90	0.21	0.04	0.00			0.00						3.24	11.54
90.0		0.44	1.74	0.93	0.23	0.03	0.01	0.00		0.00						3.39	11.68
100.0		0.44	1.83	1.08	0.21	0.04	0.01									3.61	8.82
110.0		0.45	1.90	1.11	0.22	0.06	0.01	0.01	0.00	0.00						3.76	11.96
120.0		0.52	1.99	1.18	0.30	0.06	0.03	0.01	0.00	0.00	0.00					4.08	12.30
130.0		0.49	1.93	1.25	0.31	0.05	0.01	0.00	0.00	0.00	0.00					4.04	12.60
140.0		0.41	1.79	1.19	0.35	0.06	0.01	0.00	0.00							3.82	10.26
150.0		0.42	1.97	1.25	0.56	0.11	0.03	0.01	0.00		0.00					4.35	12.50
160.0		0.44	1.86	1.42	0.60	0.15	0.02	0.01	0.00		0.00					4.50	12.03
170.0		0.43	1.69	1.05	0.47	0.15	0.03	0.01	0.00	0.00						3.82	11.69
180.0		0.40	1.44	0.86	0.38	0.13	0.02	0.01	0.00	0.00						3.26	11.40
190.0		0.40	1.26	0.61	0.29	0.09	0.03	0.01	0.00							2.69	10.85
200.0		0.37	1.13	0.52	0.24	0.06	0.03	0.01	0.00							2.36	10.22
210.0		0.35	1.04	0.39	0.18	0.05	0.01	0.01								2.03	9.96
220.0		0.37	0.93	0.35	0.14	0.03	0.01	0.00								1.83	9.81
230.0		0.41	0.86	0.31	0.11	0.03	0.01	0.00								1.74	9.74
240.0		0.36	0.88	0.23	0.10	0.03	0.01	0.00								1.61	9.51
250.0		0.41	0.89	0.23	0.08	0.03	0.01	0.00								1.64	9.38
260.0		0.37	0.72	0.14	0.06	0.03	0.01	0.00								1.32	9.38
270.0		0.49	0.87	0.24	0.13	0.06	0.01	0.00								1.80	9.27
280.0		0.40	0.74	0.24	0.13	0.07	0.02	0.00								1.59	9.13
290.0		0.42	0.71	0.25	0.14	0.07	0.03	0.00								1.63	9.08
300.0		0.42	0.73	0.37	0.18	0.10	0.03	0.00								1.83	9.37
310.0		0.38	0.75	0.46	0.27	0.08	0.01	0.00								1.96	9.73
320.0		0.39	0.79	0.54	0.39	0.08	0.01	0.00	0.00							2.20	10.45
330.0		0.35	0.76	0.59	0.39	0.06	0.01	0.00	0.00	0.00						2.16	11.39
340.0		0.35	0.87	0.65	0.41	0.06	0.00	0.01	0.00	0.00						2.36	11.54
350.0		0.34	1.09	0.76	0.20	0.04	0.01	0.01	0.00	0.00						2.46	11.70
Totals	0.00	14.73	47.36	26.98	8.15	2.05	0.48	0.15	0.05	0.03	0.01	0.00	0.00	0.00	0.00		
Cum.	0.0	14.7	62.1	89.1	97.2	99.3	99.8	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0		

Total Calm Hours: 0	Percent: 0.00 %
Total Missing Hours: 0	Percent: 0.00 %

Frequency rounded to two decimal places (ie 0.001 shown as 0.00)

WIS Station #125
Wave Period Frequency Distribution By Height (All)
Depth =18m
Date Range: 01 Jan 1980 01AM to 31 Dec 1999 06PM
Season: All

Wave	Wave Period Frequency Distribution (%)														Maximum
Height	2.00-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	9.0-10.0	10.0-11.0	11.0-12.0	12.0-13.0	13.0-14.0	14.0-15.0	Total	Period
0.00-0.5		5.18	6.69	0.89	0.13	0.01								12.90	7.64
0.5-1.0		9.55	26.68	3.01	0.27	0.03	0.01	0.00						39.55	9.15
1.0-1.5		0.00	13.22	10.52	0.75	0.07	0.02	0.01						24.60	9.53
1.5-2.0			0.76	10.73	2.14	0.14	0.01	0.01	0.00					13.79	10.10
2.0-2.5				1.78	3.54	0.41	0.03	0.01	0.01	0.00				5.78	11.33
2.5-3.0				0.05	1.18	0.71	0.07	0.01	0.00	0.00				2.03	11.76
3.0-3.5					0.14	0.57	0.15	0.01	0.00	0.00				0.88	11.41
3.5-4.0					0.00	0.10	0.16	0.03	0.01	0.01	0.00			0.30	12.27
4.0-4.5						0.00	0.03	0.03	0.01	0.01	0.00			0.08	12.89
4.5-5.0							0.01	0.01	0.01	0.00	0.00	0.00		0.03	13.49
5.0-5.5							0.00	0.01	0.00			0.00		0.01	13.52
5.5-6.0							0.00	0.01	0.00					0.02	10.22
6.0-6.5								0.00	0.01					0.01	10.57
6.5-7.0									0.01					0.01	10.85
7.0-7.5										0.00				0.00	11.40
7.5-8.0										0.00	0.00			0.00	12.60
8.0-8.5										0.00				0.00	11.68
Totals	0.00	14.73	47.36	26.98	8.15	2.05	0.48	0.15	0.05	0.03	0.01	0.00	0.00		
Cum.	0.0	14.7	62.1	89.1	97.2	99.3	99.8	99.9	100.0	100.0	100.0	100.0	100.0		

