DRAFT REPORT FOR REVIEW

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NORTH CAROLINA SEA LEVEL RISE PROJECT: INTERIM TECHNICAL REPORT

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EXECUTIVE SUMMARY

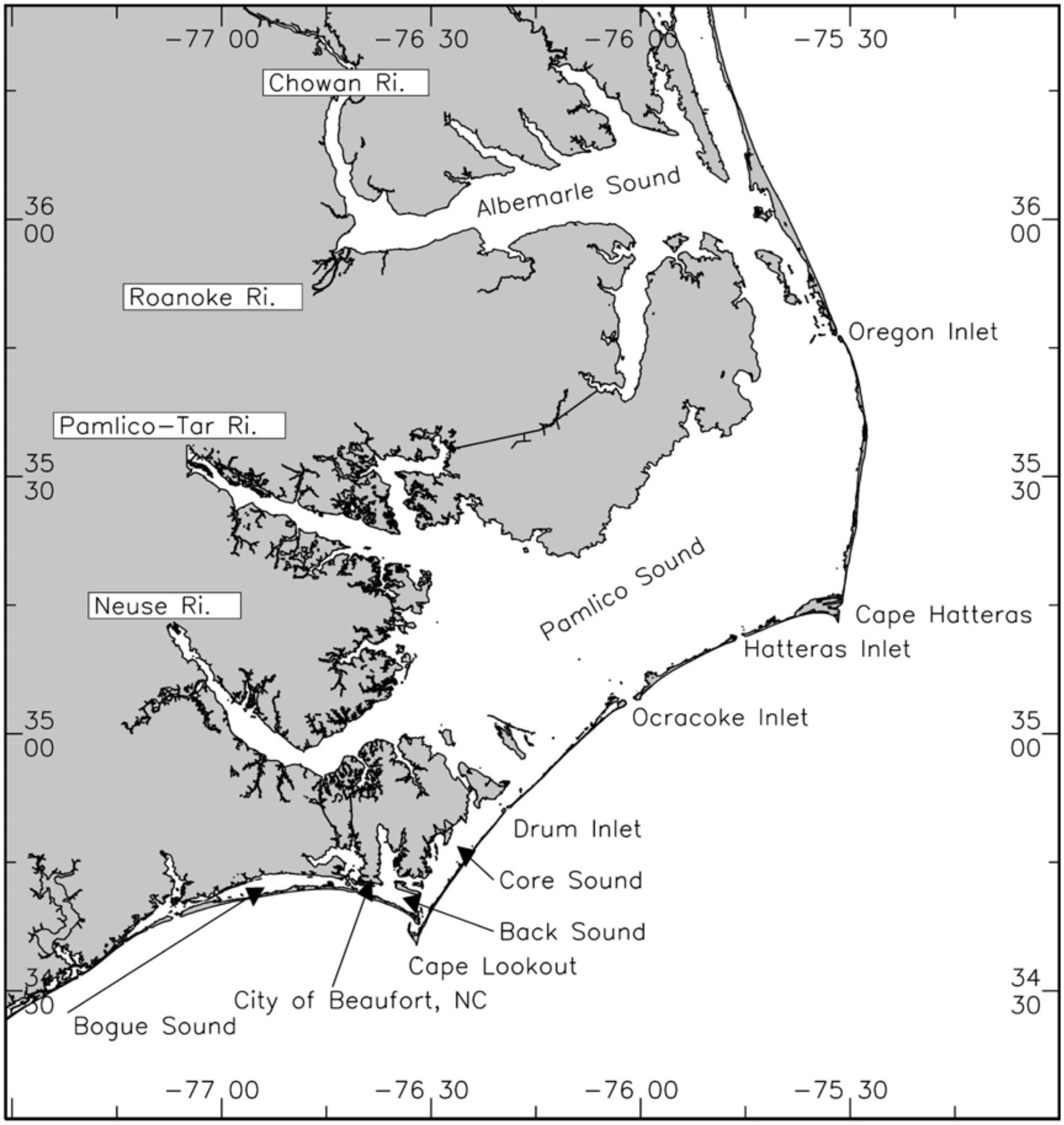
The National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA) has as begun studying the impacts of long-term sea level rise on the coastal ecosystems in the sounds and estuaries of North Carolina. NOS' Office of Coast Survey (OCS), National Geodetic Survey (NGS), and the Center for Operational Oceanographic Products and Services (CO-OPS), are cooperating to develop data sets, modeling tools, and maps that will be useful to coastal managers.

The approach is to simulate projected sea level variations for the coastal region using a coastal flooding model that combines a hydrodynamic model of water levels with a high-resolution digital elevation model (DEM). When developed, the coastal flooding model will be used to simulate long-term rises in water levels and to delineate areas where sea level rise changes inundation due to astronomic tides, winds and waves, and storm surges. Based on project resources and input from state management, the area of the DEM was selected to focus on the southern Pamlico Sound and the region around Beaufort, North Carolina.

During the past year, a hydrodynamic model for tides and water levels has been developed and used to simulate astronomical tides and determine tidal datum fields. Water depths, which NOS archives and are referenced to Mean Low Water (MLW) or Mean Lower Low Water (MLLW), were then adjusted to Mean Sea Level (MSL) using the tidal datum fields and then re-adjusted to a land elevation like the North American Vertical Datum of 1988 (NAVD 88). Finally, the bathymetry for a sub-region of the study area was then integrated with the land elevations from recent airborne lidar data to create a preliminary DEM that covers a portion of the planned area. The software conversion package VDatum was developed as part of the project.

Key words: hydrodynamic model, tides, digital elevation model, sea level rise, wetlands, coastal flooding

BASE MAP



Map of the coastal portion of central North Carolina showing locations mentioned in this report.

