Report for State of North Carolina Floodplan Mapping Project Costal Flood Analysis System

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Report for the State of North Carolina
Floodplain Mapping Project:
Coastal Flood Analysis System

Submittal N.1

Topographic/Bathymetric Data

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1 Overview

As part of the State of North Carolina Department of Emergency Management Floodplain Modernization Program, a partnership was assembled to develop a state-of-the-art system to compute still-water levels along the North Carolina coastal region waters. This was developed for input into floodplain analysis systems, as required by the Federal Emergency Management Agency (FEMA). Experts in the fields of coastal storm surge, wind-driven waves, Geospatial Information Systems (GIS), and high-performance computational systems have worked together in this effort to further advance North Carolina's leading role in flood analysis and mapping. The project partners are: Renaissance Computing Institute (RENCI), University of North Carolina (UNC)-Chapel Hill Institute of Marine Sciences, US Army Corps of Engineers (USACE) Duck Field Research Facility, Applied Research Associates (ARA)/IntraRisk, Coastal Risk Technologies, and Dewberry. The overall approach was to assemble the pieces of the system to enable the computation of still water levels using recent developments in similar projects (e.g., Louisiana Coastal Protection and Restoration/FEMA).

One of the primary components of this project was the assembly of a state-of-the-art Digital Elevation Model (DEM). The DEM merged the latest LiDAR and other data surveys of North Carolina's coastal counties and available bathymetric datasets. From the DEM, the numerical model grid topography and bathymetry were derived. Another component of the system was the combination of advanced numerical models for storm surge, oceanic and near-shore wave fields, and tropical cyclone wind fields to create a flexible software framework on RENCI's high-performance computer systems. Other vital components included the development of the necessary hurricane parameter representations through application of the Joint Probability Method (JPM) and post-processing statistical methods for derivation of return periods from the computational results and JPM statistics.

This document describes the development of version 2.4 of the DEM and vertical datum analysis, numerical model grid generation, tropical cyclone statistical development, and the archival strategy of the computational results.

2 Digital Elevation Model (DEM) Development

As a part of this larger work, RENCI developed a new and more detailed integrated topographic/bathymetric elevation Digital Elevation Model (DEM) of coastal North Carolina. A topographic/bathymetric, or "Topo-Bathy" dataset is a merged terrestrial DEM and bathymetric (water depth) product. This product provides a single, integrated raster Geographic Information System (GIS) dataset that is useful for a variety of purposes, including inundation modeling, mapping, and other purposes. Development of version 1.0 began on September 1, 2007 (Figure 2.1) and the product was delivered in March 2008.

Figure 2.1. Version 1.0 of the 10-meter raster topo-bathy dataset

Upon receipt of comments from the North Carolina Floodplain Mapping Program (NCFMP) and Dewberry in April 2008, RENCI developed version 2.3 of the DEM. Further comments received in September 2008 resulted in the development of version 2.4 of the DEM. This report summarizes the development and analysis, quality assessment, and difficulties encountered throughout the development of version 2.4 of the DEM. The completed version 2.4 DEM can be seen in Figure 2.2.

Figure 2.2. Version 2.4 of the 10-meter raster topo-bathy dataset

A 1/3 arc-second (~10 meter) elevation grid was generated from the best available digital datasets in the region. Figure 2.4 provides an illustration of the many different data sources, with varying spatial extents, used in the production in the DEM. This section of the report provides a summary of the data sources and methodology used in developing the Eastern North Carolina Topo-Bathy dataset.

2.1 Study Area

The study area covered the coastal region of North Carolina from the coastal plains, Pamlico and Albemarle sounds, the Outer Banks, and to the offshore continental shelf and a portion of the deeper ocean. The dataset covered an area approximately 540 km (335 miles) east-west by 540 km north-south. The part used in the modeling consisted of an area beginning inland at the 15-meter (~47 foot) elevation contour and extending well offshore beyond the continental shelf.

The dataset extends some 60 miles north into coastal Virginia to the Chesapeake Bay and south into coastal South Carolina to include any adjacent areas that could impact North Carolina. Figure 2.3 illustrates the extent of the study area in blue. It should be noted that the DEM show in Figure 2.2 extends beyond the study area that is presented in Figure 2.3. Figure 2.3 shows the area of the DEM covered by the ADCIRC grid.
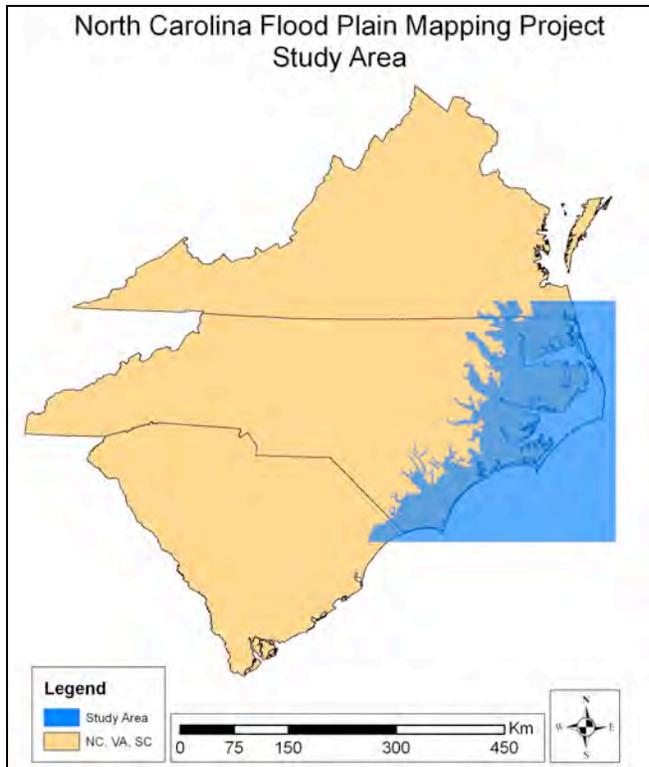
Figure 2.3. NC Flood Plain Mapping Project study area

2.2   Methodology

The integrated North Carolina coastal topo-bathy file was developed to meet the input requirements (Table 2.1) for the A Parallel Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters (ADCIRC) model (Luettich et al. 1992). ADCIRC is a system of computer programs for solving time dependent, free surface circulation and transport problems in two and three dimensions (http://adcirc.org). The best available data were obtained by RENCI and used to produce the final dataset. Data sources, processing, reprojection, integration, and quality assessment are described in the following subsections.

Table 2.1. Specifications for the Coastal North Carolina Grid

Grid Area	Eastern and coastal North Carolina: extending offshore approximately 75.00º to 80.00º W; 33.00º to 38.00º N, following the 15 meter contour inland and extending into adjacent VA and SC.
Coordinate System	Geographic decimal degrees
Horizontal Datum	NAD83
Vertical Datum	NAVD88
Vertical Units	Meters
Grid Spacing	1/3 arc-seconds (~10 meters)
Grid Format	ASCII raster grid

2.2.1   Data Sources and Processing

Shoreline, bathymetric, and topographic data (Figure 2.4) were obtained from numerous sources, including: the U.S. Geological Survey (USGS) National Elevation Data (NED); the NOAA National Ocean Service (NOS), Office of Coast Survey (OCS), and National Geophysical Data Center (NGDC); the U.S. Army Corps of Engineers (USACE); the Naval Postgraduate School; and the North Carolina Division of Emergency Management - Floodplain Mapping Program (NCDEM-FPMP).   Appendix A provides specific information regarding the source, use, and manipulation of each dataset used in version 2.4 of the DEM.
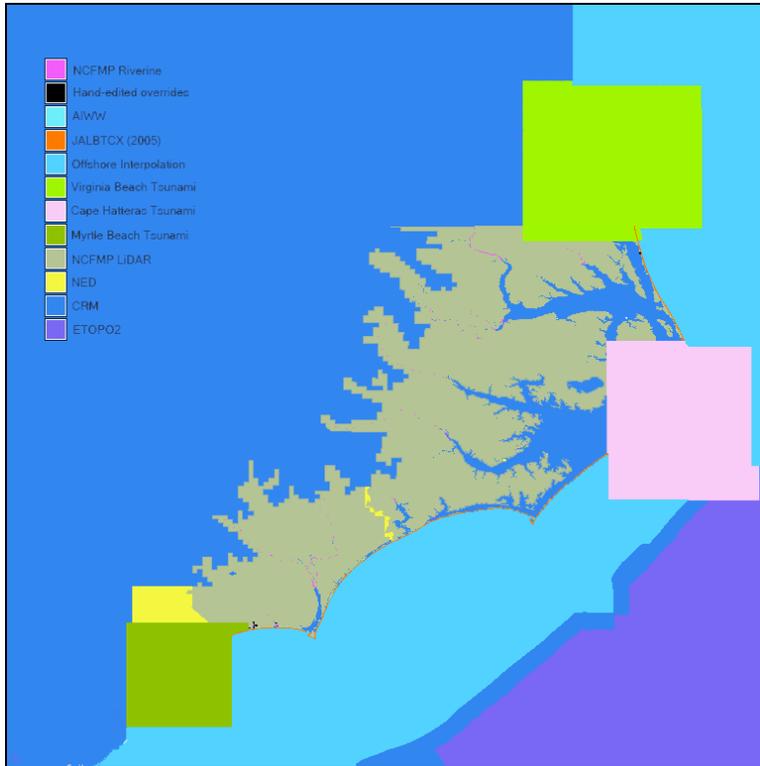

Figure 2.4. DEM data sources
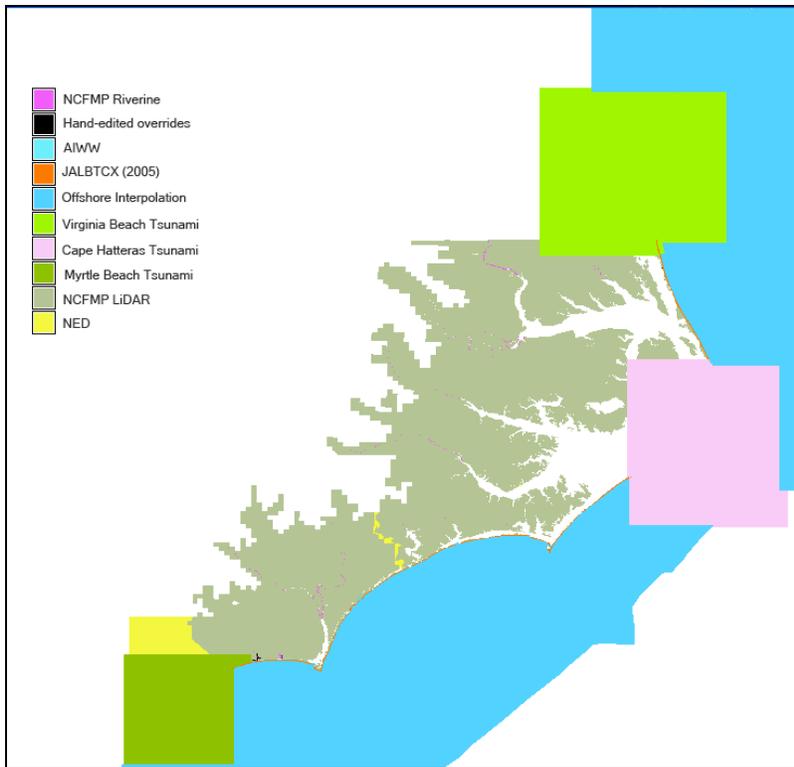
Figure 2.5. DEM data sources without ETOPO2v2 or CRM data
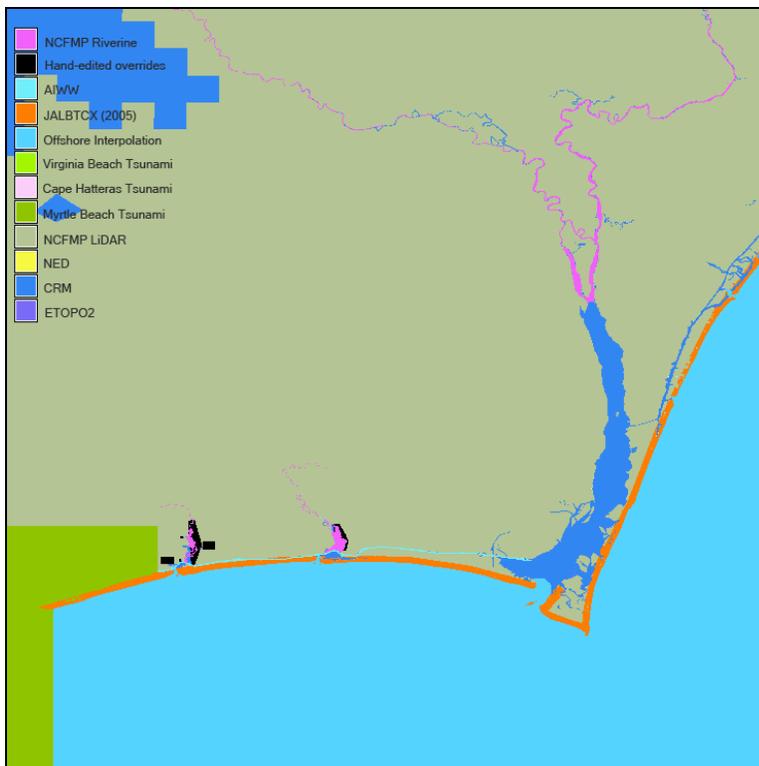
Figure 2.6. Closeup of DEM data sources

The Geographic Resources Analysis Support System (GRASS) v. 6.2 and 6.3 (http://grass.itc.it/), ESRI ArcGIS v. 9.1 (http://www.esri.com/), CorpsCon (http://crunch.tec.army.mil/software/corpscon/corpscon.html), and VDatum (http://nauticalcharts.noaa.gov/csdl/vdatum.htm) GIS software products were used to process, analyze and display data, and to conduct quality assessment. Datasets were converted into GRASS raster files and transformed to NAVD88 and NAD83 geographic coordinates. Vertical datum transformations were largely achieved using VDatum model software that was developed jointly by OCS and NOAA's National Geodetic Survey.

2.2.1.1 Vector Shoreline Data

A variety of datasets were evaluated to produce the most accurate shoreline dataset. The shoreline dataset was required to mask out inaccurate elevation data located in water features. These inaccuracies were artifacts of the data processing used to create the LiDAR-derived DEM, and were removed as a part of the data manipulation to create a seamless topo-bathy dataset. The vector shoreline data was also needed for the quality assessment process. The vector files that were acquired and evaluated are: the National Geospatial-Intelligence Agency (NGA) Global Shoreline Data; NOS medium resolution digital vector shoreline data; the "neatline" data derived from the North Carolina Floodplain Mapping LiDAR data; and the NOAA Coastal Services Center (CSC) vectorized shoreline derived from NOAA-NOS maps and photos (historical shorelines). Additionally, NOS digital charts of various scales were acquired, along with vector shoreline datasets from the North Carolina county boundary and shoreline dataset. The various vector files were reprojected where necessary and displayed and visually compared with the GIS data. In June 2007, Google Earth imagery was also used to visually compare the different datasets and to evaluate the presence or absence of small islands and other features.
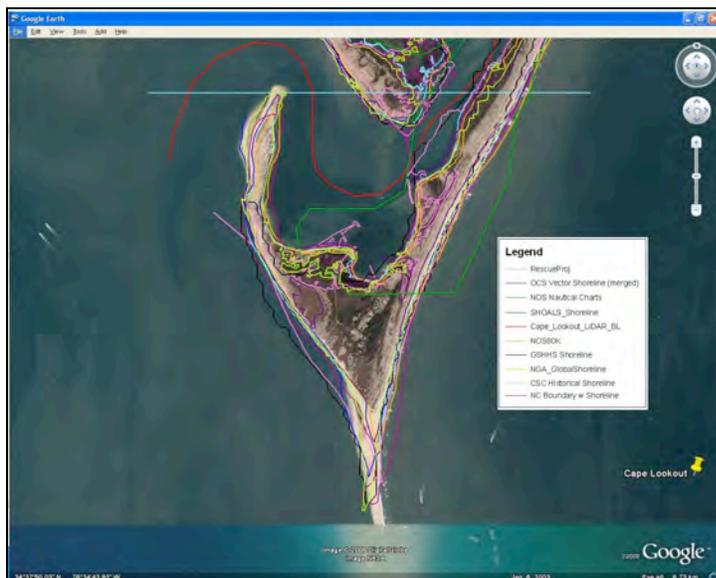

Figure 2.7. Cape Lookout shoreline vectors overlaid on Google Earth imagery dated November 2006
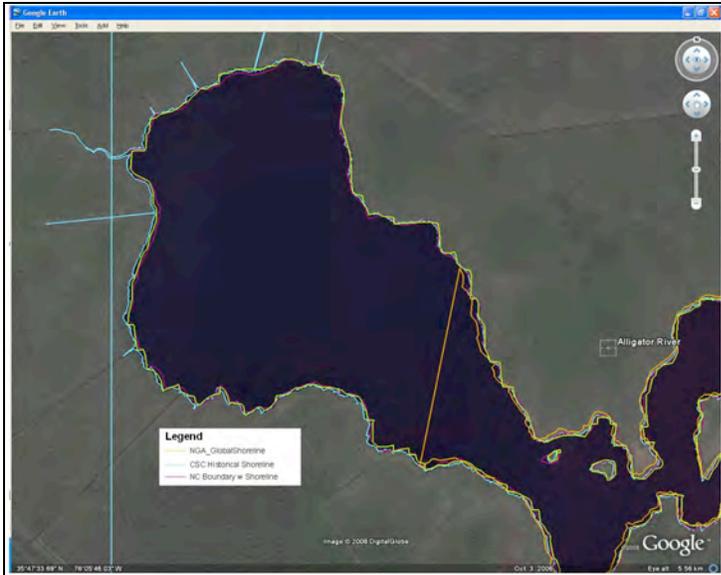
Figure 2.8. Select Alligator River shoreline vectors overlaid on Google Earth imagery dated January 2006