Total Calm Hours: 0	Percent: 0.00 %
Total Missing Hours: 0	Percent: 0.00 %

Frequency rounded to two decimal places (ie 0.001 shown as 0.00)

WIS Station #094

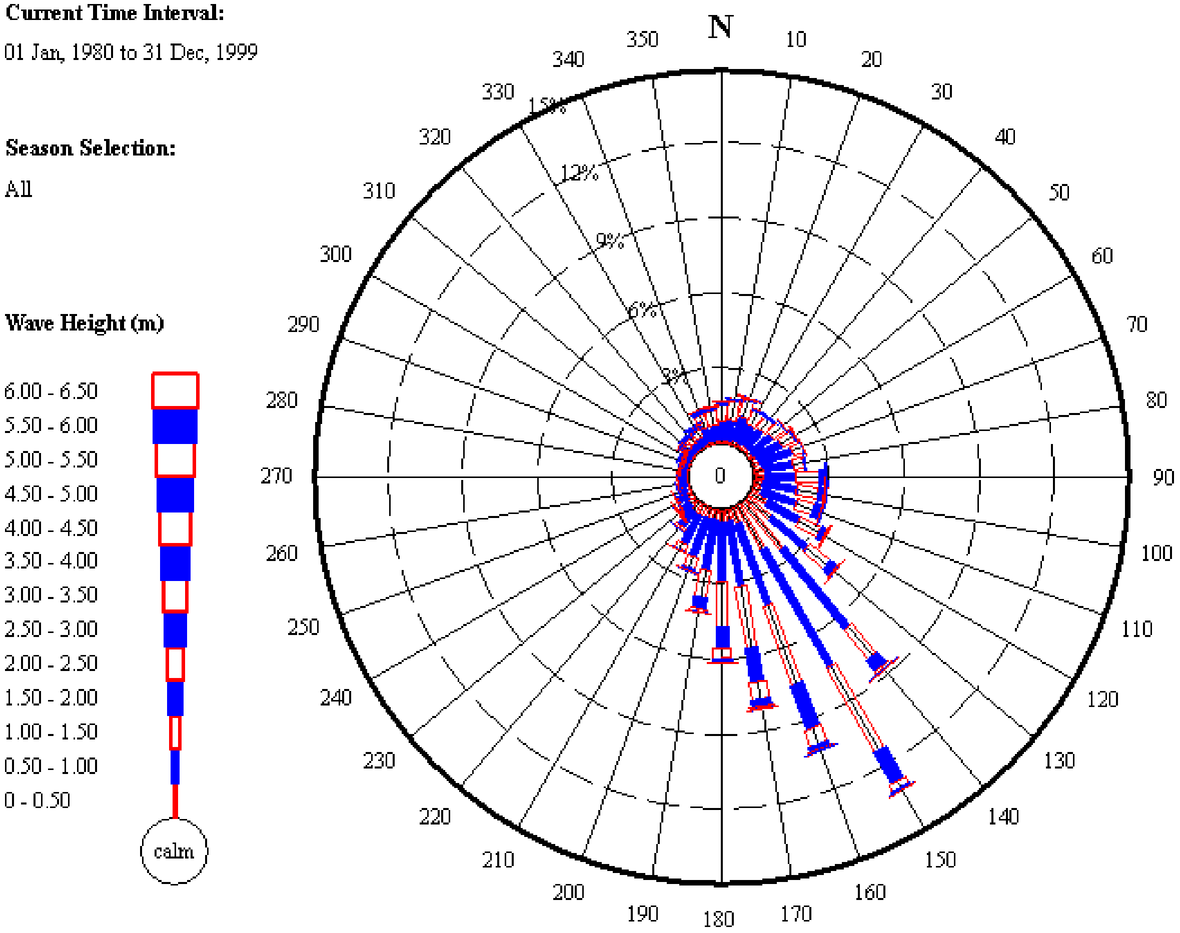
Depth =11m

Current Time Interval:

01 Jan, 1980 to 31 Dec, 1999

Season Selection:

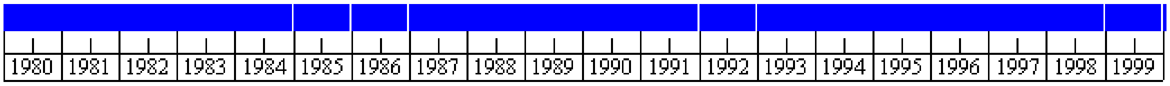
All



Time Series Legend:

Equal or < 85 % ⬜ Between 85 and 95 % 🟨 Equal or > 95 % 🟦

Minimum Scale Rate: 30 days



WIS Station #094

Depth =11m

Current Time Interval:

01 Jan, 1980 to 31 Dec, 1999

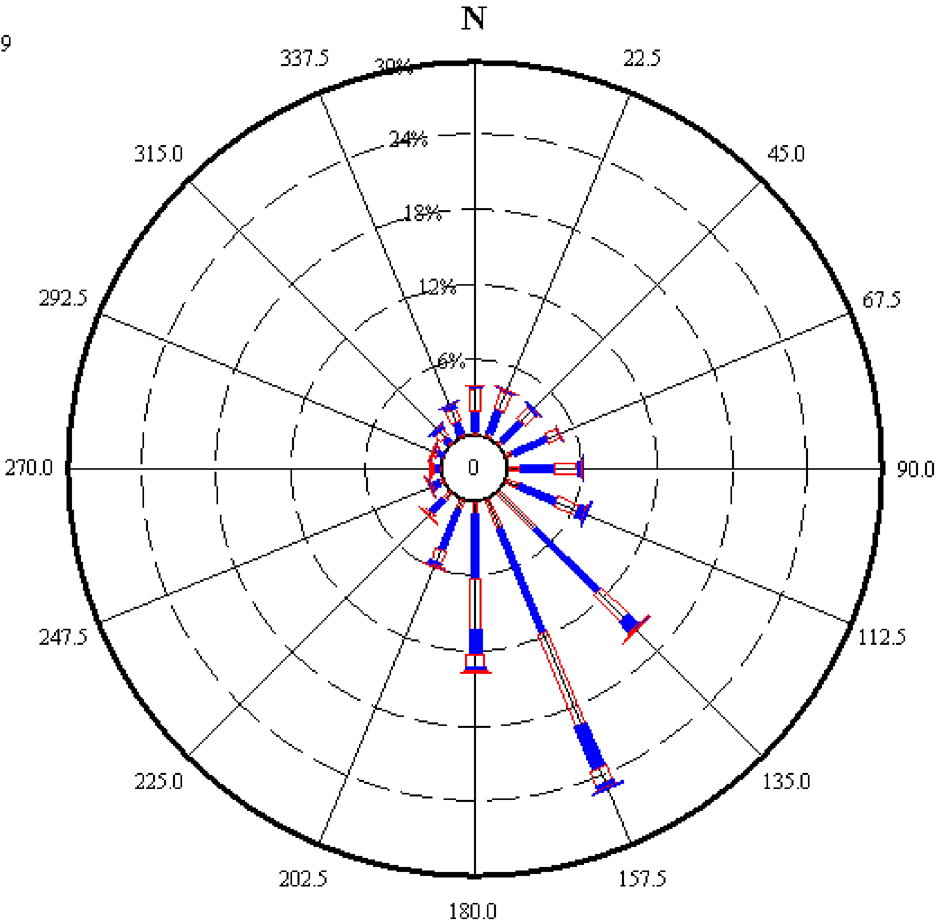
Season Selection:

All

Wave Height (m)

6.00 - 6.50	☐
5.50 - 6.00	■
5.00 - 5.50	☐
4.50 - 5.00	■
4.00 - 4.50	☐
3.50 - 4.00	■
3.00 - 3.50	☐
2.50 - 3.00	■
2.00 - 2.50	☐
1.50 - 2.00	■
1.00 - 1.50	☐
0.50 - 1.00	■
0 - 0.50	▏

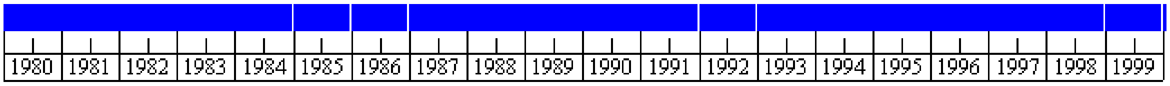
calm



Time Series Legend:

Equal or < 85 % ☐ Between 85 and 95 % 🟨 Equal or > 95 % 🟦

Minimum Scale Rate: 30 days



WIS Station #094
Wave Height Frequency Distribution By Direction
Depth =11m
Date Range: 01 Jan 1980 01AM to 31 Dec 1999 06PM
Season: All

	Wave Height Frequency Distribution (%)														Maximum
Direction	0.00-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	6.0-6.5	Total	Height
0.0	0.14	0.68	0.72	0.10	0.02									1.67	2.45
10.0	0.15	0.82	0.76	0.07	0.01	0.00								1.82	2.68
20.0	0.18	1.00	0.72	0.07		0.00	0.00							1.97	3.26
30.0	0.15	0.85	0.61	0.10	0.00									1.71	2.10
40.0	0.19	0.89	0.55	0.07	0.01	0.00								1.70	2.53
50.0	0.19	1.03	0.59	0.05	0.01									1.86	2.38
60.0	0.22	1.17	0.57	0.04	0.01									2.00	2.42
70.0	0.30	1.38	0.43	0.03	0.00									2.14	2.24
80.0	0.39	1.19	0.41	0.06	0.01	0.00								2.05	2.58
90.0	0.38	1.22	0.97	0.20	0.05	0.02	0.00	0.00						2.83	3.95
100.0	0.32	1.40	0.84	0.26	0.07	0.01	0.01	0.00						2.90	3.66
110.0	0.37	1.49	0.73	0.28	0.06	0.01	0.00	0.00						2.94	3.74
120.0	0.72	1.51	0.90	0.26	0.06	0.01	0.00							3.45	3.39
130.0	1.25	1.86	1.02	0.35	0.07	0.02	0.00		0.00					4.57	4.20
140.0	2.41	4.12	1.49	0.56	0.12	0.02	0.01	0.00	0.00	0.00	0.00			8.73	5.07
150.0	1.99	5.43	3.86	1.44	0.29	0.06	0.02	0.01	0.00					13.12	4.33
160.0	0.66	3.45	3.35	1.89	0.69	0.20	0.05	0.02	0.01	0.00				10.32	4.60
170.0	0.48	2.62	2.50	1.38	0.72	0.30	0.07	0.03	0.01					8.11	4.32
180.0	0.48	2.36	1.80	0.85	0.44	0.13	0.05	0.01	0.00					6.12	4.28
190.0	0.39	2.04	1.15	0.42	0.13	0.04	0.00							4.18	3.41
200.0	0.39	1.63	0.51	0.11	0.01	0.01	0.00							2.66	3.23
210.0	0.43	1.29	0.30	0.02	0.01	0.00	0.00							2.05	3.01
220.0	0.43	0.80	0.13	0.02	0.01	0.00								1.38	2.62
230.0	0.31	0.51	0.07	0.02	0.01		0.00							0.92	3.01
240.0	0.25	0.35	0.07	0.01	0.00	0.00	0.00							0.69	3.00
250.0	0.16	0.23	0.05	0.02	0.02	0.00								0.49	2.91
260.0	0.10	0.17	0.05	0.04	0.01	0.01								0.38	2.98
270.0	0.09	0.18	0.05	0.05	0.02	0.01	0.00							0.41	3.03
280.0	0.09	0.19	0.06	0.04	0.02	0.01	0.00							0.40	3.06
290.0	0.07	0.18	0.07	0.05	0.01	0.00	0.00							0.37	3.19
300.0	0.07	0.22	0.17	0.07	0.01	0.00								0.54	2.87
310.0	0.09	0.25	0.30	0.12	0.02									0.78	2.47
320.0	0.09	0.27	0.30	0.12	0.03	0.00								0.80	2.59
330.0	0.10	0.33	0.35	0.14	0.04	0.00								0.96	2.51
340.0	0.12	0.61	0.56	0.16	0.05									1.50	2.39
350.0	0.13	0.56	0.66	0.11	0.02									1.48	2.44
Totals	14.26	44.27	27.66	9.56	3.03	0.88	0.23	0.08	0.03	0.01	0.00	0.00	0.00		
Cum.	14.3	58.5	86.2	95.7	98.8	99.7	99.9	100.0	100.0	100.0	100.0	100.0	100.0		