1. INTRODUCTION

The National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA) has as begun studying the impacts of long-term sea level rise on the coastal ecosystems in the sounds and estuaries of North Carolina. The study is being led by the Center for Sponsored Coastal Ocean Research/Coastal Ocean Program (CSCOR/COP) of NOS' National Centers for Coastal Ocean Science, which is committed to providing decision makers with high quality scientific information and predictive tools in formats appropriate to promoting near-term improvements in coastal ecosystem management. Technical support is provided by NOS' Office of Coast Survey (OCS), National Geodetic Survey (NGS), and the Center for Operational Oceanographic Products and Services (CO-OPS), which are cooperating to develop data sets, modeling tools, and maps that will be useful to coastal managers. The technical personnel and their activities are shown in Appendix A.

The approach is to simulate projected sea level variations for the coastal region using a coastal flooding model that combines a hydrodynamic model of water levels with a high-resolution digital elevation model (DEM). When it is developed, the coastal flooding model will be used to simulate long-term rises in water levels and to delineate areas where sea level rise changes inundation due to astronomic tides, winds and waves, and storm surges. Ultimately, coastal wetland and forest ecosystems as well as human-made structures will be added to the coastal flooding model to simulate their influences and alterations. The resulting information will be depicted on maps detailed enough to allow managers to see projected shoreline changes and to display predictions of ecosystem impacts. Using these predictions, coastal managers can proactively plan mitigation.

Based on project resources and input from state management, the area of the DEM was selected to focus on the southern Pamlico Sound and the region around Beaufort (Figure 1). This area includes both types of geologic provinces: the flatter, large-lagoon geography typical of the State's coast north of Cape Lookout, and the greater-sloped, narrow-lagoon geography typical of the coast further to the south (Pilkey et al., 1998). Progress in the development of the models and DEM was discussed at a workshop in Beaufort, North Carolina, during February 4-5, 2004 (Auer et al., 2004).

As a preliminary step in creating the coastal flooding model, during the past year (March 2003 to April 2004) a hydrodynamic model for tides and water levels has been developed and used to simulate astronomical tides and determine tidal datum fields. Water depths, which NOS archives and are referenced to Mean Low Water (MLW) or Mean Lower Low Water (MLLW), were then adjusted to Mean Sea Level (MSL) using the tidal datum fields and then re-adjusted to a land elevation like the North American Vertical Datum of 1988 (NAVD 88). Finally, the bathymetry for a sub-region of the study area was then integrated with the land elevations from recent airborne lidar data to create a preliminary DEM that covers only a portion of the planned area.

The adjustment of water depths from MLLW or MLW to NAVD 88 is being carried out by use of the software tool for vertical datum transformation, VDatum (Parker et al., 2003). VDatum, which requires the tidal datum fields from the hydrodynamic model, is under development and will eventually cover most of the marine water areas in North Carolina.

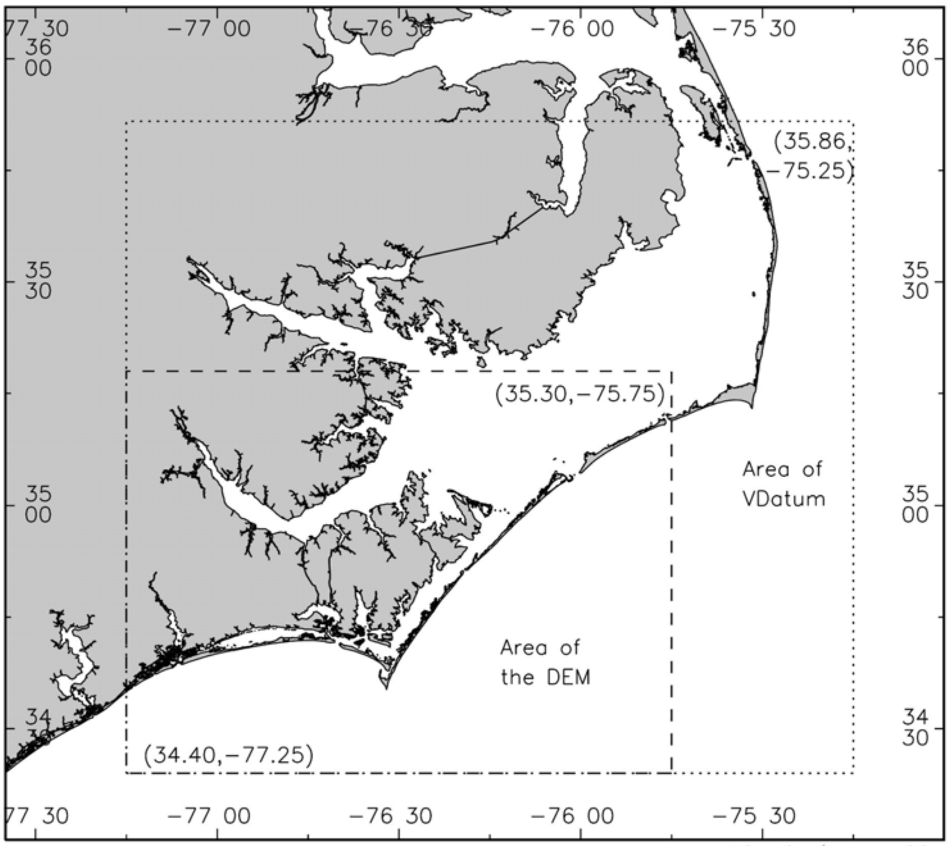


Figure 1. The Pamlico Sound area of North Carolina showing the region of the DEM and of VDatum. The DEM is defined on the lower left by point (34° 24' N, 77° 15' W) and on the upper right by point (35° 18' N, 75° 45' W). The VDatum area is defined by the same lower left point, and on the upper right by point (35° 51.6' N, 75° 15' W).

The following sections describe the technical approach and the progress to date in the major components of the study:

- Access of historical NOS bathymetric, coastline, and tidal data,
- Development of the hydrodynamic grid and model,
- Integration of the land and bathymetry into a DEM, and
- Creation of the coastal flooding model.

Appendices include a description of the project staff and the locations and names of the water level stations.