Figure 2.9. Select shoreline vector file for Shallotte Inlet overlaid on Google Earth imagery dated June 2008
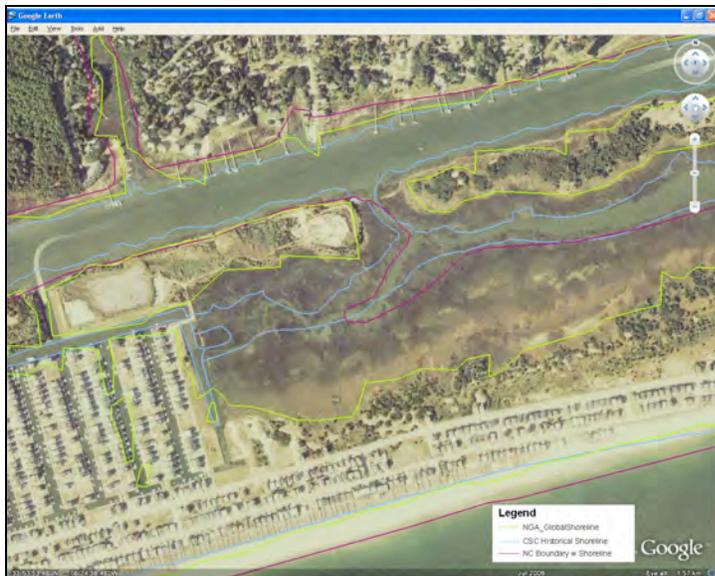
Figure 2.10. Select shoreline vector file for area south of Shallotte Inlet overlaid on Google Earth imagery dated June 2008

As a result of the varying scales, sources, collection dates, and the changing nature of the coast, the shoreline was represented differently in nearly each dataset. Figures 2.7 through 2.10 provide examples of the varied representation of the coast. In particular, the scale of some datasets (e.g., NGA Global Shoreline data) resulted in gross generalizations while the historical nature of other datasets (e.g., CSC historical shoreline dataset) resulted in inaccurate representations of current shoreline location. Based on the comparison with the imagery and the other shoreline data, the North Carolina County and shoreline boundary dataset best represented current shoreline locations. "County boundaries were digitized from 30 x 60 Series USGS mylar basemaps, which meet National Map Accuracy Standards. The digital files were plotted and over[laid] to the originals and needed line corrections were made to within one linewidth" (NCCGIA 2006). As described in Appendix A, this dataset was published by North Carolina Center for Geographic Information & Analysis in 1998. The file was manually edited in ArcGIS to remove the county boundaries.

2.2.1.2 Bathymetry

Bathymetric datasets used in the compilation of the coastal North Carolina DEM include: NOS hydrographic surveys; recent NOS shallow-water multibeam surveys; soundings extracted from Electronic Navigational Charts; detailed inlet surveys performed by various survey contractors; USACE surveys of dredged navigation channels; Office of Naval Research dataset near Duck, NC; NOAA ETOPO2v2 satellite radar data; and features digitized by UNC-CH Institute of Marine Sciences personnel. The datasets varied widely in terms of cell resolution, data sources, and publication date. They also had varied map projections and vertical and horizontal datums. The collection, conversion, and preparation of each of the datasets used in creation of the bathymetry of version 2.4 of the DEM is described below. Once compiled in a form, the complete collection of bathymetry data was interpolated using GRASS' v.surf.rst function. The settings were: -t tension=1300000, smooth=1, segmax=40, npmin=250, dmin=0.0003, and

zmult=1.0. Figure 2.11 illustrates the bathymetry data used for this project (and described below).
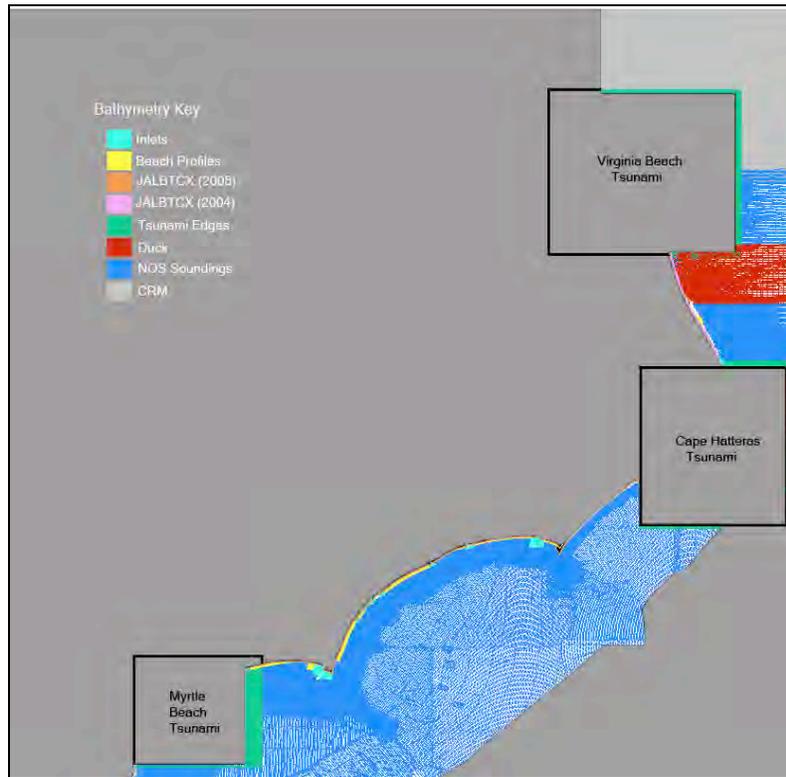
Figure 2.11. Bathymetric only data not derived from ETOPO2v2

2.2.1.2.1 NOS Hydrographic Survey Data

More than 300 NOS hydrographic surveys were conducted within the North Carolina project area between 1851 and 2002. Approximately 3,500,000 soundings were extracted from NGDC's online database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) for the region (Figure 2.12). The hydrographic survey data were originally vertically referenced to Mean Lower Low Water (MLLW) or Mean Low Water (MLW), and horizontally referenced to either NAD27 or NAD83 datums. Data point spacing for the surveys ranged from about 10 meters in shallow water to 1 kilometer in deep water.
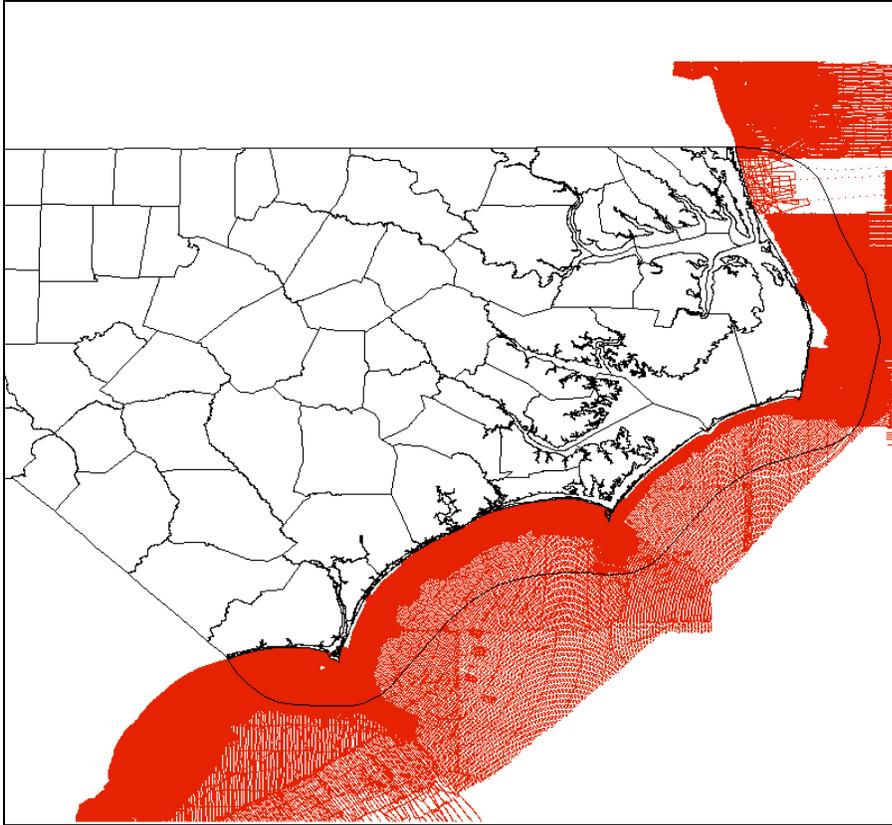
Figure 2.12. Location and density of NOS Soundings used in the development of the DEM

NOS soundings were sorted, and then merged by year and by original vertical (tidal) datum. Soundings in each survey were checked against adjacent and overlapping surveys to ensure continuous coverage. A total of 64 surveys with over 2,000,000 soundings were assembled for the offshore region of the study area. Figure 2.13 shows the dates, location, and density distribution of the offshore NOS sounding data compiled for the DEM. The majority of the data originate from the 1970s with the exception of the areas near large ports such as Wilmington Harbor and Morehead City Harbor where data are from the 1990s. There are two voids clearly visible in the data set. The smallest void lies at Wimble Shoals, north of Cape Hatteras where the shoreline changes orientation from north-south to a southeasterly orientation. This area was supplemented by extracting soundings from the electronic nautical chart. A larger void can be seen just south of the Virginia border offshore of Duck, North Carolina. This area is referred to as the "Duck Patch" and is discussed in detail in Section 2.2.1.2.2.
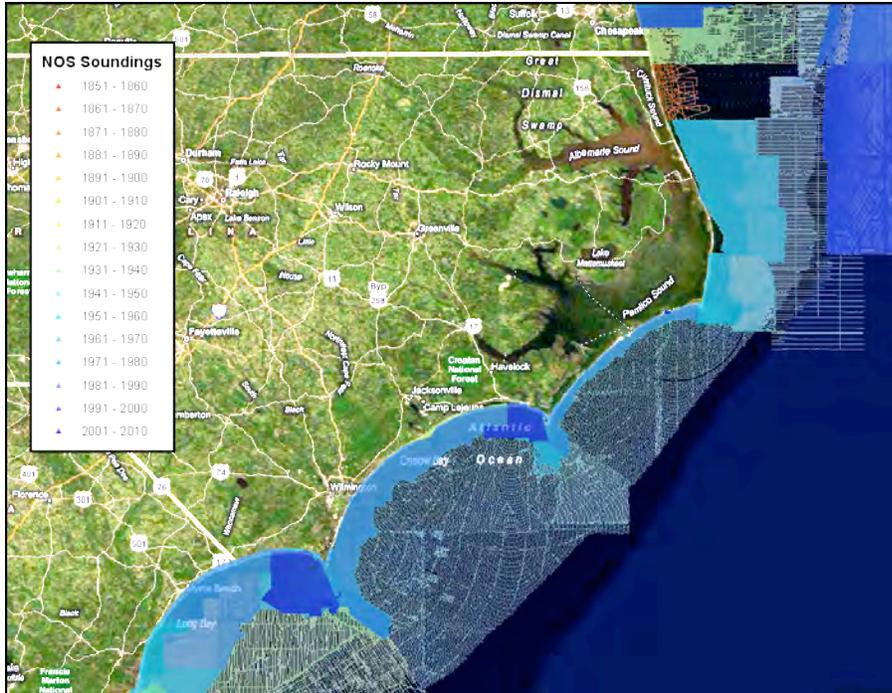
Figure 2.13. Offshore NOS soundings symbolized by survey date

The survey data were converted from their tidal datum to NAVD88 using tidal datum conversions developed for this study as described in Section 2.3. Conversion of survey data from NAD27 to NAD83 was performed using Corpscon software as described in Section 2.3. Figure 2.14 displays individual soundings symbolized as a function of elevation.

The converted data points were clipped to the continental shelf to avoid skewing interpolation values and then included in the offshore bathymetry interpolation process.
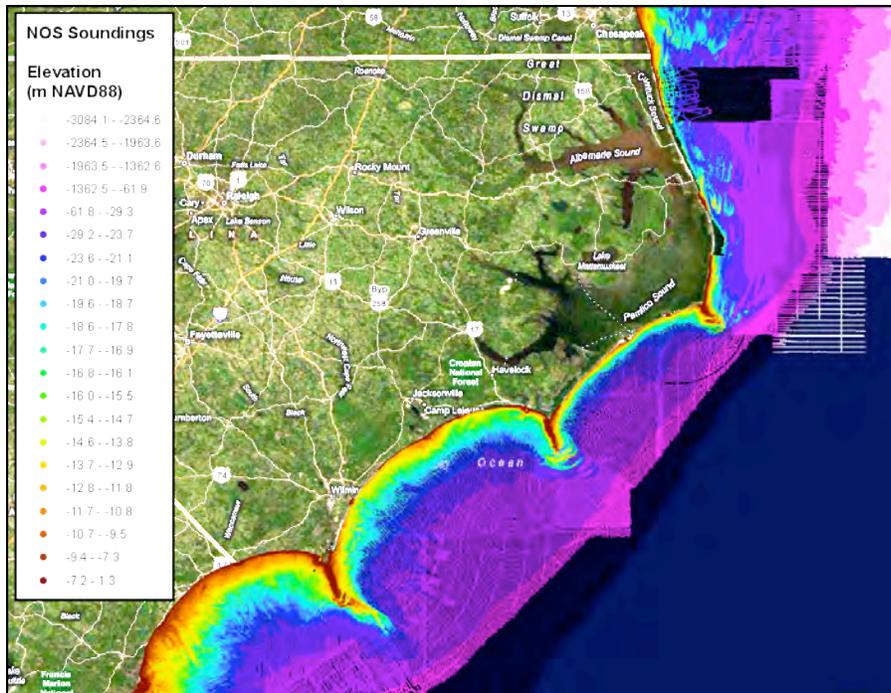
Figure 2.14. Offshore NOS soundings symbolized by elevation

2.2.1.2.2 The "Duck Patch"

A large void area off the coast of northern North Carolina near Duck, NC was visible both in the NOS soundings and in the Coastal Relief Model (see Section 2.2.1.3.4) (Figure 2.15). RENCI contacted a variety of sources and located a set of soundings acquired by Mark Orzech of the Naval Postgraduate School in Monterrey, California. Figure 2.16 illustrates the scatter point data provided by the Naval Postgraduate School in the area. The original survey data was obtained from six major sources:

1. National Ocean Service (NOS) GEOphysical DAta System (GEODAS) database of surveys from 1850 - 2000
2. Surveys conducted onboard Cape Hatteras in August - December 1994
3. Surveys conducted onboard Cape Hatteras in July and December 1997
4. Surveys conducted onboard Cape Hatteras in December 1999
5. Multibeam bathymetry surveys of Frederic Creed in December 1999
6. High resolution surveys conducted by Tom Drake during the Shoaling Waves Experiment (SHOWEX) in September 1999.

The point data were acquired and processed into a compatible raster dataset, which was referred to as the "Duck patch". The data were provided as both an ASCII XYZ scatter dataset and as a 30 meter ASCII grid and included in the offshore interpolation process.
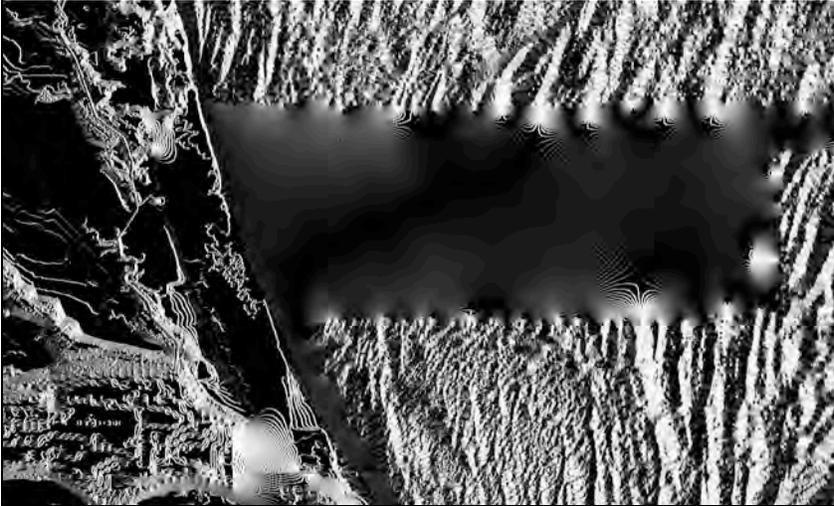
Figure 2.15. The hole in CRM data off Duck, NC

Figure 2.16. The Naval Postgraduate School transect data of the "Duck Patch" area

2.2.1.2.3 Inlet Data

The 22 tidal inlets scattered along the 515 kilometers of North Carolina shoreline act as conduits for the exchange of water and sediment between the estuaries and the open ocean. The ability to accurately resolve the inlet features in the DEM and circulation model is critical to accurately

modeling storm surge in the estuarine areas. The dynamic nature of the inlets renders much of the historic NOS surveys in there vicinity obsolete. Detailed sounding data of 12 inlet locations were obtained from various agencies and survey contractors as described in Table 2.2 as shown in Figure 2.17. The inlet surveys were collected using a combination of techniques. Comprehensive ebb shoal surveys were collected using multibeam technology at three inlets (Cape Fear, Masonboro, and Beaufort) such as shown in Figure 2.18 at Cape Fear. Single Beam surveys were conducted at the remaining inlets. At several inlets where monitoring programs are conducted to assess the impact of dredging operations at adjacent beaches, there is typically adjacent beach profile data collected concurrently with the inlet surveys as shown in Figure 2.19 at Shallotte Inlet. The inlet data sets were typically collected with horizontal datum of NAD83, North Carolina State Plane 3200 and vertical datum of either NGVD29 or NAVD88. The points for these inlets were converted to the adopted horizontal and vertical datums using Corpscon (http://crunch.tec.army.mil/software/corpscon/corpscon.html) and included in the offshore interpolation process.