Total Calm Hours: 0 Percent: 0.00 %
Total Missing Hours: 0 Percent: 0.00 %
Frequency rounded to two decimal places (ie 0.001 shown as 0.00)

WIS Station #094
Wave Period Frequency Distribution By Direction
Depth =11m
Date Range: 01 Jan 1980 01AM to 31 Dec 1999 06PM
Season: All

	Wave Period Frequency Distribution (%)														Maximum
Direction	2.00-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	9.0-10.0	10.0-11.0	11.0-12.0	12.0-13.0	13.0-14.0	14.0-15.0	Total	Period
0.0		0.56	0.95	0.16	0.01									1.67	6.69
10.0		0.65	1.02	0.14	0.00									1.82	6.27
20.0		0.80	1.06	0.11	0.00	0.00								1.97	7.54
30.0		0.62	0.95	0.13	0.01									1.71	6.73
40.0		0.70	0.88	0.12	0.00									1.70	6.83
50.0		0.79	0.96	0.10	0.00									1.86	6.57
60.0		0.92	1.00	0.07	0.01									2.00	6.66
70.0		0.98	1.08	0.08	0.00	0.00								2.14	7.52
80.0		0.78	1.09	0.17	0.01	0.00								2.05	7.02
90.0		0.66	1.64	0.47	0.06	0.01	0.00							2.83	8.60
100.0		0.61	1.61	0.59	0.06	0.01	0.00							2.90	8.82
110.0		0.60	1.69	0.57	0.07	0.01	0.00							2.94	8.89
120.0		0.66	2.08	0.63	0.08	0.01	0.00							3.45	8.14
130.0		0.64	2.83	0.99	0.10	0.02	0.00							4.57	8.10
140.0		0.65	4.08	3.19	0.69	0.10	0.01	0.00						8.73	9.04
150.0		0.70	4.39	4.60	2.02	0.77	0.36	0.17	0.06	0.03	0.01			13.12	12.99
160.0		0.68	3.66	3.30	1.88	0.52	0.21	0.05	0.02	0.00				10.32	11.67
170.0		0.62	2.92	2.38	1.30	0.63	0.20	0.04	0.01	0.00	0.00			8.11	12.48
180.0		0.64	2.63	1.61	0.80	0.33	0.10	0.01	0.00	0.00	0.00			6.12	12.55
190.0		0.63	2.20	0.93	0.31	0.09	0.02	0.00						4.18	9.55
200.0		0.62	1.60	0.37	0.07	0.01	0.00							2.66	8.73
210.0		0.53	1.35	0.16	0.01	0.00								2.05	7.39
220.0		0.41	0.89	0.07	0.01									1.38	6.87
230.0		0.29	0.56	0.06	0.01	0.00								0.92	7.19
240.0		0.27	0.38	0.03	0.00	0.00								0.69	7.16
250.0		0.20	0.23	0.05	0.01	0.00								0.49	7.02
260.0		0.16	0.16	0.05	0.01	0.00								0.38	7.19
270.0		0.15	0.16	0.07	0.03	0.00								0.41	7.00
280.0		0.14	0.18	0.06	0.02	0.00								0.40	7.04
290.0		0.12	0.19	0.06	0.01	0.00								0.37	7.01
300.0		0.18	0.24	0.11	0.01	0.00								0.54	7.20
310.0		0.21	0.39	0.18	0.01									0.78	6.82
320.0		0.20	0.42	0.17	0.01									0.80	6.86
330.0		0.27	0.49	0.20	0.01									0.96	6.61
340.0		0.48	0.76	0.25	0.01									1.50	6.27
350.0		0.47	0.84	0.17										1.48	5.89
Totals	0.00	18.60	47.51	22.39	7.65	2.51	0.92	0.27	0.09	0.03	0.02	0.00	0.00		
Cum.	0.0	18.6	66.1	88.5	96.2	98.7	99.6	99.9	100.0	100.0	100.0	100.0	100.0		