2. BATHYMETRIC, WATER LEVEL, AND COASTLINE DATA

Water level model development for the Pamlico Sound region requires several types of data. Bathymetric data is available from NOS and other sources, and model validation depends on comparisons to datums based on observed water levels. Updated tidal datums were therefore derived for several local tide stations, and a new tide station was installed in Core Sound. Historical water levels were re-analyzed to determine updated estimates of long-term sea level rise. A digital coastline was accessed and used to delineate land and water areas.

2.1. Bathymetric Data

Water depths from historic NOS bathymetric surveys of the North Carolina coast were selected for sounding values from the GEOphysical DAta System (GEODAS) created by NOAA's National Geophysical Data Center (NGDC). About 90% of the study area is covered by NOS sounding data. Bathymetric data sets were processed from nearly 1,659,000 soundings extracted from 148 hydrographic surveys spanning the years 1869 to 2001. Individual surveys lasted from several days to several months. Sounding methods reported in GEODAS assume lead line surveys before 1940, and digital echo sounder surveys from 1940 onward.

According to NGDC, the horizontal accuracy of the soundings is generally 30 m, with improved accuracy of recent surveys that employ a differential global position system (DGPS). GEODAS converts original depth units (feet or fathoms) to tenths of meters. For common reference, the original horizontal datum of each survey was transformed to NAD 83(86) using the North American Datum Conversion utility (NADCON). Soundings from the 30 oldest (about 20% of the total) surveys acquired before 1927 were initially converted to NAD 27 and then to NAD 83(86). Historic NOS survey data sets were cleaned of missing depth values (denoted by a depth value of -99999), sorted and merged by year and by original vertical datum. Soundings in each survey were checked against adjacent and overlapping surveys to ensure continuous coverage. Thirty-four spatial-temporal filters were applied to select and compile the best available NOS historical bathymetry for the project area, which resulted in approximately 1,210,910 useful soundings.

The NOS sounding data are referenced to one of several vertical datums; each sounding has associated metadata that lists whether the depth value is referenced to Mean Low Water (MLW), MLLW, or the low water datum (LWD), which is defined for North Carolina as 0.5 feet (0.15 meters) below the local Mean Water Level (MWL). MWL is the average water level over the available record. Analysis of tidal data included in NOAA hydrographic reports reveals that LWD is usually used for surveys within Pamlico Sound at locations far from inlets. Vertical accuracy of the NOS soundings conforms to the international hydrographic standard: 0.3 m in 0 to 20 m of water, 1.0 m in 20 to 100 m of water, and 1% of the water depth in waters of 100 m depth or deeper. The plots below show the age of the NOS historical data (Figure 2), as well as the sounding density (Figure 3).

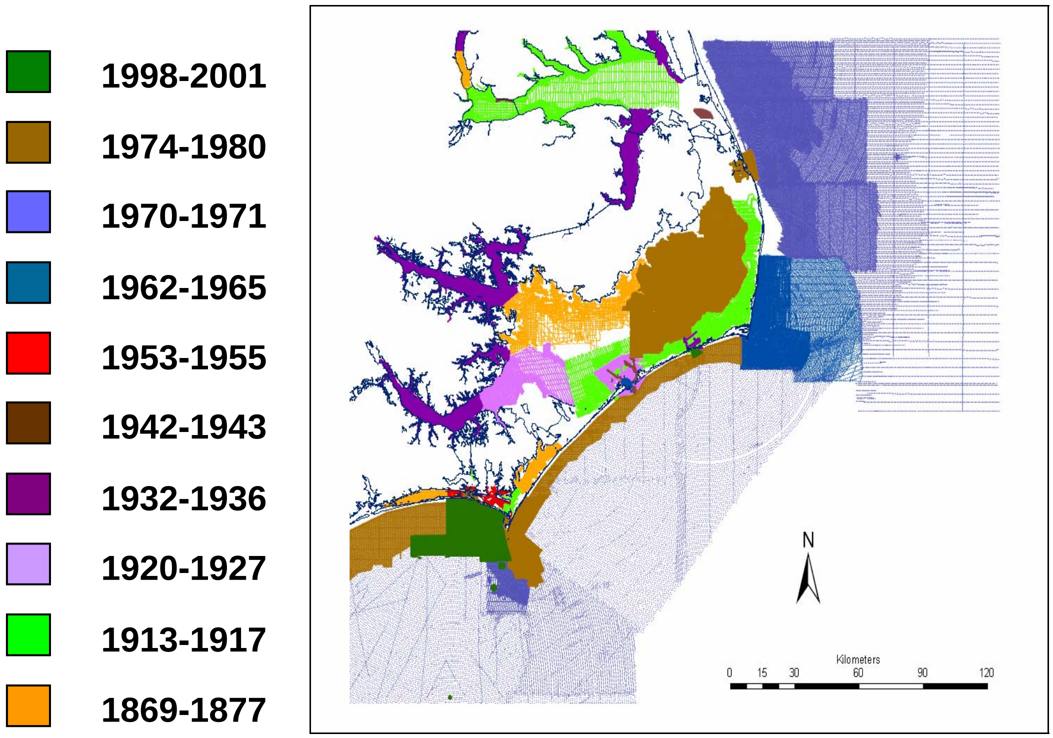


Figure 2. Dates of NOS surveys.

Figure 3. Location of soundings from NOS surveys in North Carolina.

Historical NOS bathymetry data are also available in an interpolated, gridded format as part of NOAA's Coastal Relief Model (CRM) at NGDC. CRM gridded bathymetry are available at a horizontal spacing of 3 arc-seconds, or approximately 90 m, while elevations are resolved to 0.1 m. However, CRM depths have not been corrected from their original vertical datum (MLW, MLLW, or LWD).

Recent bathymetry data from the U.S. Army Corps of Engineers (USACE) originate from 54 small surveys processed to 61,573 soundings for some of the inlets. Where applicable, these channel soundings blend with or supersede the NOS bathymetry (see Section 3.3).