Table 2.2. Inlet Survey Inventory

No	Inlet	Date	Sponsor	Surveyor
1	Shalotte Inlet	2007	USACE Wilmington District	Gahagan and Bryant and Geodynamics, Inc
2	Lockwoods Folly Inlet	2000	USACE Wilmington District	USACE, Wilmington District
3	Cape Fear Inlet	2007	Bald Head Island	Geodynamics, Inc for Olsen Associates
4	Masonboro Inlet	2008	USACE Wilmington District	Gahagan and Bryant
5	Mason Inlet	2007	Figure Eight	Gahagan and Bryant
6	Rich Inlet	2007	Figure Eight	Gahagan and Bryant
7	Topsail Inlet	2003	Topsail Beach	CP&E
8	New River Inlet	2003	Topsail Beach	CP&E
9	Bogue Inlet	2005	NC Coastal Zone Management	Geodynamics, Inc
10	Beaufort Inlet	2005	NC Coastal Zone Management	Geodynamics, Inc
11	Barden Inlet	2005	USACE Wilmington District	Geodynamics, Inc
12	Oregon Inlet	2003	USACE Wilmington District	USACE, Field Research Facility

Figure 2.17. Inlet Survey Locations
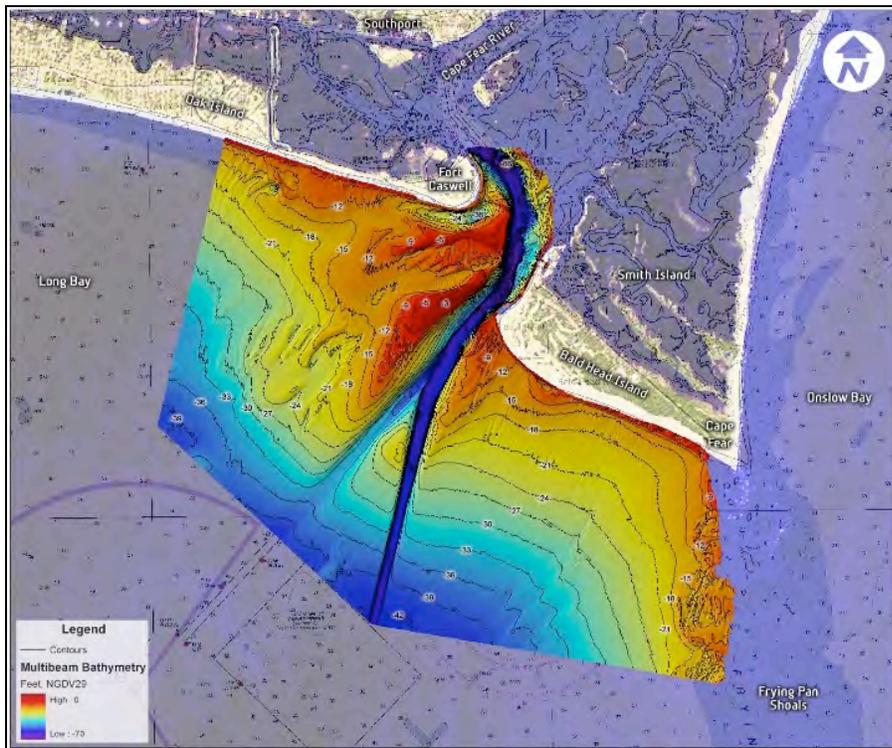
Figure 2.18. Cape Fear Inlet multibeam survey, 2006 (image courtesy Geodynamics, Inc and Olsen Associates)
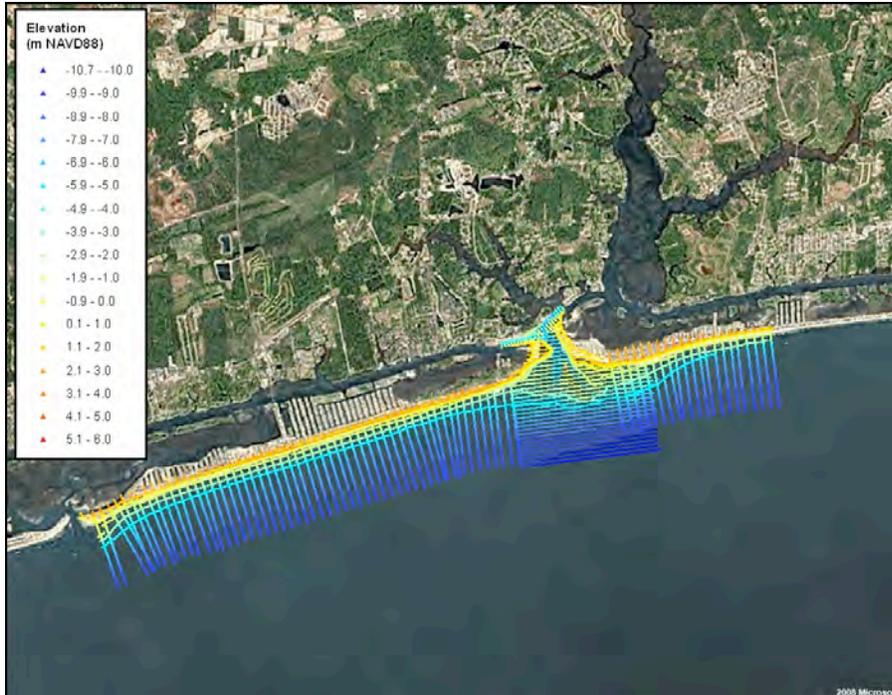
Figure 2.19. Shallotte Inlet single beam survey (2007) with adjacent beach profile survey data

2.2.1.2.4 USACE Navigation Channel Surveys

The Navigation Section of Wilmington District, USACE routinely performs channel condition surveys throughout coastal North Carolina along the Atlantic Intracoastal Waterway (AIWW), connecting channel, inlets, and deep-draft navigation channels. Recent bathymetry data from the U.S. Army Corps of Engineers (USACE) originate from 286 inlet and channel surveys conducted between 1997 and 2008. The most recent survey conditions for the individual channel reaches were extracted from the Wilmington District Web Page (http://www.saw.usace.army.mil/nav/) as Microstation files and processed to extract 322,012 soundings. This was achieved by using GlobalMapper v 9.x to batch load MicroStation files and export all points as text files that included attributes (layers, levels, colors, etc.). MATLAB code was then used to extract "Sounding" records and generate ASCII x,y,z files. These were converted from NAD83, North Carolina State Plane, feet to NAD83 Geographic. Vertical datums were converted from feet MLLW or MLW to meter MLLW or MLW. The tidal datum relationships discussed in Section 2.3 were then used to convert to NAVD88.

Survey data are typically collected at 30-meter cross-sections perpendicular to the channel centerline with soundings spaced roughly 8-meters apart. The surveys are not bank to bank, but typically cover 2 to 3 soundings outside of the authorized channel limits. Where small data gaps occurred in the survey reaches, average cross-section conditions were generated using adjacent cross-sections and used to represent the missing cross-sections. For example, a gap in the AIWW data of approx 5,000 feet (50 cross-sections) was observed. To fill in the missing cross sections, MATLAB code was used to generate cross-sections about the channel centerline at specified channel stations. Adjacent cross-sections with good data (5 to the east and 5 to the west) were extracted and used to compute an average cross-section. The average

cross-section was reprojected to missing cross-sections as xyz data.

The channel survey data are horizontally referenced to NAD83, North Carolina State Plane and vertically referenced to local MLW (feet), except for Wilmington Harbor data which is referenced to MLLW (feet). Corpscon software was used to convert the data to NAD83, Geographic and vertically to meters, keeping the data in original vertical datum. The data were then converted from their tidal datum to NAVD88 using tidal datum corrections discussed in Section 2.3. Where applicable, USACE channel soundings blend with or supersede the historical NOS bathymetry. Once converted, the data was included in the offshore interpolation process.

2.2.1.2.5 UNC Chapel Hill Institute of Marine Science "Control Points"

A series of "Control Points" were developed by UNC-CH IMS personnel for the interior bathymetric regions of the DEM based on a combination of previous ADCIRC model grids and digitizing of NOS nautical chart features at ADCIRC node locations (Figure 2.20). A well-validated ADCIRC model covering central and northern North Carolina has been successfully applied for several studies (Feyen et al., 2005 and NOAA Technical Report NOS CS 21, 2005) and served as the foundation for this study. In an effort to minimize unnecessary work and potential error, it was decided to use the established ADCIRC node elevations as over-ride values or control points for the regions the modeling team has strong confidence in the grid values. Additionally, as the ADCIRC grid was refined to accurately resolve interior bathymetric features in southeastern North Carolina, the modeling team has digitized NOS soundings from raster and electronic nautical charts at explicit node locations.
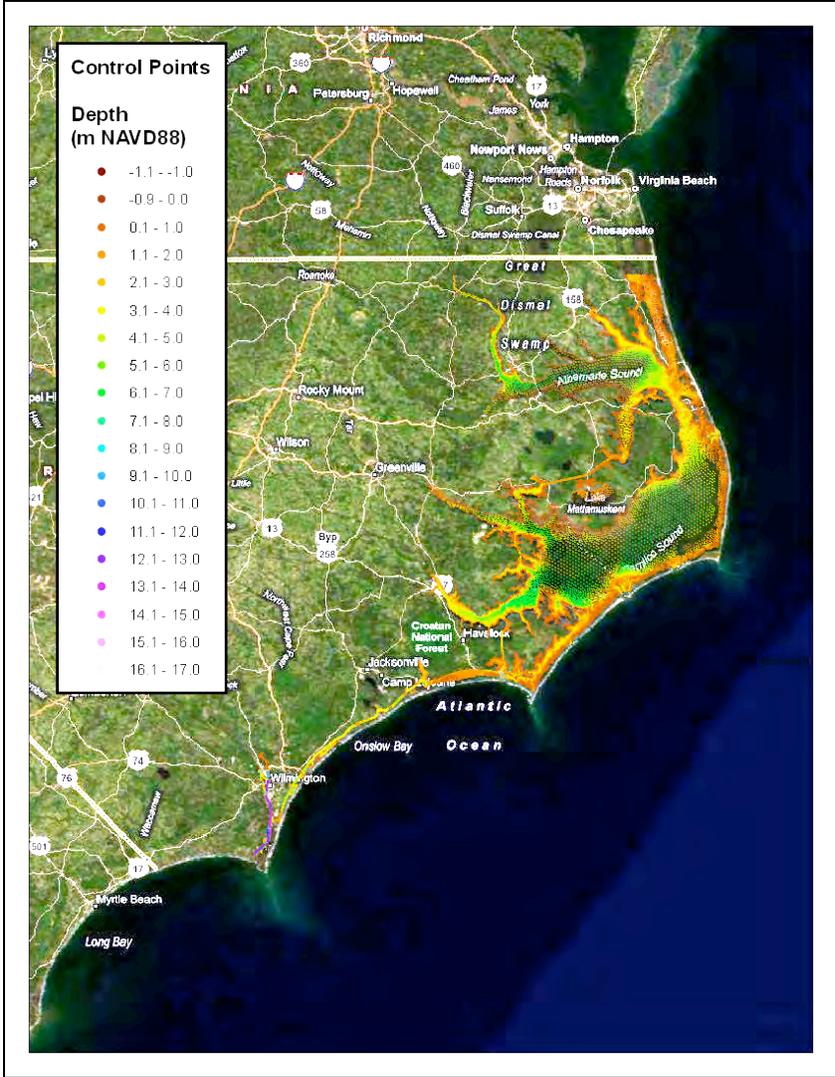
Figure 2.20. UNC Chapel Hill IMS "Control Points" coverage

2.2.1.2.6 NOAA ETOPO2v2

Portions of the study area farther offshore, including outside the coastal shelf, were not available in the NOS GEODAS database or in the Coastal Relief Model (CRM) dataset. This area was represented using the NOAA ETOPO2v2 data (US Department of Commerce 2006). The ETOPO2v2 data used in the development of the DEM are displayed in Figure 2.21. The primary source of the data for this area is the "Smith & Sandwell" database. This is a worldwide set of 2-minute gridded ocean bathymetry derived from 1978 satellite radar altimetry of the sea surface. The horizontal datum is WGS-84 and the vertical datum is Mean Sea Level (NOAA NGDC 2008). The horizontal grid spacing was 2-minutes of latitude and longitude (1 minute of latitude = 1.853 km at the Equator). The vertical precision was 1 meter. The projection was the Cylindrical Equidistant (Plate Carrée), or geographic projection. The data was obtained via Internet download and included in the offshore interpolation process.
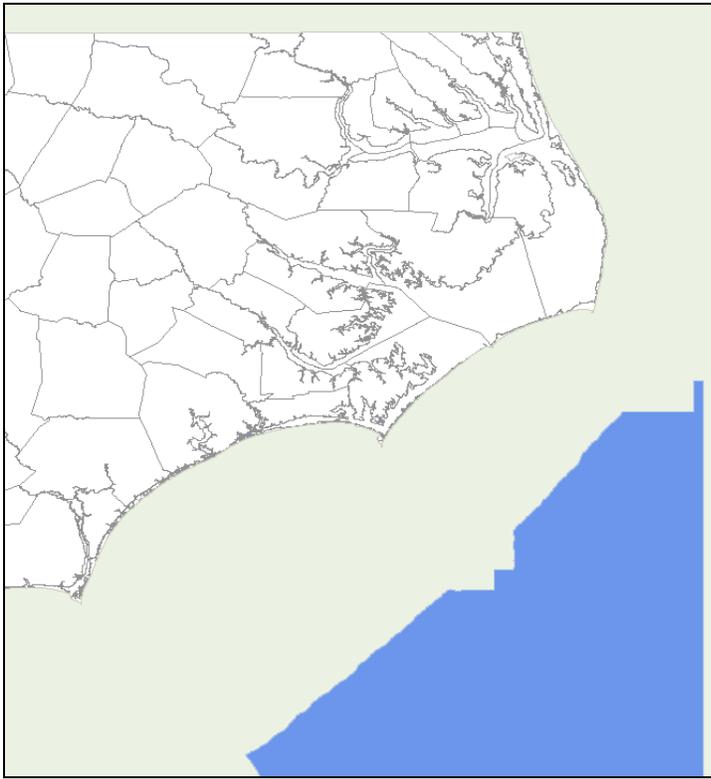
Figure 2.21. ETOPO2v2 data used in the development of the DEM (shown in blue)

2.2.1.3   Topography/Bathymetry Data

Topographic-bathymetric, or "Topo-Bathy" data sets consist of elevation measurements that cross the subaerial-submarine coastal transition zone. The data sets are often collected or assembled with the objective of accurately resolving the shoreline interface for use in storm damage or inundation analyses.