Total Calm Hours: 0 Percent: 0.00 %

Total Missing Hours: 0 Percent: 0.00 %

Frequency rounded to two decimal places (ie 0.001 shown as 0.00)

WIS Station #094
Wave Period Frequency Distribution By Height (All)

Depth =11m

Date Range: 01 Jan 1980 01AM to 31 Dec 1999 06PM

Season: All

Wave	Wave Period Frequency Distribution (%)														Maximum
Height	2.00-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	9.0-10.0	10.0-11.0	11.0-12.0	12.0-13.0	13.0-14.0	14.0-15.0	Total	Period
0.00-0.5		5.08	5.89	1.83	0.76	0.35	0.20	0.11	0.02	0.01	0.01			14.26	12.99
0.5-1.0		13.48	26.06	3.74	0.66	0.17	0.09	0.04	0.02	0.00	0.00			44.27	12.55
1.0-1.5		0.04	15.22	10.72	1.38	0.21	0.06	0.02	0.01	0.01	0.00			27.66	12.35
1.5-2.0			0.34	5.78	2.92	0.44	0.05	0.02	0.01	0.00	0.00			9.56	12.66
2.0-2.5				0.32	1.80	0.77	0.11	0.01	0.01	0.00	0.00			3.03	12.45
2.5-3.0					0.14	0.53	0.20	0.01	0.00					0.88	10.72
3.0-3.5					0.00	0.04	0.15	0.02	0.01					0.23	10.84
3.5-4.0						0.00	0.04	0.03	0.00	0.00	0.00			0.08	12.23
4.0-4.5						0.00	0.01	0.01	0.00	0.00	0.00			0.03	12.55
4.5-5.0							0.00	0.00						0.01	9.42
5.0-5.5								0.00						0.00	9.04
5.5-6.0														0.00	0.00
6.0-6.5														0.00	0.00
Totals	0.00	18.60	47.51	22.39	7.65	2.51	0.92	0.27	0.09	0.03	0.02	0.00	0.00		
Cum.	0.0	18.6	66.1	88.5	96.2	98.7	99.6	99.9	100.0	100.0	100.0	100.0	100.0		

Total Calm Hours: 0 Percent: 0.00 %

Total Missing Hours: 0 Percent: 0.00 %

Frequency rounded to two decimal places (ie 0.001 shown as 0.00)

# WIS Station #132
Depth =19m

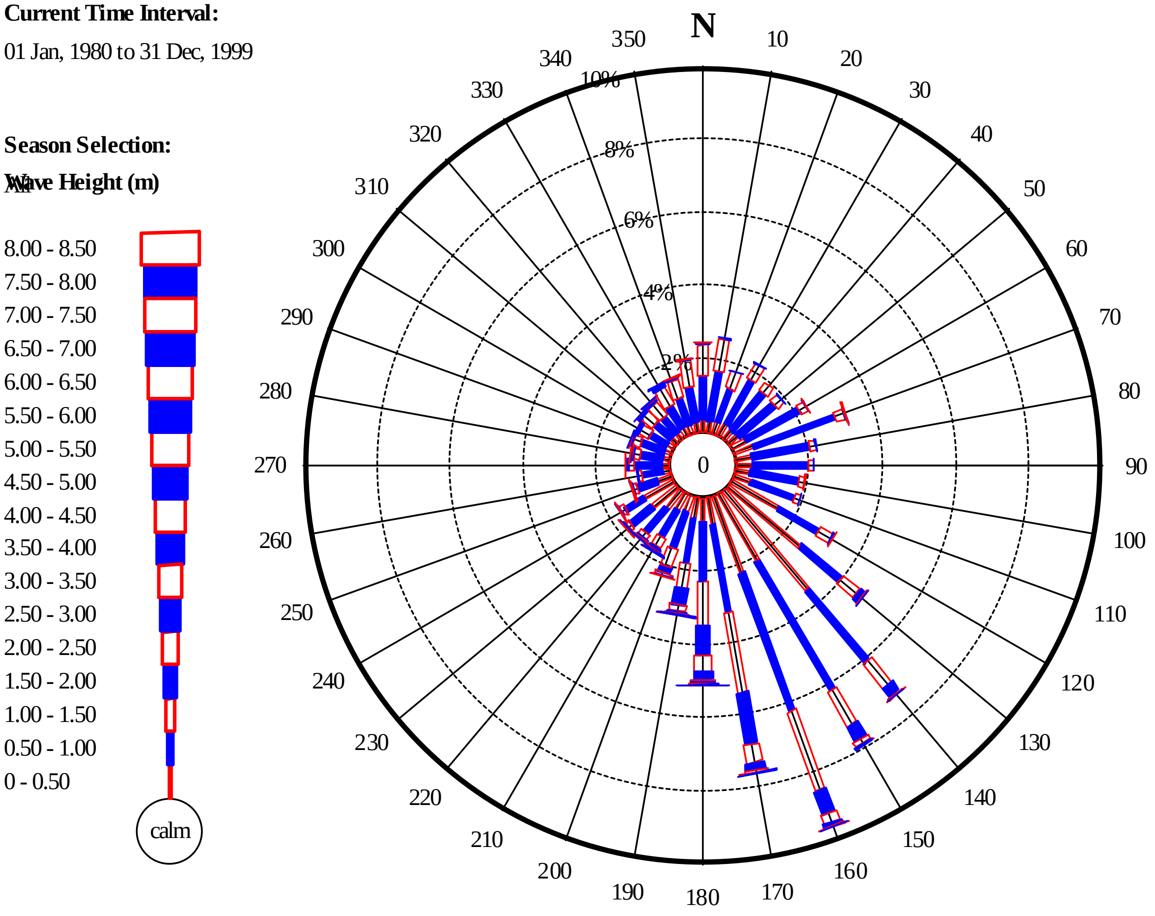
Current Time Interval:

01 Jan, 1980 to 31 Dec, 1999

Season Selection:

All

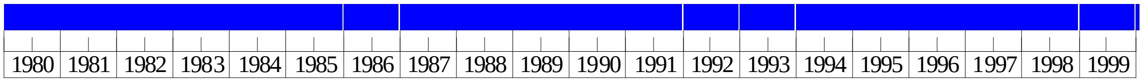
Wave Height (m)



Time Series Legend:

Equal or < 85 % ☐ Between 85 and 95 % 🟨 Equal or > 95 % 🟦

Minimum Scale Rate: 30 days



Data Range: 01 Jan 1980 01AM to 31 Dec 1999 06PM

Calm Wave Conditions: Wave heights = 0.0 m
All conditions during periods of shore ice

Waves: Source File: P:\10803.00 MMS Infrastructure\E Physical Data\WIS Data\WIS_Station132.bts
Data Coverage: 01 Jan 1980 01AM to 31 Dec 1999 06PM
Wave Transformation: Not Applied

Water Levels: No water level data.

Shore Ice: No shore ice data.

WIS Station #132

Depth =19m

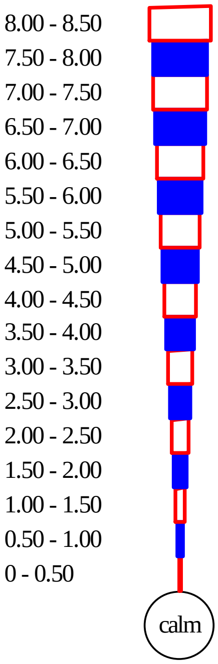
Current Time Interval:

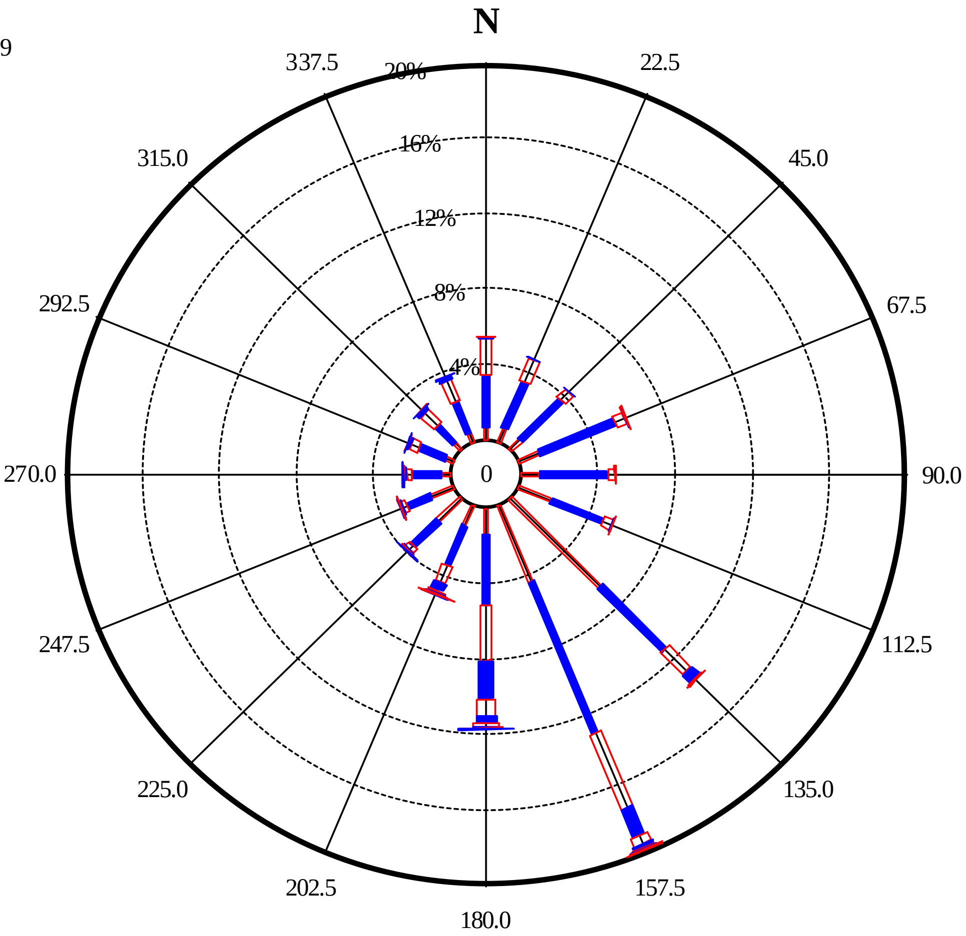
01 Jan, 1980 to 31 Dec, 1999

Season Selection:

All

Wave Height (m)

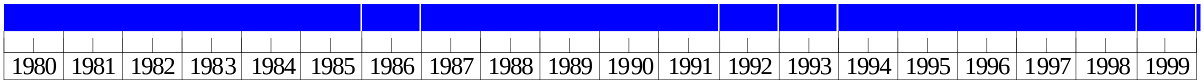




Time Series Legend:

Equal or < 85 %	☐	Between 85 and 95 %	🟨	Equal or > 95 %	🟦

Minimum Scale Rate: 30 days



Data Range: 01 Jan 1980 01AM to 31 Dec 1999 06PM

Calm Wave Conditions: Wave heights = 0.0 m
All conditions during periods of shore ice

Waves: Source File: P:\10803.00 MMS Infrastructure\E Physical Data\WIS Data\WIS_Station132.bts
Data Coverage: 01 Jan 1980 01AM to 31 Dec 1999 06PM
Wave Transformation: Not Applied

Water Levels: No water level data.