2.2. Tide and Water Level Data

Tidal datums and other data (e.g., harmonic constants and time series of water levels) are available from NOS for numerous historical stations around the region (Figure 4). These are used for comparison with the model output. Station location and tidal datum values are given in Appendix B.

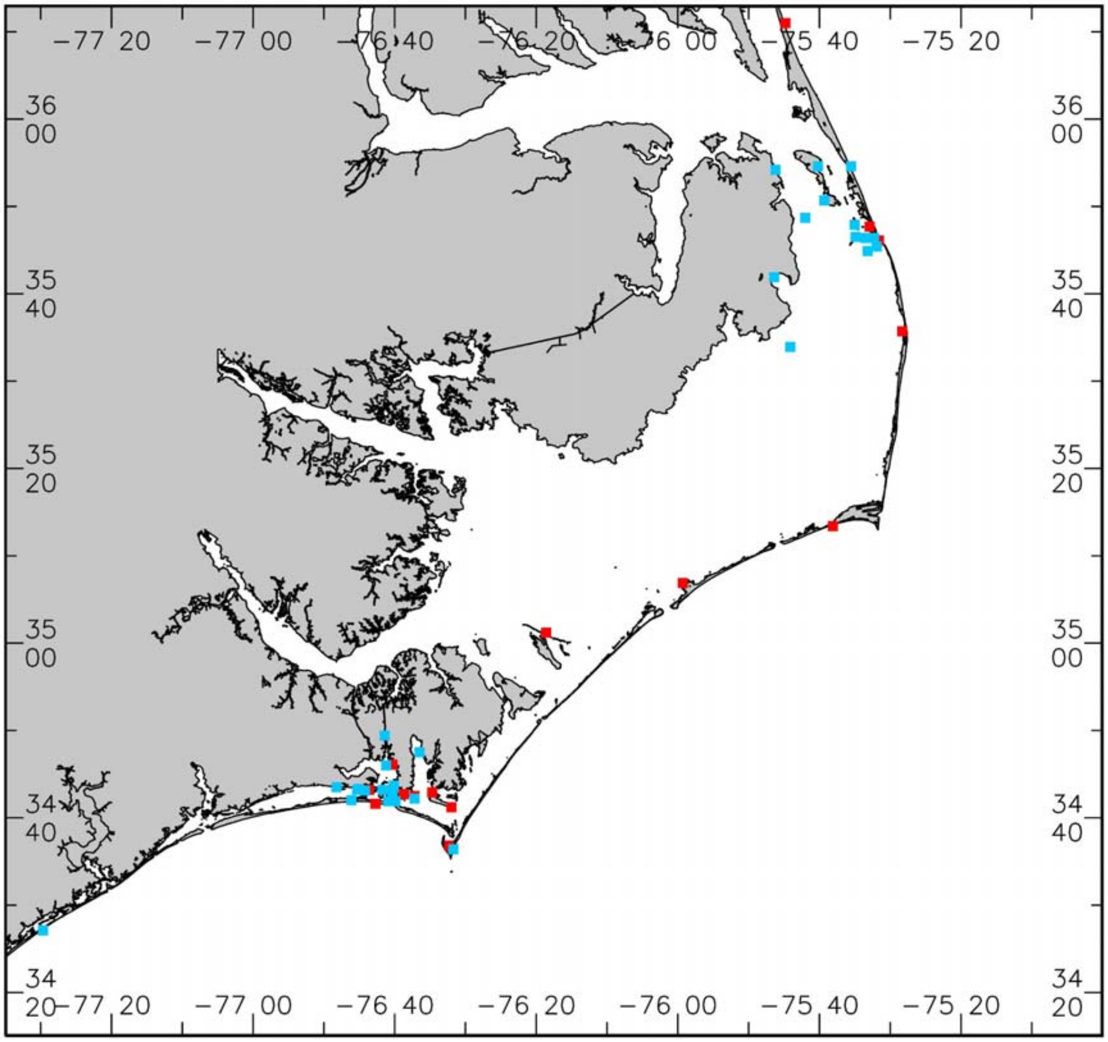


Figure 4. Locations of 45 water level stations (red and blue squares) used in the study. Datums at locations denoted by red squares have been updated to the 1983-2001 tidal datum epoch, while datums at other locations are for earlier epochs. See Appendix B for further information.

As part of the study, a short-term tide station was installed at the town of Sea Level, North Carolina, on Core Sound in late January 2004. Six-minute interval water level data are being collected every hour over GOES satellite radio transmissions and are quality controlled and processed at CO-OPS. The station will be operated from 3 to 4 months, at which time tidal datums will be computed. Tidal datum elevations relative to local benchmarks and to geodetic datum will be determined as well. Geodetic datum connections are being made in partnership with the North Carolina Geodetic Survey, which will be occupying the tidal benchmarks with GPS.

2.3. Long-term Sea Level Rise

An in-depth analysis of historical North Carolina water level data was carried out as part of the project (Zervas, 2004). MSL and tidal datum trends will be applied to a coastal DEM for North Carolina in order to predict shoreline movements and to map submerged zones that may occur 25 to 50 years in the future. MSL trends were obtained from monthly data from eight North Carolina stations (Duck, Oregon Inlet Marina, Cape Hatteras, Beaufort, Atlantic Beach, Wilmington, Southport, and Yaupon Beach). Where there were significant gaps in the data, comparisons were made with the stations with more complete records to narrow the trend confidence intervals. The calculated MSL rise increases with latitude from 1.79 mm/yr at Yaupon Beach in the south to 4.27 mm/yr at Duck in the north, with an overall average rise of 2.74 mm/yr. Average seasonal cycles were similar for all stations, with the highest monthly water levels in the early fall and lowest monthly water levels in the winter. The longest time series (68 years at Wilmington) shows no significant changes in the average rate of rise over the period of the data.