2.2.1.3.1   USACE CHARTS Topographic LiDAR Data

Ultra-high-resolution topographic LiDAR data (1/3 meter postings) collected along the North Carolina coastline by the Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX) (http://shoals.sam.usace.army.mil/) following the 2004 and 2005 hurricane seasons were acquired. These data were collected along the North Carolina coast using the Compact Hydrographic Airborne Rapid Total Survey (CHARTS) system. The CHARTS system includes an Optech, Inc. SHOALS/CHARTS-3000 LiDAR instrument integrated with an Itres CASI-1500 hyperspectral imager. The system can collects both 20 kHz topographic LiDAR data and 3 kHz bathymetric LiDAR data, each concurrent with digital RGB and hyperspectral imagery. The 3kHz laser scans the region from the shoreline to approximately 1 kilometer offshore at 5-meter spacing, and topographic data were collected from the shoreline to 0.5 km onshore at 1-meter spacing as shown in Figure 2.22.   The topographic data are collected in opposing flight

directions, resulting in 200% coverage of the land portion of the survey. All data were positioned using post-processed kinematic GPS and National Geodetic Survey monuments (JALBTCX 2008)
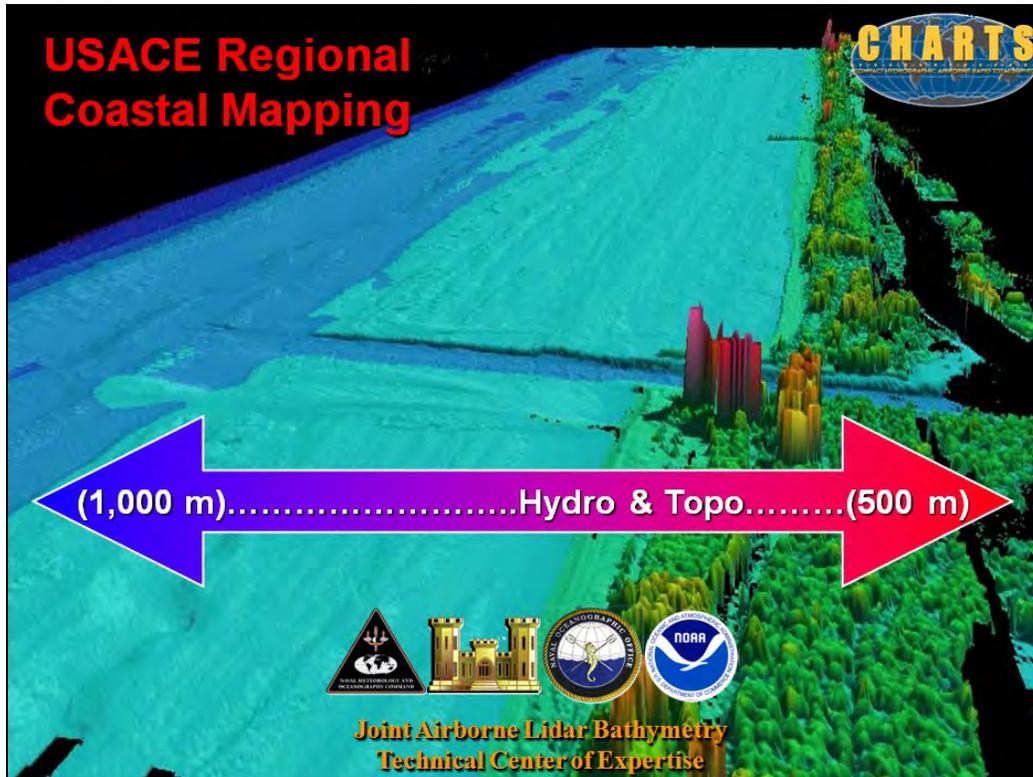
Figure 2.22. CHARTS LiDAR coverage limits (Image courtesy of JABLTCX)

Both bathymetric and topographic LiDAR data were collected for the 2004 survey; however, the post-hurricane survey collected in 2005 did not acquire any bathymetric data due to water clarity conditions following the significant storm event. For the fall of 2004 survey, limited bathymetric data were collected south of Cape Hatteras. The 2005 CHARTS topographic LiDAR data was selected over the combined topo-bathy data set of 2004 due to coverage limits, improved quality control, and post-processing techniques used to derive bare earth products. The topographic LiDAR data covers significant portions of most of the North Carolina barrier islands as shown in Figure 2.23 for Ocean Isle Beach. The data were received from USACE Wilmington in bare earth form as 1-meter raster files in .tiff file format. The files were referenced to adopted datums and required no conversion. Figure 2.24 shows the extent of the CHARTS dataset with reference to the study area.
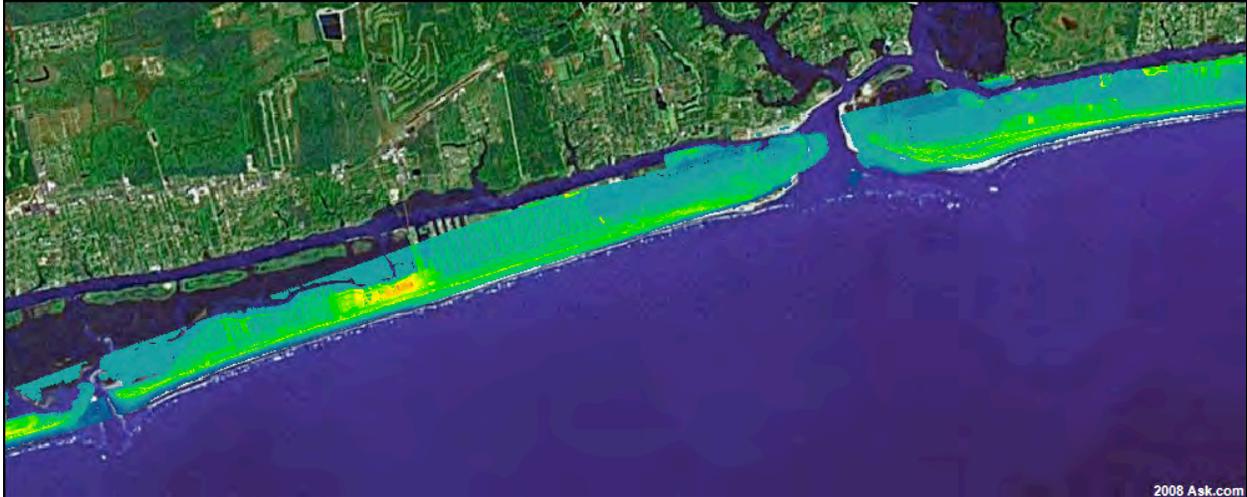
Figure 2.23. CHARTS 2005 survey Topographic LiDAR coverage extents near Ocean Isle Beach, NC
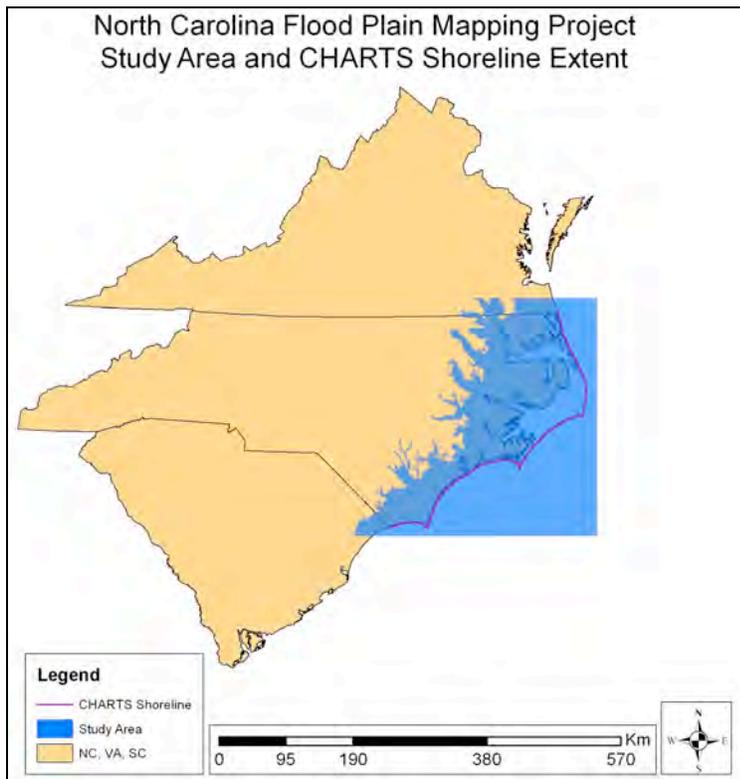
Figure 2.24. Extent of the 2005 CHARTS data

The 2004 hydro LiDAR data were used in limited regions of Dare and Currituck Counties to fill in nearshore data voids between NOS soundings and the shoreline where no recent beach profile survey data were available. The data sets were provided as ASCII XYZ data files in NAD83 Geographic coordinates and meters NAVD88. The points were thinned by 50% by importing the data into Microsoft Access and writing out a new table using the following SQL statement:

```
SELECT TOP 1900000 Charts_2004_hydro_clipped2.Field1,
Charts_2004_hydro_clipped2.Field2, Charts_2004_hydro_clipped2.Field3,
Charts_2004_hydro_clipped2.Number INTO 1900000table
FROM Charts_2004_hydro_clipped2
ORDER BY Rnd(Number);
```

The data was then converted from .dbf into CSV format using an open source file conversion found at http://sourceforge.net/projects/dbf/. The XYZ coordinates were then combined with the other XYZ data for the interpolation of the northern piece of the offshore bathymetry data.

2.2.1.3.2 Beach Profile Data

Many developed coastal communities that have had beach nourishment or dredged material disposal activities commonly perform beach profile monitoring to assess the project performance. The beach profiles are typically collected at 1000-foot intervals alongshore with point spacing every 3 to 8 meters along the specified profile azimuth. The profiles typically extend from the landward side of the dune to the -10 meter contour or 1500 meters from seaward of shoreline. Figure 2.25 display the beach profile locations for Brunswick County, NC. Table 2.3 shows the locations where beach profile data were obtained and used in DEM development.
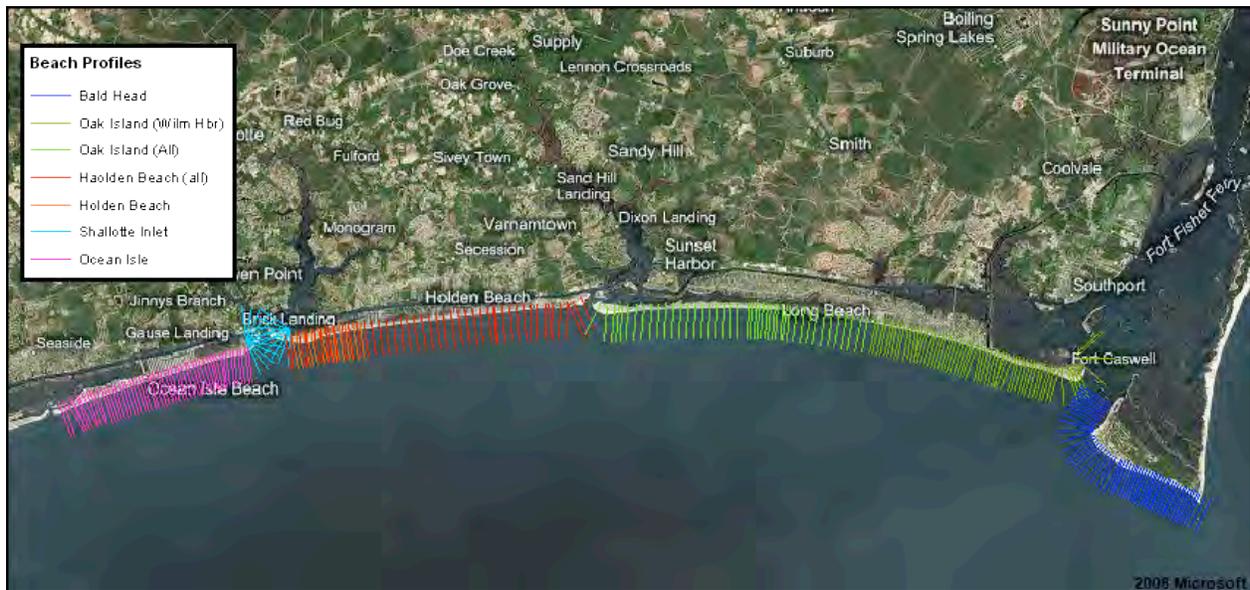
Figure 2.25. Beach Profile Locations in Brunswick County, NC

Table 2.3. North Carolina Beach Profile Survey Data Locations

No	Location	Date	Sponsor
1	Ocean Isle Beach	2007	USACE Wilmington District
2	Holden Beach	1998/2007	USACE Wilmington District
3	Oak Island	2000/2007	USACE Wilmington District
4	Bald Head Island	2007	USACE Wilmington District
5	Fort Fisher	2007	USACE Wilmington District
6	Carolina Beach	2007	USACE Wilmington District
7	Kure Beach	2007	USACE Wilmington District
8	Masonboro Island	2007	USACE Wilmington District
9	Wrightsville Beach	2007	USACE Wilmington District
10	FigureEight	2007	Figure Eight
11	Topsail Beach	2006	USACE Wilmington District
12	Bear Island	2007	Carteret County Shore Protection
13	Bogue Banks	2007	Carteret County Shore Protection
14	Shackleford Banks	2007	Carteret County Shore Protection
15	Bodie Island	2003	USACE Wilmington District
16	Pea Island	2003	USACE Wilmington District
17	Dare County	2006	USACE Wilmington District
18	Duck	2007	USACE, Field Research Facility

The beach profile data sets were commonly referenced to NAD83, North Carolina State Plane-3200 (feet) with a vertical datum of either NGVD29 or NAVD88 (feet). Corpscon was used to convert the data sets to adopted datums. The beach profile data sets were evaluated with adjacent CHARTS topographic LiDAR and NOS soundings to determine if significant vertical offsets occurred at the data interfaces. Figure 2.26 displays very good agreement for the three data sets extracted along an Ocean Isle Beach profile location.
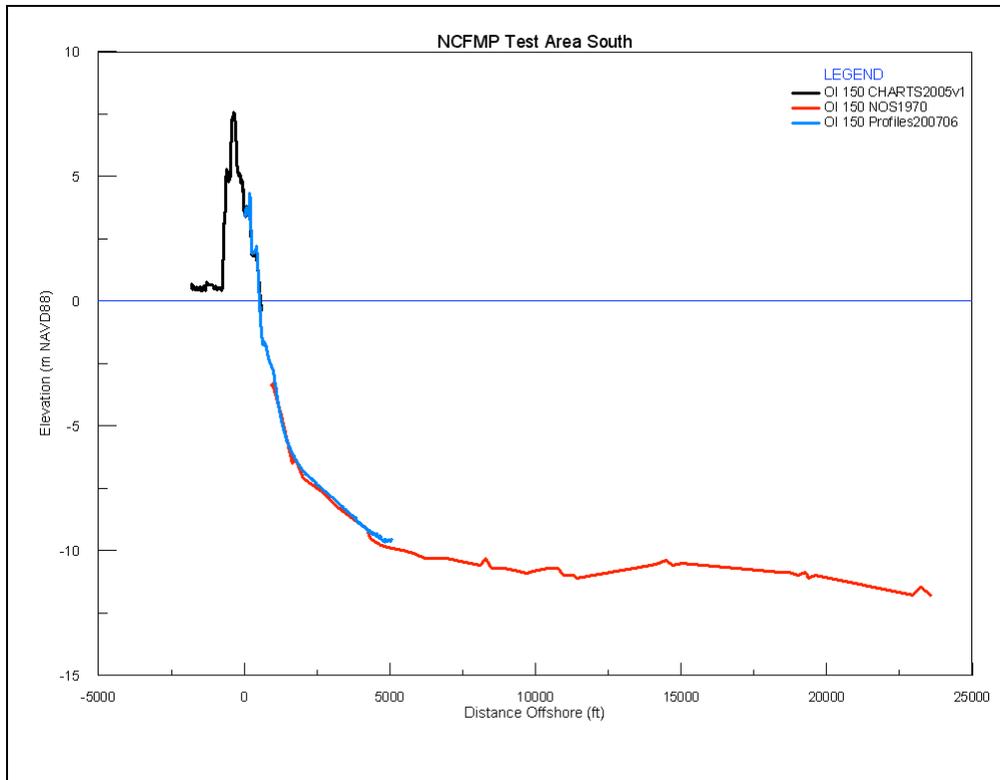
Figure 2.26. Overlapping Beach Profile, CHARTS LiDAR, and NOS Soundings at an Ocean Isle Beach Profile Location

The irregular spacing of the beach profile data required several iterations to generate an accurate surface (uniform raster), especially when including the berm and dune sections of the profiles. Given the accuracy and coverage density of the CHARTS data, it was decided to clip the beach profile to include points greater than +0.55 meters in elevation. This was done so that the CHARTS data would take precedence in the DEM. The beach profile points were incorporated into the NOS soundings as scatter point data for interpolation.