Shore Ice: No shore ice data.

WIS Station #132
Wave Height Frequency Distribution By Direction
Depth =19m
Date Range: 01 Jan 1980 01AM to 31 Dec 1999 06PM
Season: All

	Wave Height Frequency Distribution (%)																		Maximum
Direction	0.00-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	6.0-6.5	6.5-7.0	7.0-7.5	7.5-8.0	8.0-8.5	Total	Height
0.0	0.31	1.22	0.86	0.08	0.00													2.47	2.07
10.0	0.32	1.37	0.91	0.04														2.64	1.89
20.0	0.36	0.97	0.49	0.00														1.82	1.77
30.0	0.40	1.38	0.47	0.00														2.25	1.59
40.0	0.33	1.35	0.29															1.96	1.38
50.0	0.36	1.31	0.25	0.00														1.92	1.90
60.0	0.46	1.67	0.22	0.00	0.00													2.36	2.23
70.0	0.60	2.34	0.28	0.03	0.00	0.00	0.00											3.24	3.05
80.0	0.45	1.62	0.18	0.00														2.26	1.51
90.0	0.43	1.55	0.16	0.00														2.14	1.73
100.0	0.41	1.34	0.17	0.01	0.00													1.93	2.03
110.0	0.47	1.31	0.14	0.01														1.93	1.97
120.0	1.48	1.26	0.40	0.05	0.00													3.19	2.30
130.0	2.56	1.43	0.62	0.16	0.02	0.00												4.78	2.51
140.0	3.54	2.57	0.85	0.30	0.06	0.01	0.00											7.33	3.19
150.0	2.11	4.09	1.10	0.43	0.16	0.04	0.00											7.93	3.15
160.0	2.24	4.00	2.30	0.68	0.25	0.11	0.02	0.00	0.00									9.60	4.39
170.0	0.77	2.43	2.21	1.45	0.49	0.21	0.07	0.02	0.00	0.00	0.00	0.00						7.65	5.71
180.0	0.65	1.61	1.22	0.82	0.45	0.21	0.09	0.03	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00		5.12	7.68
190.0	0.60	1.21	0.73	0.45	0.17	0.06	0.03	0.01	0.00	0.00	0.00	0.00	0.00					3.26	6.23
200.0	0.47	1.07	0.50	0.18	0.10	0.02	0.01											2.35	3.41
210.0	0.51	0.86	0.30	0.09	0.05	0.02	0.01	0.00										1.85	3.54
220.0	0.65	0.87	0.15	0.04	0.03	0.02	0.01	0.00										1.77	3.50
230.0	0.88	0.77	0.11	0.04	0.02	0.01	0.00											1.83	3.42
240.0	0.91	0.64	0.10	0.03	0.01	0.01	0.00											1.71	3.37
250.0	0.41	0.59	0.10	0.02	0.01	0.00	0.00											1.14	3.27
260.0	0.20	0.59	0.10	0.02	0.01	0.00	0.00	0.00										0.93	3.50
270.0	0.21	0.76	0.16	0.06	0.01	0.00	0.00											1.21	3.46
280.0	0.21	0.65	0.16	0.05	0.03	0.00	0.00											1.09	3.08
290.0	0.22	0.69	0.21	0.07	0.02	0.00												1.20	2.72
300.0	0.21	0.56	0.30	0.07	0.01	0.00												1.15	2.71
310.0	0.22	0.61	0.37	0.11	0.01	0.00												1.31	2.69
320.0	0.21	0.59	0.45	0.10	0.01	0.01												1.36	2.81
330.0	0.25	0.69	0.54	0.12	0.01	0.00												1.61	2.86
340.0	0.24	0.82	0.50	0.09	0.00													1.64	2.32
350.0	0.28	0.98	0.74	0.05	0.00													2.05	2.11
Totals	24.89	47.76	18.63	5.64	1.97	0.73	0.25	0.06	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00		
Cum.	24.9	72.7	91.3	96.9	98.9	99.6	99.9	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		

Total Calm Hours: 0	Percent: 0.00 %
Total Missing Hours: 0	Percent: 0.00 %

Frequency rounded to two decimal places (ie 0.001 shown as 0.00)

WIS Station #132
Wave Period Frequency Distribution By Direction
Depth =19m
Date Range: 01 Jan 1980 01AM to 31 Dec 1999 06PM
Season: All