The mean and great diurnal ranges were analyzed to determine any long-term changes in tidal range. Oregon Inlet Marina, Beaufort, and Wilmington have large (greater than 3 mm/yr) and statistically significant increases in tidal range. Stations directly on the Atlantic Ocean had no such increase in tidal range. Harmonic analyses were carried out for a period near the installation date of the above three stations and for 2002. The observed increases in the amplitude of the largest tidal constituent (M_2) agree with the calculated increases in tidal range. For these three stations, the Mean Higher High Water (MHHW), MHW, MLW, and MLLW trends were calculated. Continual dredging of the channels connecting these stations to the ocean has resulted in significant variation in the trends of the different tidal datums. High water datums have been rising at a rate significantly faster than the MSL trend. Whether or not this difference in trend continues depends on future dredging activity and on the opening or closing of inlets in North Carolina's chain of barrier islands.

2.4. Digitized Coastline

Digital files containing the mean high water (MHW) and the mean lower low water (MLLW) line were obtained from the Coast Survey’s Extracted Vector Shoreline (EVS) project. The digital files contain points defining the coastline that were extracted from digital images of NOS’ nautical charts, and were used for identifying the land-water boundary. A sample is shown in Figure 5.

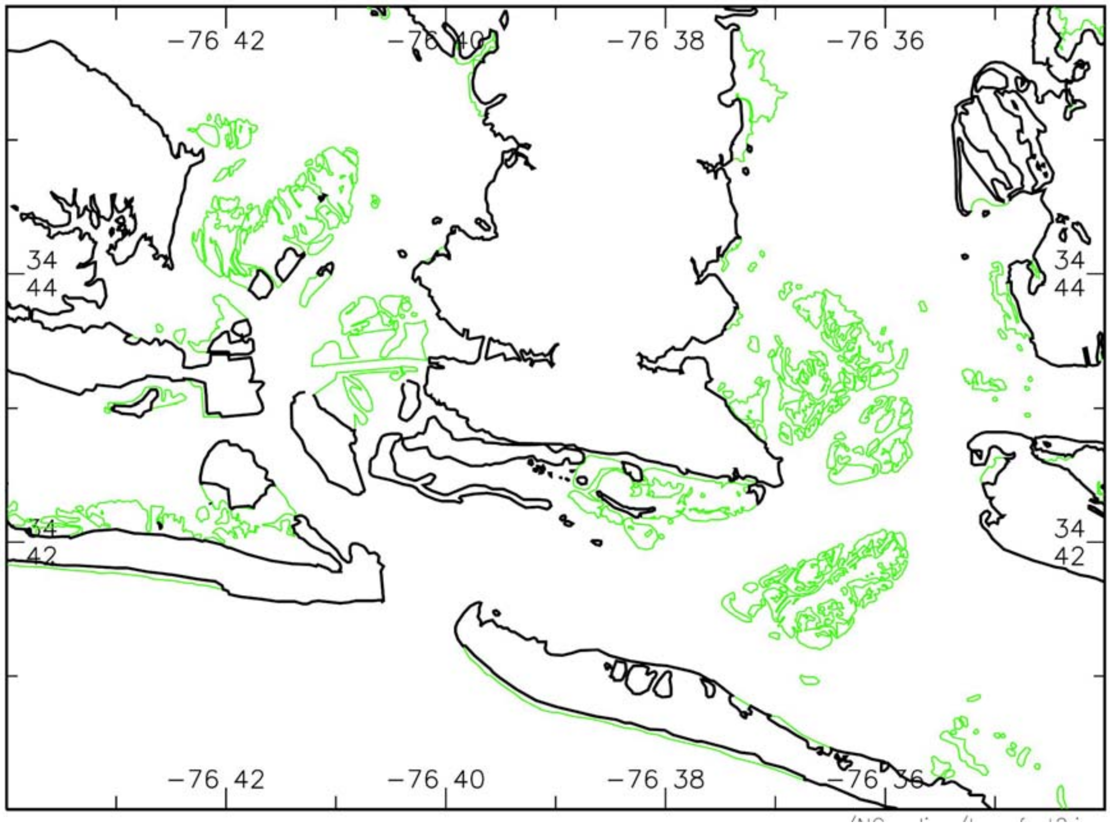


Figure 5. Sample of the extracted vector shoreline for MHW (black) and MLLW (green).

3. TIDAL AND HYDRODYNAMIC MODELING

As part of the tidal model development, a high-resolution finite element hydrodynamic model was created for the study area. Historical bathymetry from NOS and other sources was used to populate the grid with depths. The model was run numerous times to simulate astronomical tides, and further revised and calibrated until it produced relatively accurate tidal datum information. Tidal datum fields have been produced, and bathymetry was re-referenced to MSL.

3.1. The ADCIRC Model

Tide modeling was accomplished using ADCIRC, the ADvanced CIRCulation model for oceanic, coastal and estuarine waters. The model runs in two-dimensional (i.e., barotropic) mode on an unstructured grid composed of triangular elements; this type of grid is ideally suitable for representing complex coastlines to any desired resolution, and can be easily modified to add spatial resolution in any geographic area with little effort. The grid must then be populated by bathymetry to represent the region, and boundary forcing must be added to simulate astronomical tides and other causes of water level variability.

The ADCIRC model was developed by Dr. Rick Luettich at the University of North Carolina at Chapel Hill, Institute of Marine Sciences, and by Dr. Joannes Westerink at University of Notre Dame, Department of Civil Engineering and Geologic Sciences (Luettich, et al., 1992; Luettich and Westerink, 2003). This model is a system of computer programs that solves time-dependent, free surface circulation and transport problems in two and three dimensions. The ADCIRC Two-Dimensional Depth Integrated (2DDI) version, used for the North Carolina area studies, is the barotropic version of the model. ADCIRC utilizes the finite element method in space, taking advantage of highly flexible, irregularly spaced grids. Numerous studies have shown this model to be robust throughout the Eastern North Atlantic and Gulf of Mexico regions (Luettich and Westerink, 1995; Mukai et al., 2001).