2.2.1.3.3 NOAA Tsunami datasets

Prior to the start of this project, the NOAA Pacific Marine Environmental Laboratory, center for Tsunami Inundation Mapping Efforts (TIME) project completed detailed topo-bathy datasets for the Virginia Beach, Cape Hatteras, and Myrtle Beach areas (Taylor et al. 2006A, 2006B, and 2007) (http://www.ngdc.noaa.gov/mgg/inundation/). The extents of the combined bathymetric-topographic DEMs data are shown in Figure 2.27.
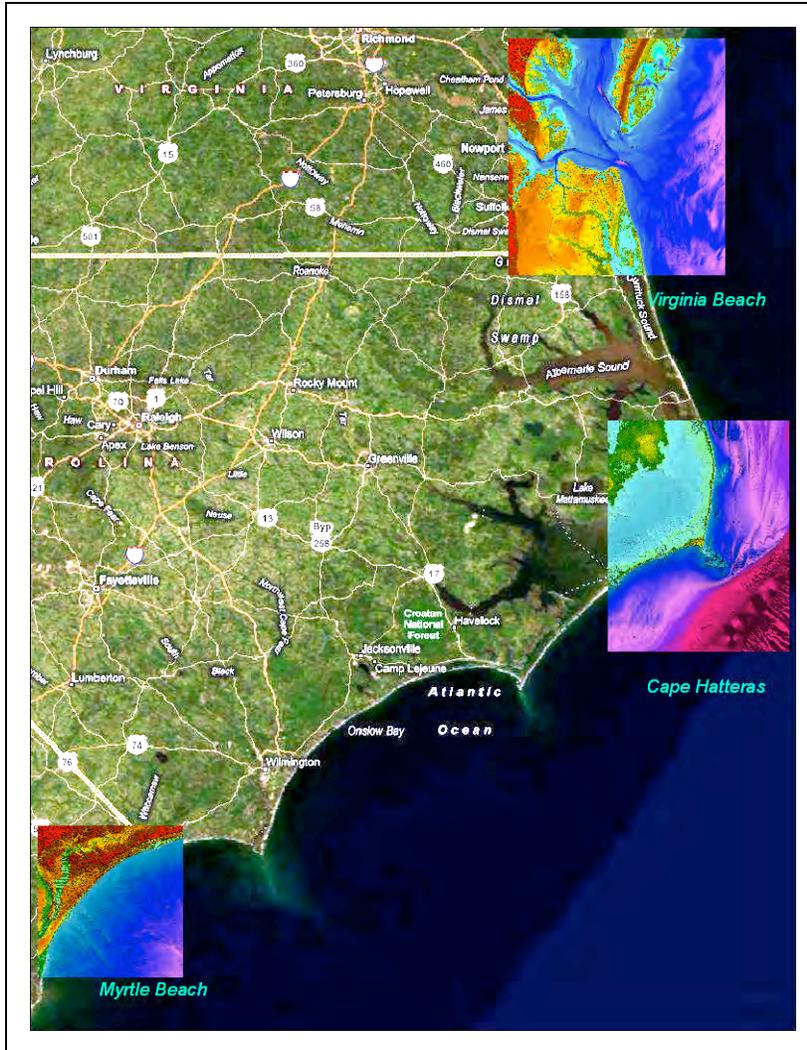
Figure 2.27. Coverage limits for NOAA Tsunami DEMs at Myrtle Beach, Cape Hatteras, and Virginia Beach

The data have a cell size of 1/3 arc-seconds (~10 meters), and are compilations of multiple different datasets of varying sources and detail. All three datasets were created using similar approaches and the best available data. Individual bathymetric datasets used in the compilation of the DEM included multiple NOS hydrographic surveys, OCS electronic nautical charts, and LiDAR survey sand deep-water multibeam surveys of the U.S. Atlantic margin conducted by the Center for Coastal and Ocean Mapping/Joint Hydrographic Center (CCOM/JHC). Comparable datasets for the Wilmington and Morehead City areas are in development by NOAA.

The topo-bathy datasets were obtained via Internet download and originally vertically referenced to Mean High Water and horizontally referenced to geographic coordinates (WGS 84). The data were converted to the NAVD88 and NAD83 using a single offset value recommended by NGDC personnel (Eakins, personal communication, 2007) and then displayed in GRASS and ArcMap. The datasets were compared to current topographic LiDAR data, the NGA coastline, and Google Earth satellite imagery to identify any errors.

2.2.1.3.4 The NOAA Coastal Relief Model (CRM)

The Coastal Relief Gridded database (http://www.ngdc.noaa.gov/mgg/coastal/coastal.html) provides a comprehensive view of the US Coastal Zone extending from the coastal state boundaries to as far offshore as the NOS hydrographic data will support a continuous view of the seafloor (Divins and Metzger 2007). The CRM dataset was used extensively in version 2.4 of the DEM for the Albemarle and Pamlico sounds.

Bathymetric data sources for the CRM dataset include the NOS Hydrographic Database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html), the USGS, the USACE LiDAR (CHARTS), and various academic institutions. Topographic data are from the USGS 3-arc-second DEMs and Shuttle Radar Topography Mission (SRTM) data. The data provide a consistent dataset of the US coastal zone. The database is assembled by gridding the NOS sounding data at the same 3 arc-second (~90 meters) resolution and registration as the USGS 3-arc-second DEMs and splicing the two data sets at the NOS medium-resolution vector shoreline (http://seaserver.nos.noaa.gov/projects/shoreline/shoreline.html). The principal component of the database is 3-arc-second elevation grids of areas 1° in longitude by 1° in latitude, in which elevations are resolved to 1/10 of a meter.

The data was obtained via Internet download and vertically corrected as a series of ASCII grids. The CRM bathymetric data are referenced to their original datum (MLW, MLLW, or LWD). Since approximately 90% of the bathymetric data in the database are referenced to MLW, the data were corrected to NAVD88 using the MLW to NAVD88 datum corrections discussed in Section 2.3. Figure 2.28 represents the Coastal Relief Model tiles extracted for this study.
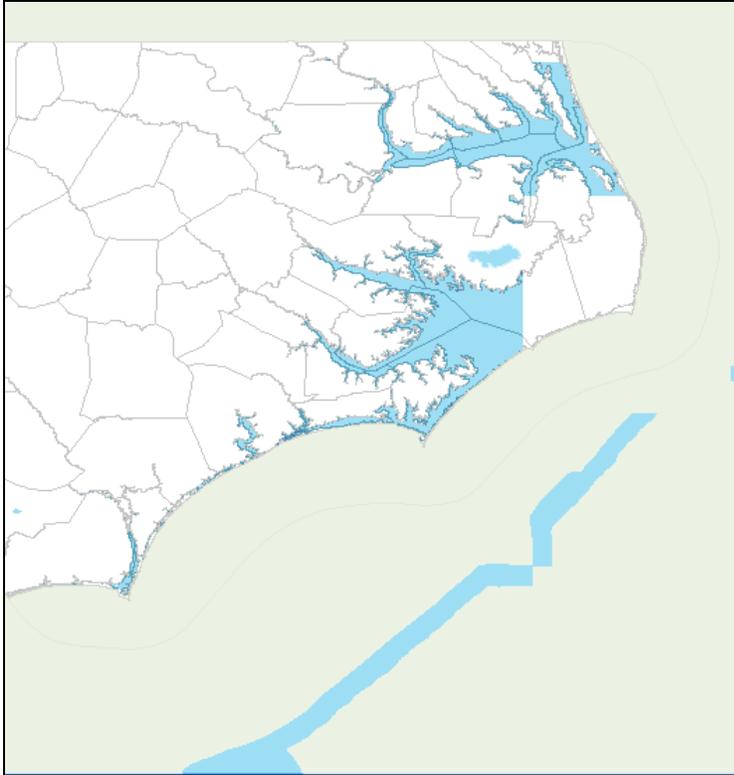
Figure 2.28. CRM data used in the development of the DEM (shown in blue)

2.2.1.3.5 Manually Edited Points

Some inshore areas of the CRM bathymetry had obvious errors with elevations off by as much as 5 meters. These areas were located in Lockwoods Folly and Shallotte estuaries and in Whale's Head Bay. Additionally, where the Virginia Beach Tsunami data merged with the CHARTS data on the outer beach area, there was a slight mismatch in beachfront data. All of these areas were hand-edited using the GRASS method d.rast.edit. Data values where determined from surrounding values, in effect performing a manual interpolation of the data.

Additionally, after incorporation of the Shallotte inlet Riverine data, erroneous elevations were observed in the inlet. To correct this, a local mask was created to remove any values greater than 0. A new Shallotte inlet DEM was generated and incorporated into the overall DEM.

Erroneous elevations were observed in streams that converged with the Cape Fear river. To correct these elevations, nearest available bathymetric data was used to extrapolate local bathymetry and manually edit a small region of the DEM using d.rast.edit. The result override points were then patched into the overall DEM.

In the southern portion of the Cape Hatteras Tsunami dataset, an abrupt change in bathymetric data was observed along the edge of the offshore interpolation dataset. To correct this, a large nearest neighbor analysis was performed to smooth the transition between the two datasets.

Radio Island, near Beaufort, NC, was missing from the previous version of the DEM because the CB100 shoreline masked it out. A small override mask was created to allow the NCFPMP LiDAR to show through the CRM dataset.

A double shoreline was observed in multiple locations. A GRASS r.mapcalc script was created to perform a nearest neighbor analysis. This script only included bathymetric data to correct erroneous elevations along the shoreline.

2.2.1.4   Topographic Data

Several topographic datasets were available for the study area. These data varied widely in terms of resolution, data sources, and publication date. They also had varied map projections and vertical and horizontal datums. Each of the datasets used in creation of version 2.4 of the DEM is described below.

2.2.1.4.1   NCDEM Terrestrial LiDAR Data

High-resolution topographic LiDAR data collected and processed in 2001 by the NCDEM-FPMP were used for land areas. These data were collected as part of NCDEM-FPMP's effort to modernize FEMA Flood Insurance Rate Maps (FIRM) statewide and in response to the damage caused by Hurricane Floyd in 1999. The data were collected at 5-meter nominal post spacing and referenced to NAD83 North Carolina State Plane horizontal and NAVD88 vertical datums, units of feet.

The data were received on disk in ASCII xyz format organized in 10,000 foot x 10,000 foot tiles using the North Carolina Bureau of Land Records Management standards. The tiles associated with the study area were identified and a script was written to import the multiple data files into GRASS. Additionally, the data were converted to the NAVD88 and NAD83 Geographic using Corpscon software.

Significant TIN artifacts were present in the data, including large areas of water that were included. The vector shoreline data discussed in Section 2.2.1.1 was used to mask the LiDAR data and remove the artifacts.

2.2.1.4.2   Additional Terrestrial Elevation Data

There were three areas where elevation data from the previously discussed higher resolution sources were not available. One was in South Carolina, between the northern boundary of the Myrtle Beach Tsunami dataset and the North Carolina border as shown in Figure 2.29.
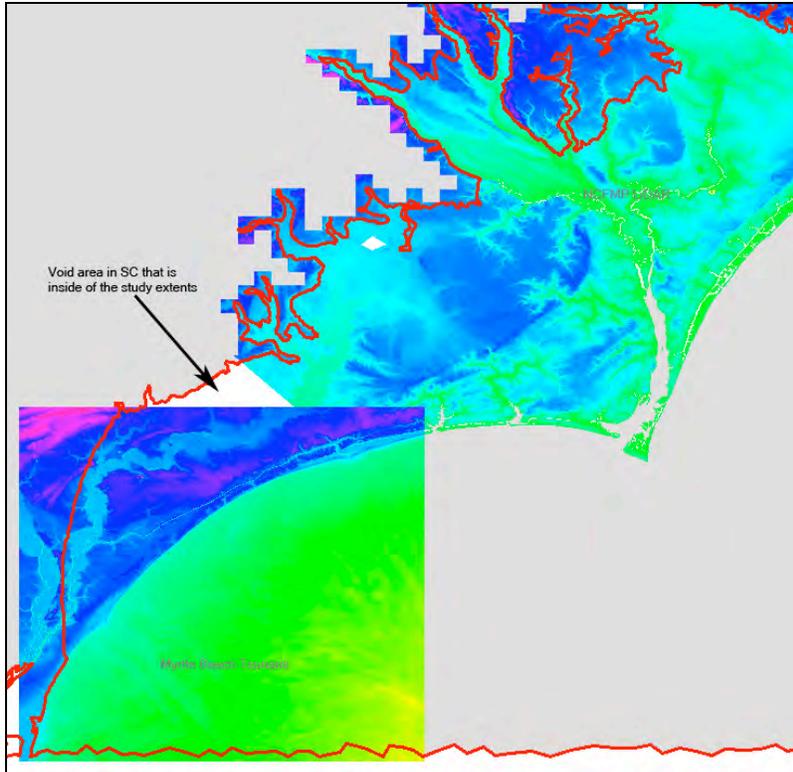
Figure 2.29. Missing LiDAR data in South Carolina

The second was a small area in southern, coastal North Carolina that was omitted from the North Carolina LiDAR dataset. This hole appears to be a seam in between the areas covered by two LiDAR contractors. Figure 2.30 illustrates the location and extent of these two areas.
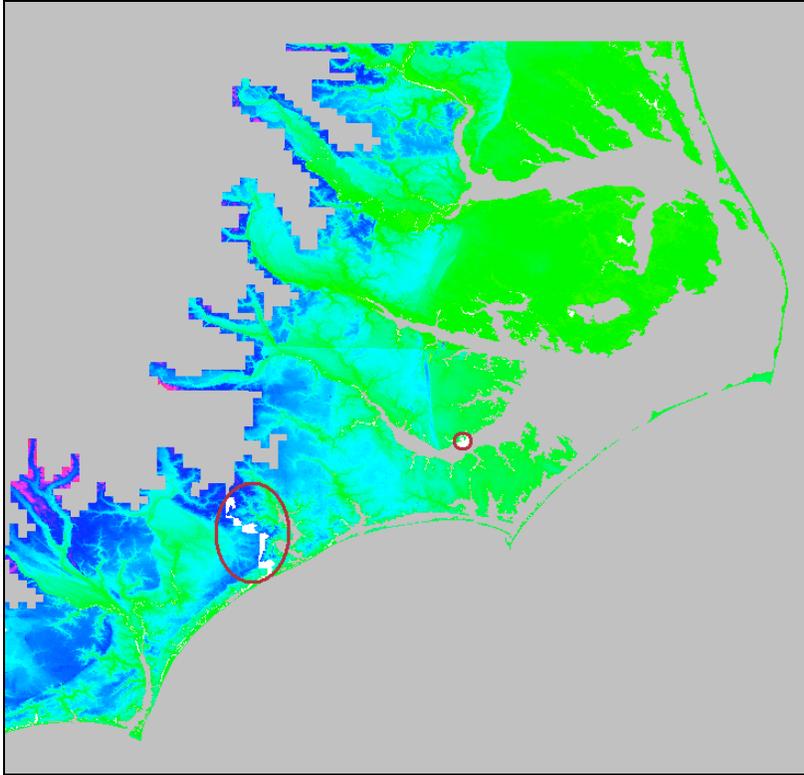
Figure 2.30. Missing North Carolina LiDAR data

The third area of missing data was near Oriental, NC where the higher resolution LiDAR data was unavailable for a single quadrant with the coordinates of N:35:01:12.18N, S:35:00:21.30N, W:76:43:44W, and E:76:42:42.38W. Figure 2.31 illustrates the area of missing data.
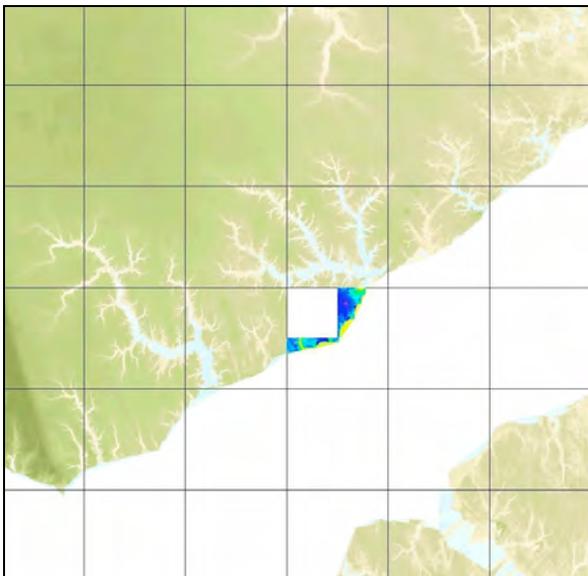
Figure 2.31. Missing quadrant of NC LiDAR data near Oriental, NC on the Neuse River

These three areas were resolved using the 10-meter (1/3 arc-second) USGS NED elevation data (NOAA NED Release Notes 2004). The USGS NED was developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. The data were downloaded from the USGS seamless data server (http://seamless.usgs.gov/viewer.htm) in geographic coordinates, NAD83, NAVD88, raster format.

The NED datasets were patched using GRASS' r.patch to join the DEM with the rest of the pieces in the DEM.

2.2.1.5 Riverine Data

2.2.1.5.1 River Channel DTM Creation

All major river channels are incorporated into the seamless NC Digital Elevation Model (DEM). Much of the data is obtained from LIDAR derived topography, NOAA Navigation charts, USGS maps, USCOE soundings and similar sources. Because the LIDAR data collection procedure does not penetrate water surfaces, other methods were used to obtain below water elevations. Since current Flood Insurance Studies are believed to be the most reliable source of quality assured data, they are used to provide river bottom elevation data in select riverine locations as described below.

The Flood Insurance Studies (FIS) are compiled on a county-wide basis throughout North Carolina. Counties in the Coastal plain contain both 'Coastal' and 'Riverine' flooding sources, whereas inland counties normally contain only 'Riverine' flooding sources. Floodplains for rivers are 'engineered' by using hydrology and hydraulic models (HEC-2, HEC-RAS) based on physical conditions of the channels and over-banks. The hydraulic models contain cross sections normally perpendicular to the water flow direction thus defining the channel banks and shape. Often, these data are field collected by survey crews, thereby providing 'hard' data at the time of the survey.

The North Carolina Floodplain Mapping Program (NCFMP) is the repository for the County-wide FIS which are stored as Technical Services Design Notebooks (TSDN) in digital format. These files contain final hydraulic models by stream name. There are approximately 500 riverine models of flooding sources in the coastal plain counties. NCFMP assembled these data into a geodatabase consisting of the X, Y, Z and W (latitude, longitude, elevation and width to correct datum feet). Some of the models extended farther inland than needed for the coastal surge study(these were clipped at the 15 meter land/water interface), some were too small (width) to have an impact on the ADCIRC grid, some were in less developed areas or of less reliable underwater data (limited detail study) and some of the riverine models were not incorporated due to project time constraints.