	Wave Period Frequency Distribution (%)														Maximum
Direction	2.00-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	9.0-10.0	10.0-11.0	11.0-12.0	12.0-13.0	13.0-14.0	14.0-15.0	Total	Period
0.0		1.39	1.02	0.06	0.01									2.47	6.80
10.0		1.48	1.11	0.05	0.00									2.64	6.79
20.0		1.18	0.62	0.02	0.00									1.82	6.33
30.0		1.66	0.58	0.01										2.25	5.99
40.0		1.49	0.46	0.01	0.00									1.96	6.19
50.0		1.47	0.42	0.02	0.00									1.92	6.45
60.0		1.91	0.43	0.02	0.00									2.36	6.58
70.0		2.44	0.73	0.06	0.01	0.00								3.24	7.31
80.0		1.49	0.73	0.03	0.00									2.26	6.12
90.0		1.20	0.91	0.04	0.00									2.14	6.10
100.0		0.97	0.92	0.04	0.00									1.93	6.05
110.0		0.94	0.93	0.07	0.00									1.93	6.00
120.0		1.31	1.71	0.16	0.01									3.19	6.36
130.0		1.45	2.88	0.43	0.01									4.78	6.63
140.0		1.23	4.85	1.17	0.07	0.00								7.33	7.35
150.0		1.05	3.98	2.49	0.35	0.06								7.93	7.65
160.0		0.97	3.58	3.88	1.01	0.14	0.03	0.00						9.60	9.68
170.0		0.88	2.42	2.37	1.38	0.42	0.11	0.04	0.01	0.01	0.01			7.65	12.54
180.0		0.81	1.71	1.27	0.77	0.38	0.12	0.04	0.02	0.00	0.00			5.12	12.18
190.0		0.65	1.14	0.82	0.44	0.13	0.05	0.02	0.01	0.00				3.26	11.81
200.0		0.63	1.00	0.52	0.16	0.04	0.00	0.00						2.35	9.14
210.0		0.70	0.83	0.24	0.06	0.01								1.85	7.68
220.0		0.84	0.77	0.10	0.05	0.01								1.77	7.67
230.0		1.00	0.71	0.10	0.03	0.00								1.83	7.57
240.0		0.98	0.63	0.07	0.02	0.00								1.71	7.45
250.0		0.66	0.42	0.04	0.01	0.00								1.14	7.40
260.0		0.57	0.30	0.04	0.01	0.00								0.93	7.22
270.0		0.64	0.47	0.09	0.01									1.21	6.98
280.0		0.63	0.37	0.09	0.01	0.00								1.09	7.25
290.0		0.68	0.42	0.10	0.01									1.20	6.45
300.0		0.63	0.44	0.08	0.00									1.15	6.44
310.0		0.65	0.57	0.09	0.00	0.00								1.31	7.03
320.0		0.64	0.63	0.08	0.01									1.36	6.81
330.0		0.76	0.75	0.10	0.00									1.61	6.79
340.0		0.92	0.67	0.05										1.64	5.93
350.0		1.12	0.89	0.04	0.00									2.05	6.24
Totals	0.00	38.02	40.97	14.87	4.46	1.20	0.32	0.10	0.04	0.01	0.01	0.00	0.00		
Cum.	0.0	38.0	79.0	93.9	98.3	99.5	99.8	99.9	100.0	100.0	100.0	100.0	100.0		

Total Calm Hours: 0 Percent: 0.00 %
Total Missing Hours: 0 Percent: 0.00 %
Frequency rounded to two decimal places (ie 0.001 shown as 0.00)

WIS Station #132
Wave Period Frequency Distribution By Height (All)
Depth =19m
Date Range: 01 Jan 1980 01AM to 31 Dec 1999 06PM
Season: All

Wave	Wave Period Frequency Distribution (%)														Maximum
Height	2.00-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	9.0-10.0	10.0-11.0	11.0-12.0	12.0-13.0	13.0-14.0	14.0-15.0	Total	Period
0.00-0.5		13.25	8.88	1.96	0.53	0.16	0.07	0.03	0.00	0.01	0.00			24.89	12.54
0.5-1.0		24.22	19.97	3.11	0.35	0.09	0.02							47.76	8.81
1.0-1.5		0.56	11.73	5.63	0.61	0.08	0.03	0.01	0.00					18.63	10.08
1.5-2.0			0.39	3.85	1.19	0.14	0.04	0.02	0.01	0.00				5.64	11.26
2.0-2.5				0.31	1.39	0.20	0.04	0.02	0.00	0.00	0.00			1.97	12.05
2.5-3.0				0.01	0.38	0.30	0.04	0.01	0.00					0.73	10.30
3.0-3.5					0.01	0.19	0.04	0.01	0.00					0.25	10.80
3.5-4.0					0.00	0.03	0.02	0.00	0.01					0.06	10.74
4.0-4.5						0.00	0.01	0.00	0.00					0.02	10.73
4.5-5.0							0.01	0.00	0.00					0.01	10.95
5.0-5.5							0.00	0.01	0.00	0.00				0.01	11.26
5.5-6.0								0.00	0.00	0.00				0.01	11.61
6.0-6.5								0.00	0.00	0.00				0.00	11.87
6.5-7.0									0.00		0.00			0.00	12.14
7.0-7.5									0.00	0.00	0.00			0.00	12.18
7.5-8.0										0.00	0.00			0.00	12.07
8.0-8.5														0.00	0.00
Totals	0.00	38.02	40.97	14.87	4.46	1.20	0.32	0.10	0.04	0.01	0.01	0.00	0.00		
Cum.	0.0	38.0	79.0	93.9	98.3	99.5	99.8	99.9	100.0	100.0	100.0	100.0	100.0		

Total Calm Hours: 0 Percent: 0.00 %

Total Missing Hours: 0 Percent: 0.00 %

Frequency rounded to two decimal places (ie 0.001 shown as 0.00)