3.2. Model Grid Development

The modeling strategy was to create a regional grid (Figure 6) by taking a portion of a larger scale grid, in this case, a course grid of the western North Atlantic grid (Westerink et al., 1994). Then, additional cells were added to incorporate the sounds, which were not present in the original grid. The grid in the sounds was combined with a grid obtained from Rick Leuttich. Finally, additional cells were added to the area around Beaufort. The final grid contains 36,409 nodes, and the smallest cells have a node spacing on the order of 20 m. A portion of the high-resolution part of the grid around Beaufort is shown in Figure 7.

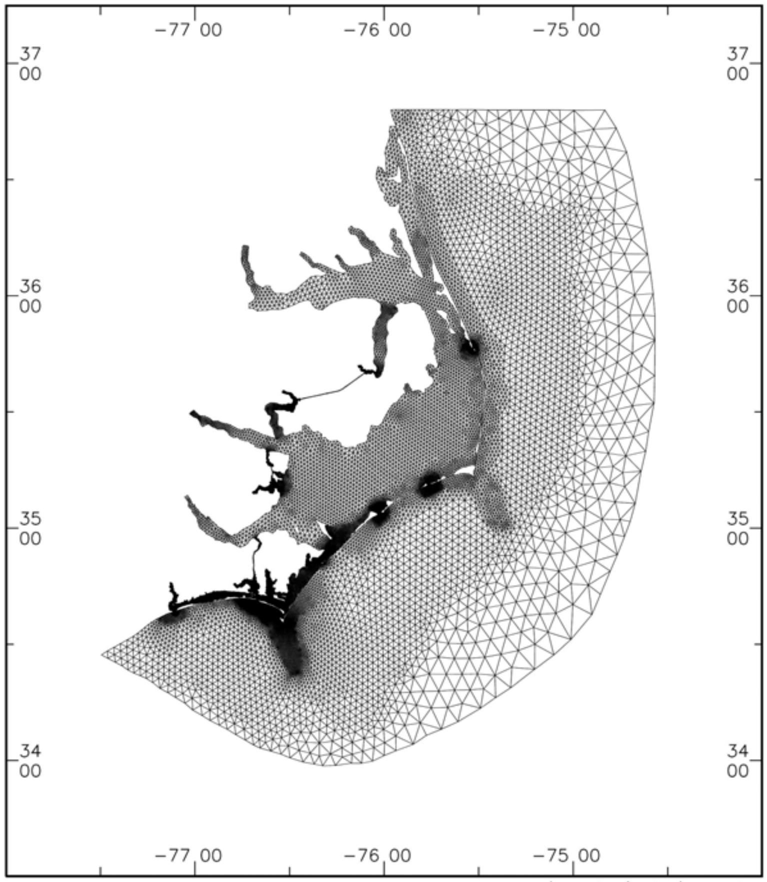


Figure 6. Model finite element grid for the regional model.

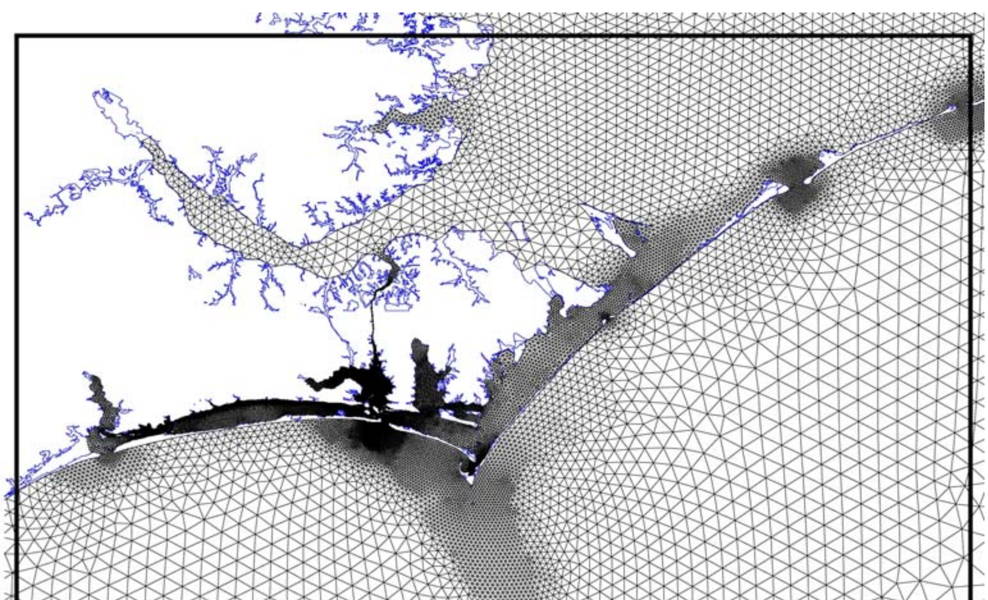


Figure 7. Model finite element grid with DEM boundary (dark black box) and MHW coastline (blue).

3.3. Bathymetric Data for the Model Grid

The bathymetric data used to populate the model grid came from five different sources. These data are: (1) Post-Hurricane Isabel Army Corps of Engineers sounding data, (2) Pre-Hurricane Isabel Army Corps of Engineers sounding data, (3) NOS historical sounding data, (4) Coastal Relief Model (CRM) data, and (5) manually digitized NOAA paper nautical charts. The Post-Hurricane Isabel Army Corps of Engineers sounding data, henceforth referred to as POST-ISA, is referenced to MLW, and was obtained after the passage of Hurricane Isabel on September 18, 2003. The Pre-Hurricane Isabel Army Corps of Engineers sounding data, henceforth referred to as PRE-ISA, is referenced to MLLW. The NOS sounding data is referenced to one of several datums; each sounding has associated metadata that lists whether the point is referenced to MLW, MLLW, or a low water datum (LWD). The CRM data is referenced to MLW. The NOAA paper nautical chart data, digitized 15 years ago at the University of North Carolina, are referenced to MLW; these data points were incorporated into a finite element grid, which was made available to NOS.

The depth value for each node in the grid was obtained by averaging the depth values from the highest-priority source located within the area covered by all triangular cells with a vertex at the node.