Following an evaluation of the major rivers in the coastal plain of NC using aerial photography and HEC-RAS cross section data, it was determined that 14 river channels would be incorporated into the final DEM. Selection criteria included river channel cross sections with a top of channel width of at least 30 meters in order to capture at least three 10 meter mesh

elements. This analysis did not include coastal portions of rivers and other embayments for which HEC-RAS models do not exist. The following is a brief description of the major river channels and how individual stream DTMs were created to be incorporated into the NC DEM

2.2.1.5.1.1 Selected Major River Channels

Table 2.4. Rivers Identified for Inclusion

Item	River	County(ies)	Study Type(s)	NCFMP Contractor
1	Cape Fear River	New Hanover,Columbus	Redelin/LDS	WC
2	Cashie River	Bertie	DS	WC
3	Chowan River	Chowan, Hertford, Gates	Redelin/LDS	WC
4	Cypress Branch	Onslow	DS	WC
5	Lockwood Folly River	Brunswick	DS	G&O
6	Neuse River	Pamlico, Craven	Redelin/DS	WC
7	New River	Onslow	Redelin/DS	WC
8	Newport River	Carteret	Redelin/DS	WC
9	Northeast Cape Fear	New Hanover, Pender	Redelin/LDS	WC
10	Pasquotank River	Pasquotank, Camden	DS/LDS	WC
11	Roanoke River	Washington, Bertie, Martin	Redelin/DS/LDS	WC
12	Shallotte River	Brunswick	DS	G&O
13	Tar River	Beaufort, Pitt	Redelin/DS	WC
14	White Oak River	Onslow	Redelin/LDS	WC

Note: Redelin = Redelineation, DS = Detailed Study, LDS = Limited Detailed Study
WC = Watershed Concepts, a Division of HSMM AECOM, Cary, NC
G&O = Greenhorne & O'Mara, Inc, Raleigh, NC

2.2.1.5.1.2 HEC-RAS River Channel Data

North Carolina Floodplain Mapping Program (NCFMP) extracted channel geometry data available from the HEC and or HEC-RAS models for the coastal plain rivers indicated above. These data included underwater point data, which provided bed and bank height elevations. Elevations for the channel bank and the bottom were extrapolated between points providing

constant elevations along the modeled sections of the rivers. Cross sections were linearly interpolated at approximately 20 ft intervals using the HEC-RAS model cross section interpolation tool. A GIS export file was then generated from the HEC-RAS models for cross section stations within bank stations.

For those rivers where HEC-RAS data was not available or was incomplete, flood profiles from the effective Flood Insurance Study (FIS) reports were used. Using known locations along the flood profile, the bottom elevations were geospatially referenced to an ArcGIS shapefile of these river channel bottom points, assigned with the proper elevation extracted from the flood profile. The elevations were converted from NGVD 29 to NAVD88. Elevations in between known elevations were extrapolated, assuming a constant river channel slope.

2.2.1.5.1.3 Ancillary Data

While viewing the available HEC-RAS data, some channel points did not follow the main river channel or river alignment as compared with other data sources. In some instances, the interpolation of the data between cross sections in the HEC-RAS model followed straight lines, regardless of the actual river path. For these reasons, two additional datasets were identified to augment the river channel depth approximations.

2.2.1.5.1.3.1 North Carolina Statewide LIDAR

This data, readily available from the NCFMP website, contains both bare-earth LIDAR points as well as hydrographic breaklines. The hydrographic breaklines were used to position the banks and the centerline of the river channels. Additionally, the LIDAR was used as a source of elevations for the channel bank heights. This would provide a smooth transition into the final DEM, as this is the same LIDAR was used for the creation of the DEM, particularly in the coastal plains.

2.2.1.5.1.3.2 North Carolina Hydrographic Features

The North Carolina Center for Geographic Information and Analysis developed this dataset in cooperation with NC Division of Water Quality. The information is based upon 1:24,000 scale Digital Line Graphs and additional sources as needed. This dataset provided bank locations and centerline locations of the rivers, and was used only to supplement those areas where the aforementioned breaklines were not available.

2.2.1.5.1.4 Data Processing

1.   The initial step "snapped" the stream bottom elevations to the stream centerline dataset. For this process, an ArcGIS extension was downloaded called Hawthorne Tools. The

"Snap Points to Vector" tool was used to snap the model data to the centerline. A maximum "snapping" tolerance of 50 feet was used for vectors.

2.   Then, the 2D vector bank lines were converted to 3D features. This was accomplished by using the ArcGIS 3D Analyst tool, "Convert Features to 3D". The tool extracts the elevation from a given topographic data source, in this case, the LIDAR DEM.

3.   Since 2 elevation sources were available (i.e., the river channel bottom and bank heights), a Triangulated Irregular Network (TIN) was created using the river channel bottom points as mass points and 3D bank vectors as hard breaklines. This process created a "channel" in a TIN format. For modeling purposes, the channel representation in the DEM approximated a trapezoidal shape (i.e., a best fit to the broad coastal river channel shapes).

4.   To accomplish a trapezoidal shaped TIN, the river centerline was converted to 3D vectors in a similar manner to the banks, with the elevation source set to the TIN created in a previous step. The 3D vector was offset on both sides of the centerline. The offset was generally between 20 feet to 50 feet, depending on the width of the river, and remained constant for the entire length of the river. From the newly created stream centerlines and previous bank vectors, a new TIN was created.

5.   To complete the river channel incorporation, the TIN was converted to ESRI Raster format using 3D analyst. The cell size was set to 32.808 feet, which equals 10m. The final step was to convert the horizontal projection from State Plane Feet to Decimal Degrees, North American Datum of 1983 using ESRI ArcGIS.
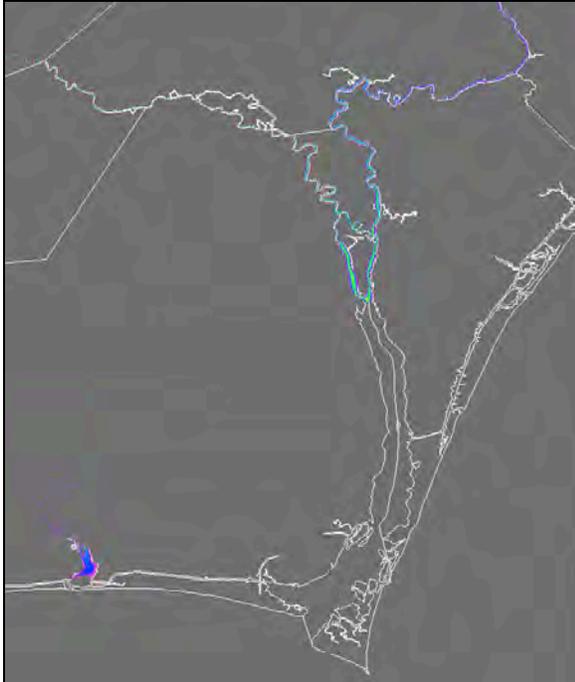
Figure 2.32. Closeup of Shallotte, NE Cape Fear, and Cape Fear River Riverine data

2.3   Establishing Common Datums

2.3.1   Vertical Datum Transformations

Datasets used in the compilation of the coastal North Carolina DEM were originally referenced to a number of vertical datums including: Mean Lower Low Water (MLLW), Mean Low Water (MLW), Mean High Water (MHW), National Geodetic Vertical Datum of 1929 (NGVD29), and North American Vertical Datum of 1988 (NAVD88). All datasets were transformed to NAVD88 to comply with NFIP standards and develop a hydrodynamic model capable of accurately simulating inundation processes. Existing tools were available to confidently perform transformations between the Geodetic Datums (NGVD29 and NAVD88); however, significant analyses were required to improve tidal datums throughout the bathymetric regions of the study and to develop the tidal and geodetic datum relationships. Appendix A shows the datasets, their original vertical datum, and how the data were converted.

2.3.1.1   Topographic Data

The topographic LiDAR and beach profile datasets, represented as orthometric heights, were converted to NAVD88, if necessary, using Corpscon, Version 6.0, a MS-Windows-based program which allows the user to convert between a number of horizontal and vertical datums. Corpscon performs vertical conversions to and from the National Geodetic Vertical Datum of 1929 (NGVD29) and the North American Vertical Datum of 1988 (NAVD88).

Vertical conversions are based on the National Geodetic Survey program Vertcon.

2.3.1.2   Bathymetric Data

Hydrodynamic models are generally populated by bathymetric data that is relative to local tidal datums. However, extending these models to overland regions to simulate inundation processes requires combining bathymetry with topography that is relative to different datums. Traditionally, conversion of bathymetric data to a geodetic datum such as NAVD88 has been performed using established datum relationships at a finite number of NOS stations and various spatial approximation or interpolation techniques. However, these estimates are overly simplistic as the relationship between different datums significantly varies spatially throughout a domain as extensive and complex as the North Carolina coastal region. For example, the distance between MLW and NAVD88 can vary according to the shallow water hydrodynamic response. Figure 2.33 shows the spatial distribution of NOS stations throughout the study area. The limited number of NOS stations and spatial variability of hydrodynamic responses makes it necessary to provide a systematic methodology to define vertical datum transformations in the coastal zone that accounts for these variations.
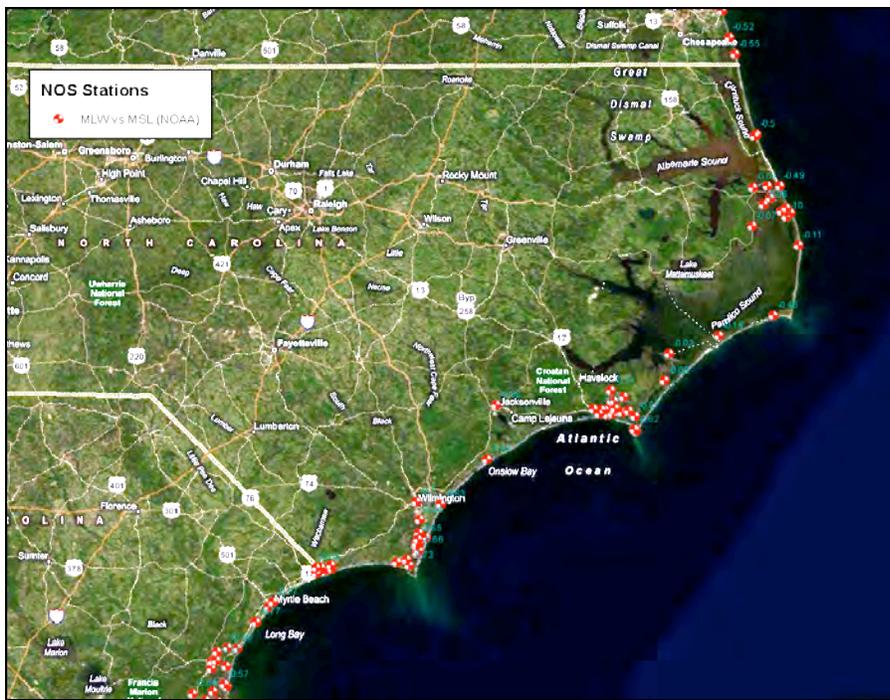
Figure 2.33. NOS Station locations in the vicinity of the study area.

The VDatum vertical transformation tool has been developed by NOAA's NOS to provide a methodology for combining data from a range of datums (Milbert 2002, Parker 2002, Parker et al. 2003). This includes study of tidal and wind-driven inundation, storm surge, and sea level rise.

A software tool called VDatum (Milbert 2002; Parker 2002; Parker et al. 2003) is designed to

transform among approximately 30 vertical reference datums. For example, using VDatum, ellipsoidal elevations can be converted, by parametric equations, to elevations relative to the NAD83; NAD83 elevations can be converted to elevations relative to the NAVD88 using a gridded geoid model such as Geoid99; NAVD88 elevations can be converted to elevations relative to LMSL using a gridded field called the sea surface topography; and LMSL elevations can be converted to elevations relative to other tidal datums, such as MLLW, by using gridded tidal datum fields. VDatum is being developed on a regional basis for the U.S. coastline by NOS' Coast Survey Development Laboratory (CSDL), National Geodetic Survey (NGS), and Center for Operational Oceanographic Products and Services (CO-OPS). A version covering the North Carolina Outer Banks and Albemarle-Pamlico sound system (Figure 2.34) has been developed (Hess et al. 2004, Hess et al. 2005) and is available at the VDatum web page: http://nauticalcharts.noaa.gov/csdl/vdatum.htm. The VDatum application in North Carolina provides the ability to adjust all geophysical data collected to a common vertical datum to support the study and modeling of processes across the land/water interface.
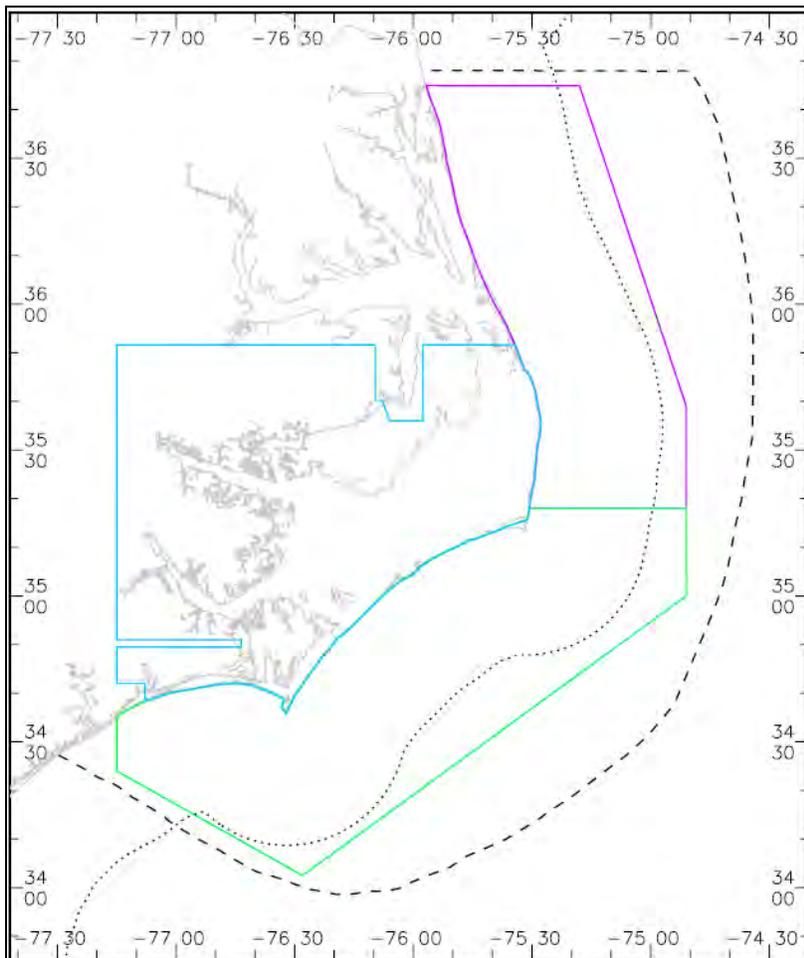

Figure 2.34. NOAA North Carolina VDatum coverage extents. The bounding polygons for the Coastal North area (purple line), Coastal Central area (green line), and Pamlico Sound area (blue line).