The depths were adjusted to MSL by an iterative process. Initially, a MSL-to-LWD difference of 15 cm in the portions of Pamlico Sound where LWD was used, and estimated MSL-to-MLW and MSL-to-MLLW differences of 50 cm elsewhere were applied to the bathymetric depths. After the first and each subsequent 30-day tide simulation, the computed water levels at each node were saved and analyzed to extract the tidal datums. Then the MSL-to-MLW, MSL-to-MLLW, and MSL-to-LWD differences were averaged for each triangular element and applied to the bathymetric depths from the original sources within that element. Depth adjustments at most locations converged to within 1 cm of their final values after three simulations. Note that the modeled MSL, determined by averaging 6-min values at each node, differs from the model's zero elevation in Pamlico Sound by approximately 5 cm.

Inter-tidal areas often did not have depth values, since neither NOS nor USGS measures depths in those areas, and lidar data are usually not collected at the times when the water level is at or below MLLW. Therefore, depths in those inter-tidal areas that had no elevation values were assumed to be everywhere 15 cm below MSL.

3.4. Boundary Forcing

The outer coastal boundary of the regional grid (Figure 6) is forced with periodic water level variations to simulate astronomical tides. The water level, relative to the model's zero elevation, at each node along the outer boundary is

$$H = h_o + \sum f_n A_n \cos (\omega_n t + [Vo + u]_n - \kappa_n) \quad (1)$$

where H is the total water level (m), h_o represents a constant offset (here taken to be zero), and the remaining term represents the astronomical tide. A_n is the constituent amplitude (m), ω_n is the constituent speed (degrees/hr), *t* is the time, $[Vo + u]_n$ is the equilibrium angle (degrees), and κ_n is the phase relative to Greenwich time (degrees). There is a unique set of harmonic constants at each grid node along the coastal boundary; a sample is shown in Table 1.

Table 1. Sample of the tidal constituents and harmonic constants used to force the regional model.

Constituent	Amplitude (m) A_n	Phase (deg) κ_n
K_1	0.091433	177.978
O_1	0.068979	191.636
Q_1	0.012528	177.459
M_2	0.408000	351.313
S_2	0.074515	10.154
N_2	0.096141	336.247
K_2	0.017007	16.020

For the simulation of water levels that are to be used to generate tidal datums, as opposed to simulating the tide for a specific date, the day and year of the simulation is not important. Therefore, for the following model runs the lunar node factor, f_n, was set to 1.0 and the equilibrium angle $[Vo + u]_n$ was set to 0.0.

3.5. Results of Model Water Level Simulations

The model was run to simulate astronomical tides, and the time series of water levels were analyzed to determine tidal datums. The datums at each node in the grid were found by extracting the high and low waters, categorizing them as highs, higher highs, lows, or lower lows, then averaging. The computed datums were compared to those based on observations at 45 water level stations. The root mean square (RMS) difference between the modeled and observed MHHW, MHW, MLW, and MLLW datum values, relative to MSL, was 5.1 cm. A plot of the MHHW and MLLW comparisons is shown in Figure 8.

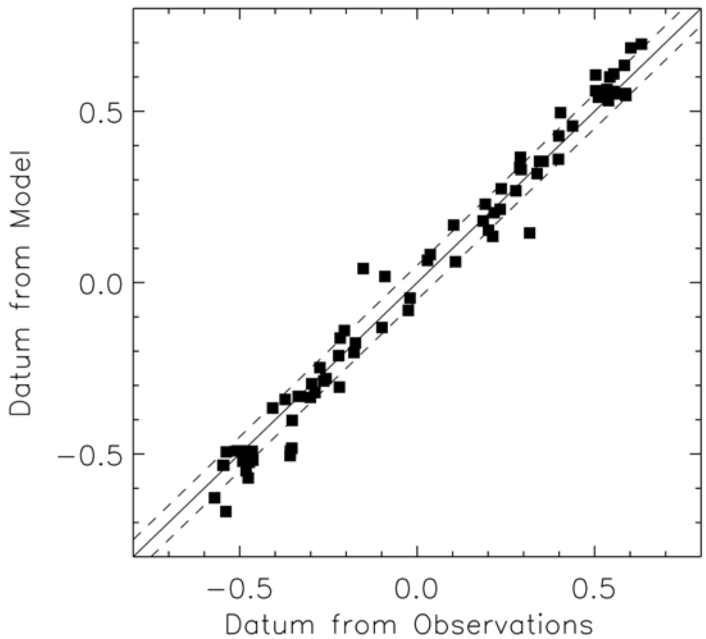


Figure 8. Comparison of the MHHW and MLLW tidal datums (m) obtained from observations (horizontal axis) and the hydrodynamic model (vertical axis). RMS error for both datums was 4.5 cm.

As described in Section 3.3, the tidal datums were used to correct the NOS bathymetry, which is referenced to MLW, MLLW, or LWD. The bathymetric data were used in the hydrodynamic model when re-referenced to the model's zero elevation. The modeled fields for MSL and tide range (MHW minus MLW) are shown in Figures 9 and 10.

Freshwater flows for the Neuse, Pamlico-Tar, Roanoke, and Chowan Rivers were added to the water level model to assess their influence on mean levels. The differences between the tide-only and the tide plus river forcing was negligible, except in the upper reaches on the rivers, where differences on the order of less than 1 cm was found. The simulated flowrates (Amein and Airan, 1976) are shown in Table 2.

Table 2. Freshwater inputs to the major rivers to Pamlico and Albemarle Sounds (from Amein and Airan, 1976). The estimated flow from marshes directly into the sounds was 4,000 cfs.