The limited coverage of the existing North Carolina VDatum application required

development of datum relationships throughout the coastal North Carolina region to accurately transform bathymetric datasets. Although the analysis was not an official VDatum application, NOAA personnel were deeply involved to ensure accurate results. VDatum Standard Operating Procedures (DRAFT, Hess, 2008) along with various numerical tools were provided by NOAA personnel to assist in the analysis. There were three main components of the "expanded" North Carolina VDatum implementation. First, a hydrodynamic model, ADCIRC, was used to simulate tidal circulation over a one month period. The ADCIRC model mesh version v6a was initially used for tide-only simulation. The hydrodynamic model was forced by a reconstructed tide at the ocean boundary, using harmonic constants from a basin-scale tidal model. A constituent file (fort.53) was generated and used to develop water level time series at each node. The NOAA Fortran program lv5_adcirc was used to analyze the water level time series for high and low waters, then averaging produced the initial tidal datum fields (MHHW, MHW, MSL, MTL, DTL, MLW, and MLLW). Figure 2.35 displays the modeled MLW tidal datum relative to MSL. Modeled tidal datums were compared against CO-OPS observed tidal datum stations at 100 historical NOS tide stations. The tidal datums from the model did not exactly match the NOS datums reported at water level stations located in the domain, primarily because the model runs reflect only tidal forcing and the datums reported by NOS include meteorological effects. A spatial interpolation of the error in the modeled datums was made to adjust the hydrodynamic model results to match the NOS data at the stations. The interpolated error field was generated by taking the error at each individual water level station, and creating an interpolated field using the Tidal Constituent And Residual Interpolation (TCARI) model (Hess, 2002; Hess, 2003). The modeled datum fields were 'corrected' by subtracting the interpolated error field. The corrected fields closely match the observed datums at the water level stations.
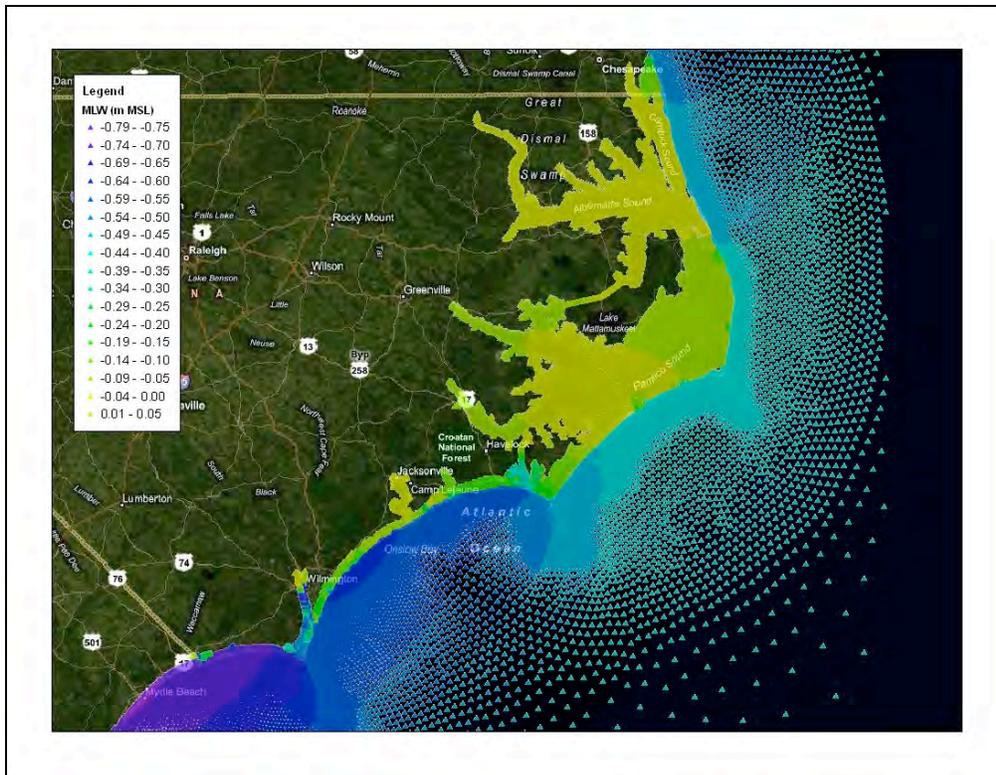
Figure 2.35. Modeled tidal datum relationship (MLW relative to MSL)

Second, the sea surface topography (TSS), or difference between LMSL and the NAVD88 geopotential surface, was generated by a minimum curvature algorithm using data at 37 historical tide stations with benchmark data. Figure 2.36 shows the variability in the TSS values. In the open ocean, NAVD88 ranges 0.1 to 0.2 meters above MSL whereas in the estuarine environment, NAVD88 is approximately 0.0 to 0.1 meters above MSL.
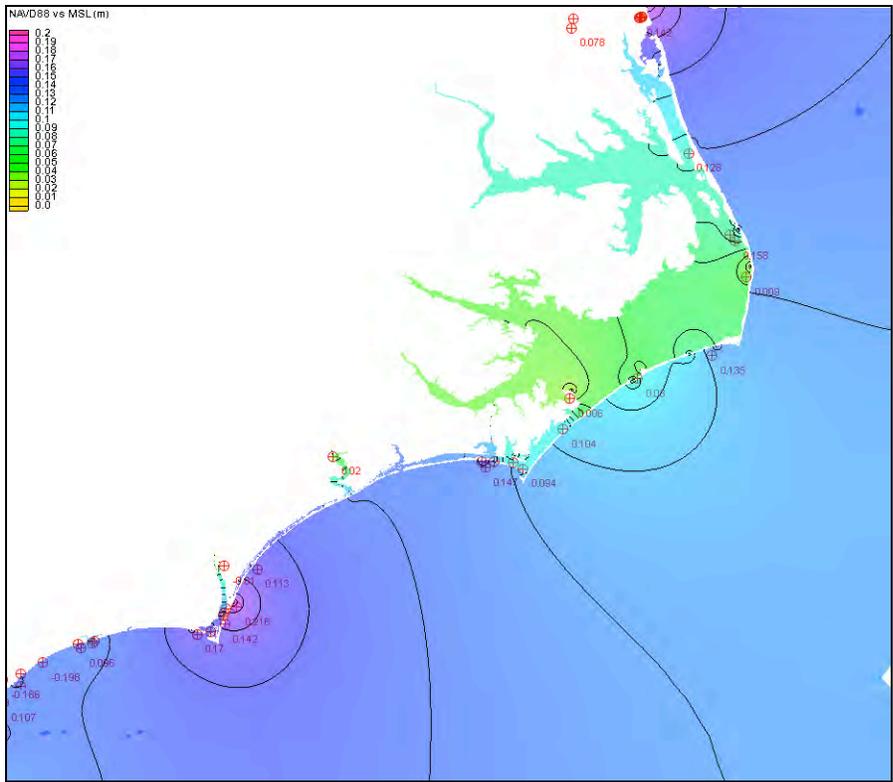
Figure 2.36. Sea surface topography, or difference between NAVD88 and MSL (meters)

The final step in the analysis was to combine the corrected tidal datum transformations (such as the difference between MLW and MSL) with the topography of the sea surface (difference between MSL and NAVD88) to provide direct conversion values between tidal and geodetic datums (i.e., NAVD88 relative to MLW, Figure 2.37). Whereas NOS developed gridded fields to be used with the VDatum software, this application only provided the results at the explicit ADCIRC nodes. For the open ocean. the datum transformation results were interpolated to a uniform grid and used to convert NOS soundings via raster calculator. For the interior waterways, such as the AIWW, the conversion factors for the individual soundings were selected using the nearest neighbor.
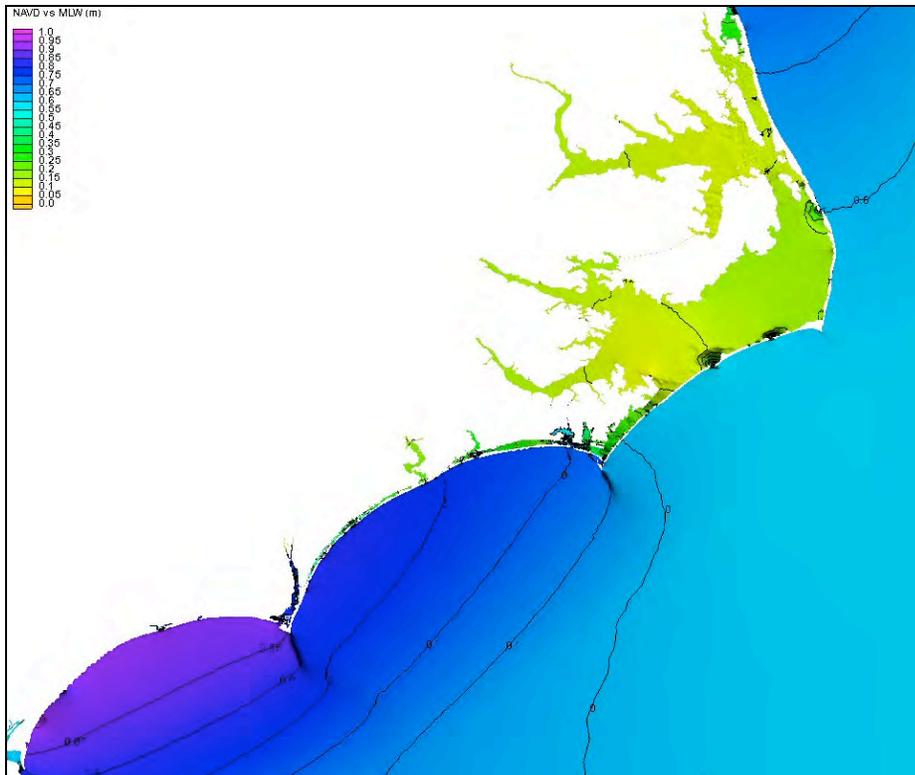
Figure 2.37. Conversions factors between tidal datum (MLW) and NAVD88

2.3.2   Horizontal Datum Transformations

Horizontal datums in FIRMs are expressed in several ways, including North Carolina State Plane/feet (NC State Plane NAD83 feet); North American Datum of 1983 in degree, minute and second; and 1000-meter Universal Transverse Mercator (UTM) grid ticks. The ultimate product horizontal coordinate system of this work is North Carolina State Plane NAD83 feet. Again, intermediate units may contain decimal degrees or UTM meters as processing may require.

Datasets used to compile the grid were originally horizontally referenced to NAD83, WGS84, NAD27, or North Carolina State Plane horizontal datums; the relationships and transformational equations between these horizontal datums are well established. All data were converted to a horizontal datum of NAD83, Geographic in decimal degrees using both the GRASS r.proj function and Corpscon. Corpscon allows the user to convert coordinates between Geographic, State Plane, UTM, and US National Grid systems on the North American Datum of 1927 (NAD27), the North American Datum of 1983 (NAD83) and High Accuracy Reference Networks (HARNs). Corpscon uses the National Geodetic Survey (NGS) program North American Datum Conversion Utility (NADCON) to convert between NAD27, NAD83 and HARNs.

2.3.3   Raster Transformations

Datasets were acquired with various raster cell sizes. All data were converted to a common 10

meter raster cell size using GRASS' g.region function.

2.4   Integrated Topo-Bathy Digital Elevation Model Development

2.4.1   Subdividing Study Areas

Three general study areas were delineated (North, Central, and South). Based on the number of points and spatial distribution of the points, each of these areas were then subdivided when necessary. The northern study area did not require subdivision so it contained one large study area.   The central area was subdivided into two smaller areas and the southern area was subdivided into three smaller study areas. All subdivided study areas included a minimum of a 10,000 meter overlap to ensure data continuity.

These smaller study areas allowed for successful interpolation in GRASS. The interpolations were performed in small pieces to conform with GRASS computational requirements. Figure 2.38 illustrates the geographic extent of the study areas.
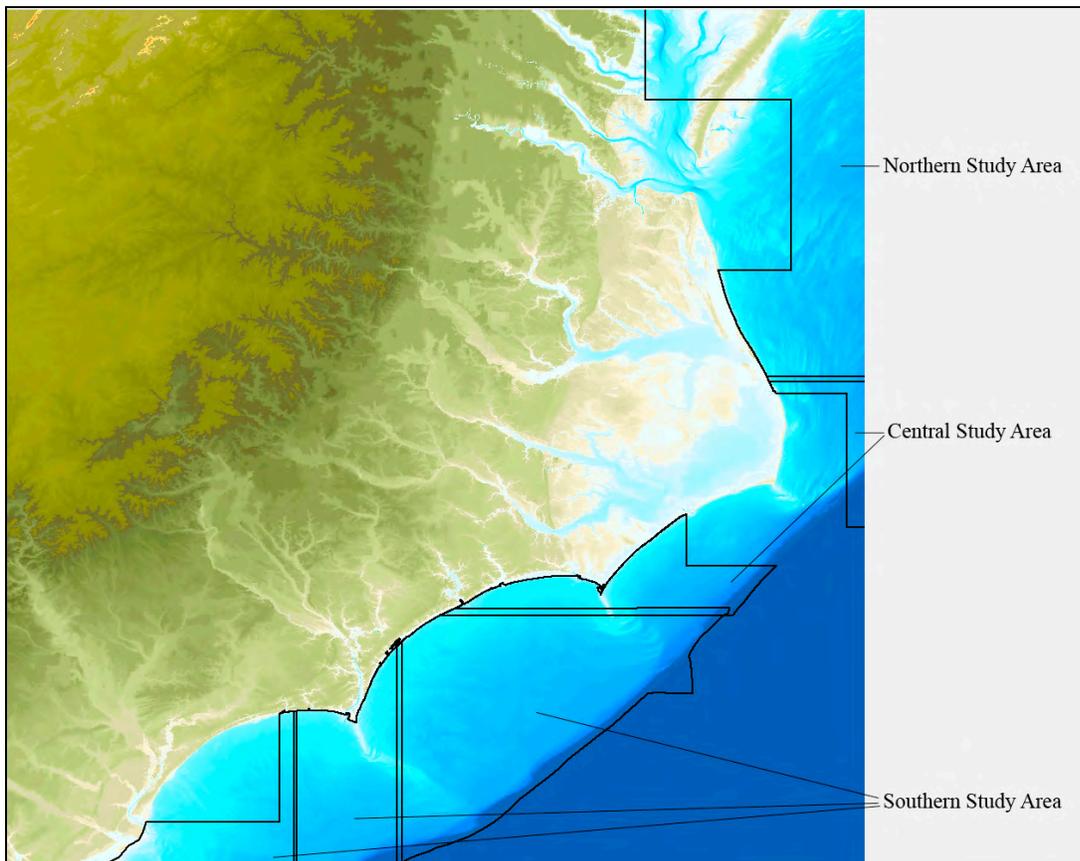

Figure 2.38. Geographic extent of northern, central, and southern study areas and sub-areas

2.4.1.1 Masking the Data

Shapefiles of the smaller study areas were created to use as masks for the interpolation process. This included creating detailed outline of the shore areas using the CHARTS data shapefile as the guide. Additionally, the distribution of the inlet point data was used for creating a detailed outline of the inlet areas. The shapefiles were created with a 250 foot buffer into the CHART shoreline, thus masking off the CHARTS data at that point for use in the interpolation.

2.4.2 Interpolating Offshore Data and Making Corrections

Once all offshore data was gathered, converted, and selected, the points were read into GRASS using the v.in.ascii function to create an observed point coverage. A regularized spline tension interpolation was performed on each subdivided study area using GRASS' v.surf.rst function. The interpolation settings were: -t tension=1300000, smooth=1, segmax=40, npmin=250, dmin=0.0003, and zmult=1.0.

2.4.2.1 Correcting Visible Segments

Each resulting interpolated dataset was examined for outliers and anomalies. When visible segments of no data were observed, a random sampling of data points in that area were gathered using GRASS' r.random and added back into main dataset of xyz points. The interpolation was performed again and the dataset was reexamined.

2.4.2.2 Correcting Outliers

When potential outliers were observed, the points were examined in detail to determine if the outlier was valid. When necessary, the points were removed from the NOS Sounding data by deleting the point from the main xyz point file. The deleted points are summarized in Table 2.5 and an example is displayed in Figure 2.39.

Table 2.5. NOS Sounding Outlier Points Deleted from DEM

Longitude	Latitude	Elevation
-77.5924470	33.9524600	-2.76
-77.4820660	33.8660110	-1.33
-77.5061900	34.3432910	-123.88
-79.0050340	33.0047130	-205.87
-76.5644870	34.2284630	-268.84
-76.4526640	34.3144810	-250.53
-76.6003670	34.1872100	-238.35
-76.6517160	34.1437690	-183.55
-76.5705400	34.0577850	-299.33
-76.6470070	34.0242020	-247.53
-76.6428380	34.0236820	-259.73
-79.6861070	33.9758490	-131.87

| Longitude	Latitude	Elevation
-75.8348420	34.4365860	-158.78
-75.0825380	36.2865540	-7.51
-75.3625230	36.1697500	-19.93
-75.3811280	36.1928600	-62.23
-75.1203640	36.0106740	-6.81
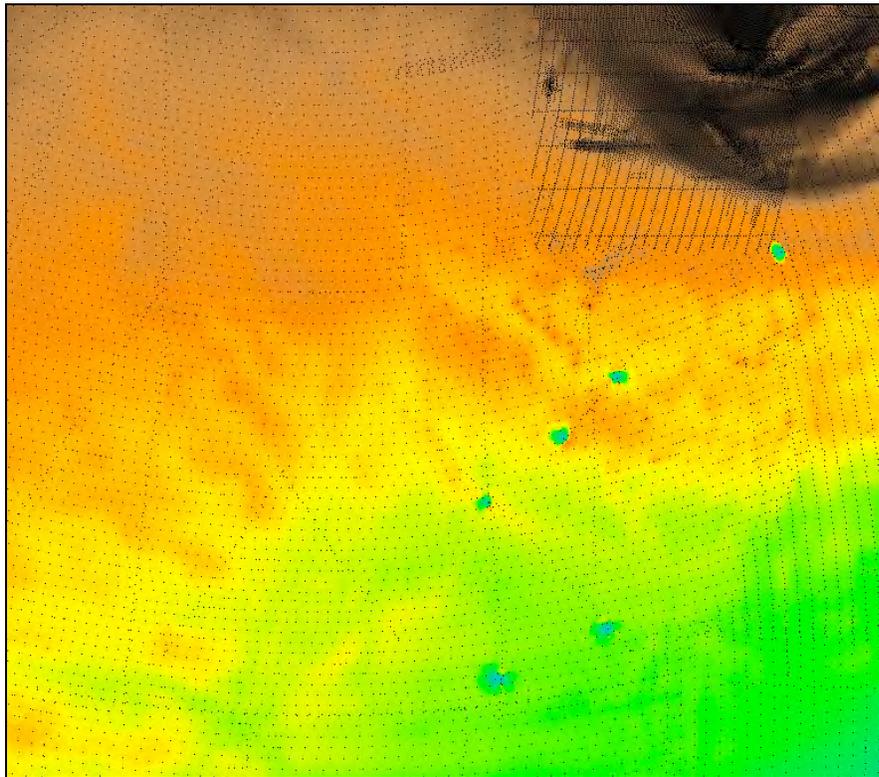
Figure 2.39. Erroneous depths found in NOS Soundings data displayed in blue or blue/green color

2.4.2.3 Correcting Mismatched Shoreline

A mismatch in the shoreline was observed between the Cape Hatteras Tsunami dataset and the CHARTS dataset near Ocracoke Inlet where the two datasets met. To correct this error prior to creation of the DEM, a small mask was created to allow the CHARTS data to overlap the Tsunami dataset on the southern side of the inlet. As a result, the DEM shows one consistent shoreline.

2.4.3 Data Patching

When the six subdivided study areas in the South, Central, and North areas were successfully interpolated, the datasets were patched into one new offshore DEM using GRASS' r.patch function (GRASS GIS Reference Manual: http://grass.itc.it/grass62/manuals/html62_user/r.patch.html).

The offshore dataset was then patched with the topographic datasets in the following order:

Riverine dataset (highest priority)
Manually edited override points
AIWW
CHARTS
Offshore Interpolation (all offshore bathymetry)
Radio Island override mask
Tsunami Datasets of Virginia Beach, Cape Hatteras, Myrtle Beach
NCFMP LiDAR
NED
CRM
ETOPO2 (lowest priority)

The order of patching in GRASS is important as the process will place the first dataset "on top" and fill in areas around it with the second, third, and continue on to the last dataset. Therefore the best data are placed on top of data of successively poorer resolution.

This resulting patched product was called DEM version 2.4 and was formally delivered on September 15, 2008 with this report. The file was a single 10-meter cell resolution ASCII dataset consisting of 54,000 rows by 54,000 columns. The version 2.4 file is over 21 Gb in size.

2.4.4   Data Sources

The relative amount of data from each of the individual sources for the entire dataset is shown in Table 2.6. More information regarding sources and manipulation can be found in Appendix A.

Table 2.6. Datasets and Percentage of Use in Version 2.4 of the DEM

Dataset	Percentage
Riverine	0.04%
Manual Overrides	0.00%
AIWW	0.00%
CHARTS (2005)	0.09%
Offshore Interpolation	19.01%
Virginia Beach Tsunami	4.61%
Cape Hatteras Tsunami	3.94%
Myrtle Beach Tsunami	1.98%
NCFMP LiDAR	12.09%
NED	0.44%
CRM	48.18%
ETOPO2v2	9.61%

For the area of the ADCIRC modeling, below the 15 meter elevation contour, the relative amount of data from each source is shown in Table 2.7.

Table 2.7. Datasets and Percentage of Use for ADCIRC Modeling

Dataset	Percentage
Riverine	0.09%
Manual Overrides	0.01%
AIWW	0.01%
CHARTS (2005)	0.23%
Offshore Interpolation	31.77%
Virginia Beach Tsunami	8.72%
Cape Hatteras Tsunami	8.62%
Myrtle Beach Tsunami	4.18%
NCFMP LiDAR	25.65%
NED	0.19%
CRM	8.92%
ETOPO2v2	11.62%

2.5   Quality Assessment

2.5.1   Visual Inspection and Profile Generation

Both the offshore bathymetry and the complete DEM were reviewed for quality assessment using visual inspection and profile generation. These inspections were performed using both GRASS and ArcGIS and compared to recent Google Earth Imagery.

Because the offshore DEM was generated from six smaller study areas, the DEM was systematically inspected at each of the convergence seams. GRASS' r.mapcalc function was used to limit the profile data area (to narrow the range of elevations used in calculating the profile curve) and r.profile (http://grass.itc.it/grass60/manuals/html60_user/r.profile.html) was used to generate profiles in the GRASS GUI interface. These profiles were used to cut and measure vertical profiles across the "joins" of different datasets to obtain a representation of the change in elevation across the different data sources. This provided a quantitative analysis of the vertical difference where datasets joined. A series of 3 to 5 profiles were performed across each seam and captured. Figures 2.40 provides an example of the seam profiles. Additional images can be found in Appendix B. No large jumps in elevation changes were observed, indicating that the overlap between the datasets allowed for a smooth transition between the datasets.
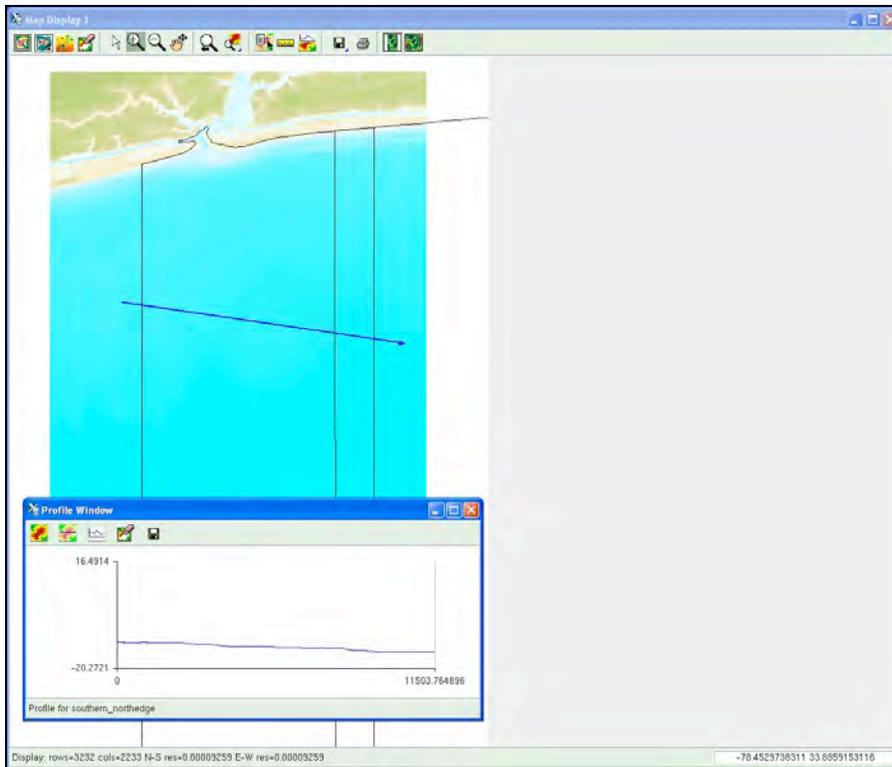
Figure 2.40. Profile for seam between two of the southern study subareas

Profiles were also generated from the shoreline and outward area of the offshore DEM. These profiles were used to examine the data for large elevation changes. A smooth profile indicated a smooth transition between near-shore and offshore datasets. At least three of these profiles were generated for each study area with a shoreline segment. Additionally, profiles were also generated for significant inlets as a method of performing quality assessment on the bathymetry for erroneous elevation changes. Lastly, smooth transitions between the riverine data and other DEM data were verified using similar profiles. Figures 2.41 and 2.42 provide an example of the near-shore profiles and riverine profiles. Additional images can be found in Appendix B.
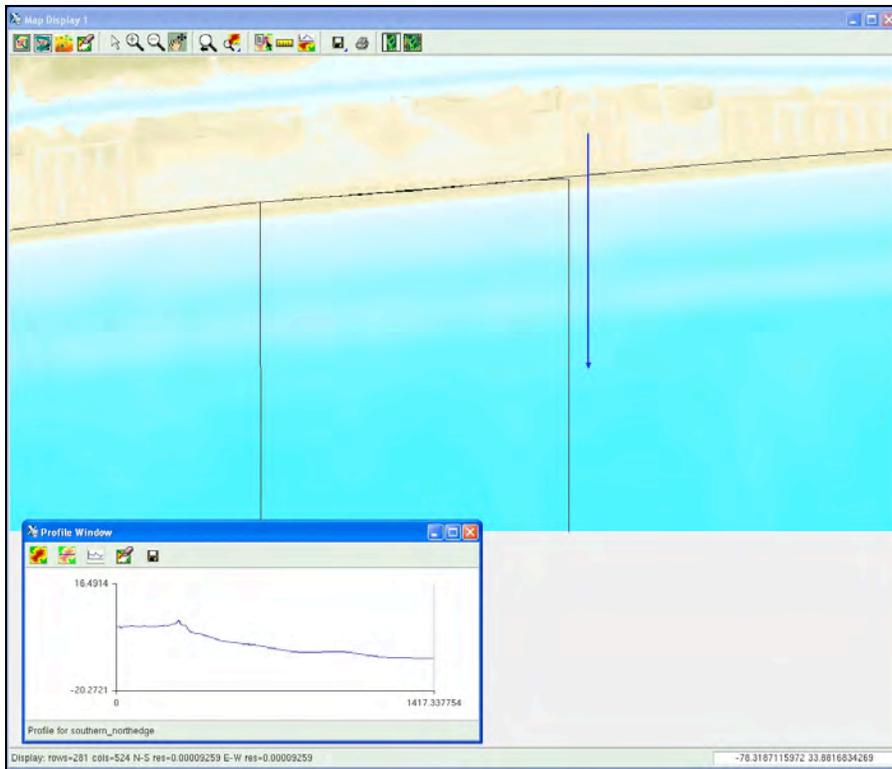
Figure 2.41. Near-shore profile for portion of southern study area
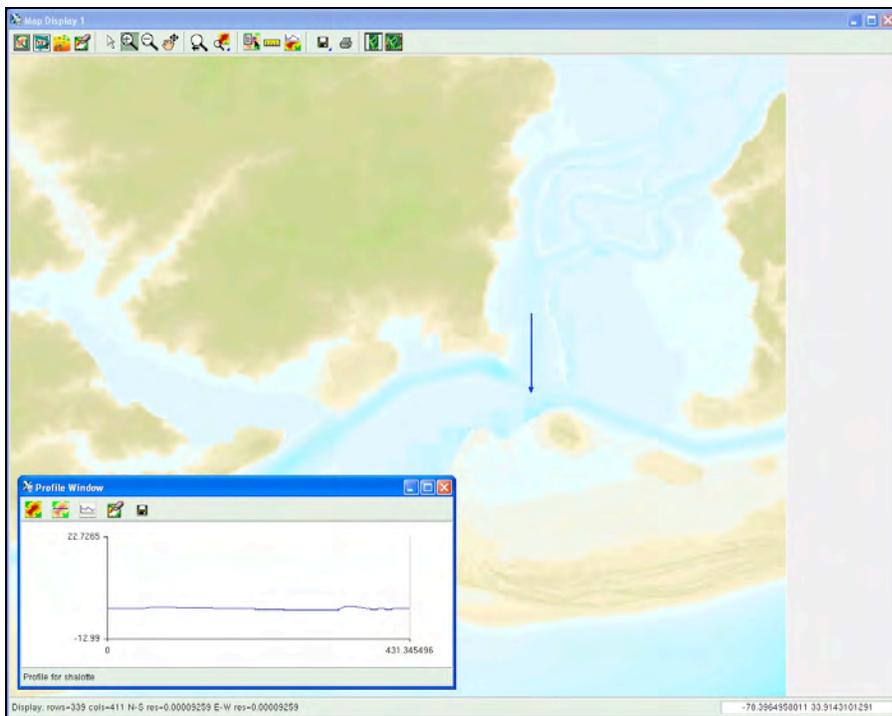
Figure 2.42. Shallotte River profile of interface between riverine and other data

2.5.2   Aspect View

Throughout the DEM, GRASS module r.slope.aspect (http://grass.itc.it/grass60/manuals/html60_user/r.slope.aspect.html) was used to generate a slope map to allow for visual inspection and identification of artificial slopes along boundaries between datasets. Figures 2.43 provides an example of how the aspect view was used to look for slope anomalies across the seams and within the data. In many cases, this was performed while the previously discussed profiles were created and can be seen in profile examples in Appendix B.
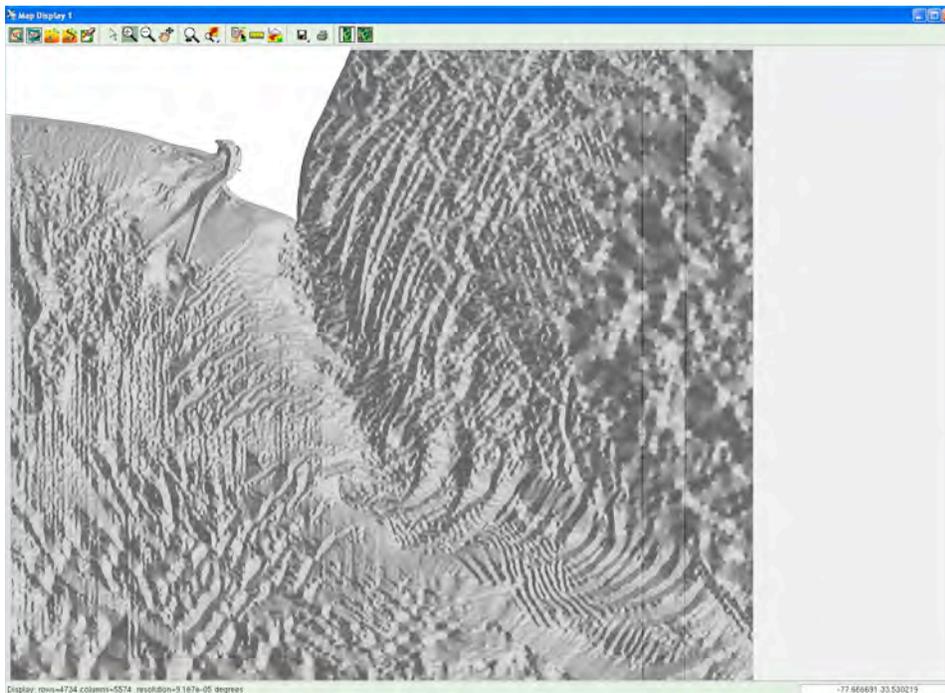

Figure 2.43. Aspect view of seam between two southern study areas - near Cape Fear River

2.5.3   Complete DEM Review

Upon completion of the patch of the offshore DEM and the topographic datasets, the quality assurance process was repeated for the entire DEM.   Visual inspection and profiles were generated to examine the data for any erroneous elevation changes or other anomalies. Previously identified problem areas were closely examined and compared to Google Earth Imagery. Figure 2.45 illustrates how Cape Hatteras appears in the DEM and overlaid Google Earth.   Additionally, the DEM was analyzed and more profiles were generated along the land/water interface. Figures 2.46 provides an example of profiles generated in this process. Additional images can be found in Appendix B.

Figure 2.44. Image of Cape Hatteras overlaid on Google Earth imagery
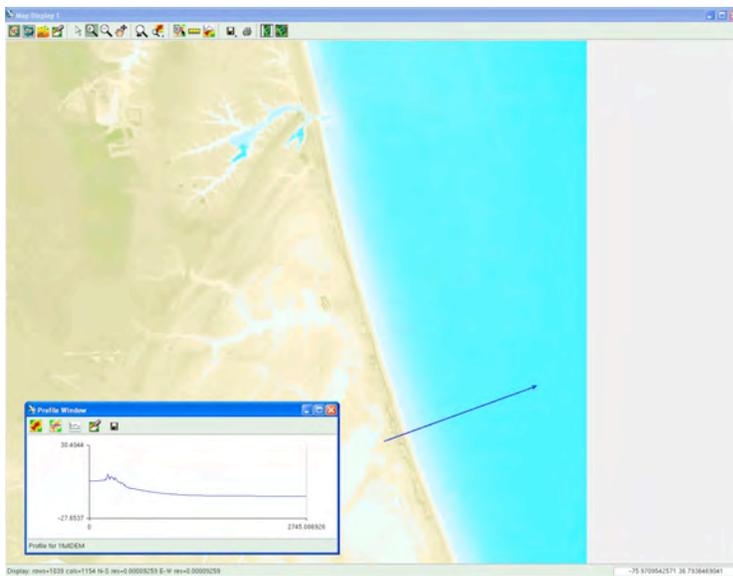
Figure 2.45. Profile of northern shore area

2.6   Difficulty Encountered

Throughout the visual inspection of the quality assessment process, one significant area of concern was identified. There are a number of inland areas (inland from the shoreline but they often represent land/water interfaces on the interior) where what appears to be land in Google Earth is represented as having negative or 0 elevations in the DEM or what appears to be water in Google Earth is represented as having positive elevations in the DEM. For

example, CRM data continues to show missing elevations in some areas (e.g., Mossey Islands).   The control points discussed in 2.2.1.2.5 and prepared by UNC-CH IMS personnel are intended to correct these areas in the inland waterways.

2.7   Summary and Conclusions

An integrated topographic/bathymetric DEM with cell spacing of 1/3 arc-second (~10 meters) of the eastern coastal North Carolina area has been developed with significant revision for the project. The best available data from U.S. federal agencies, state agencies, and universities were obtained and processed for compilation. The comments received in April 2008 were taken into consideration and changes in the interpolation and patching processes were made accordingly.

The data were processed, gridded, and assessed using GRASS, ArcGIS, FME, GMT and MB-System software. The version 2.4 resampled 10-meter raster dataset consists of 54,000 rows by 54,000 columns, and over 2,916,000,000 individual cells and is over 21 Gb in size.

The new coastal statewide DEM is a substantial improvement over the previous version 1.0 DEM and the existing pieces of data currently available for the North Carolina coastal region. However, the limitations of the data used to create the DEM are the limitations of this DEM. As newer, better resolution datasets are gathered, this DEM can be improved by assessing and including those datasets.

Additionally, the changing nature of the shoreline presents a major problem for modeling the coastline as one snapshot in time. As major weather events and standard coastal changes take place, the DEM shoreline will become less accurate. It is recommended that the DEM be reviewed periodically and updated as new data becomes available.

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