River	Gauged Flowrate (cfs)	Estimated Ungauged Flowrate (cfs)	Total Flowrate (cfs)	Total Flowrate (m^3/s)
Neuse	3938	1242	5180	146.6
Pamlico-Tar	2420	2150	4570	129.4
Roanoke	8155	1185	9340	264.4
Chowan	315	5020	5335	151.0

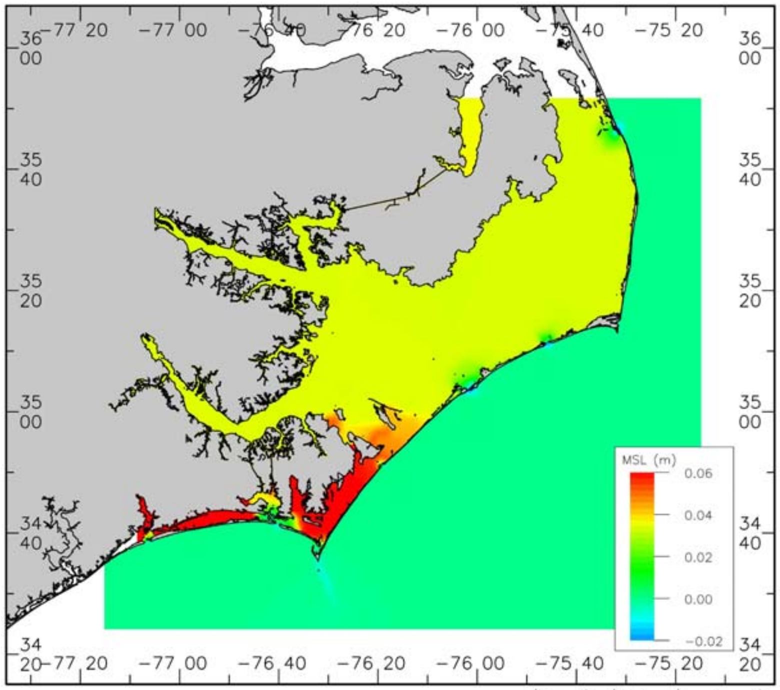


Figure 9. Mean sea level (relative to the hydrodynamic model's zero elevation) as computed by the hydrodynamic model.

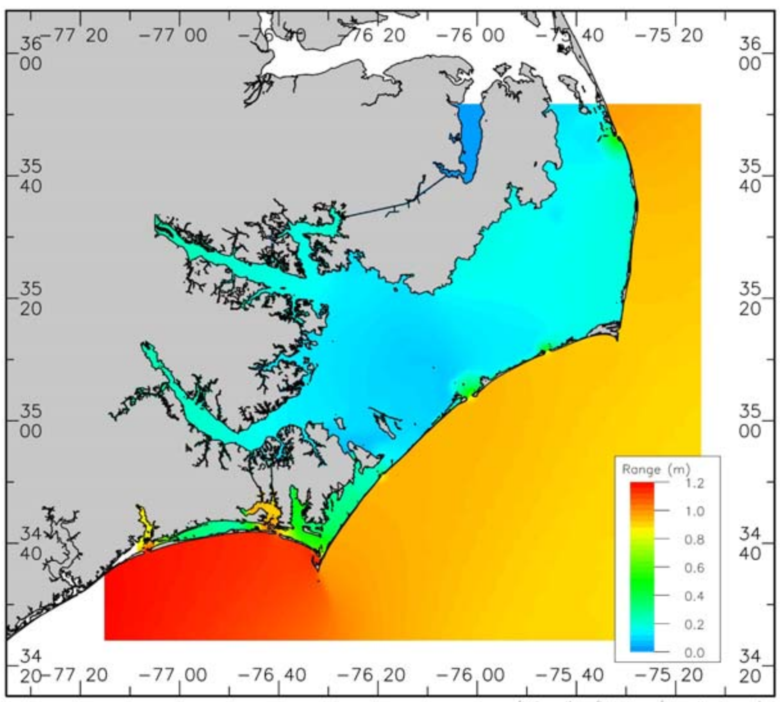


Figure 10. Tide range (i.e., the difference between MHW and MLW) as computed by the hydrodynamic model.

4. CREATION OF THE DIGITAL ELEVATION MODEL

North Carolina land elevation data from several sources, including the Federal Emergency Management Agency (FEMA) sponsored statewide lidar survey, was acquired and processing was begun on a limited area (White and Sellars, 2004). Using existing benchmark data, a sea surface topography (TSS) was generated. A preliminary DEM for part of the study area has been developed. The DEM integrates the bathymetry and the land elevations at a 6-m horizontal resolution.

4.1. Data Sources

For developing a combined topographic/bathymetric digital elevation model, various data sources were evaluated. Three different data sources of elevation data were assessed for this part of the elevation model. All three data sources are available through the Web. These sources are:

- North Carolina FEMA lidar data,
- Shuttle Radar Topographic Mission (SRTM) Data, and
- USGS' digital National Elevation Dataset (NED)

The raw FEMA lidar data has a horizontal resolution of 4 to 6 m and a vertical accuracy of 20 centimeters in coastal counties and 25 cm in inland counties. The available elevations consists of the original data and the bare earth data. The bare earth data are the original point data that have been thinned to consist of only the lidar returns that represent the ground surface. This includes removing lidar returns capturing vegetation, buildings, power lines, birds, etc. However, once the original lidar point data were thinned, there are holes and gaps in the lidar returns.

The bare earth data have two formats: the point data and the regularly gridded data. The second format is a regular raster grid representing a bare earth surface. These raster cells have a 6.1-m spacing and are filled with a z-value depicting the vertical elevation within the bounds of the cell. The raster dataset was obtained by first creating a Triangular Irregular Network (TIN) from the bare-earth point data. A regular grid was then populated through the extraction of elevation information for each grid cell from the corresponding TIN using linear interpolation. The use of tinning, however, produces artificial elevations along coastal areas where water bodies are not properly masked out. Therefore, the bare earth point data were used for the preliminary DEM.

General issues that are apparent when reviewing the North Carolina FEMA lidar data are that both the bare-earth point data and the regular grid bare-earth data contain sites of missing data within the study area. Since there are no lidar data for some areas, data from another source (e.g., the NED) would have to be utilized to fill in gaps. The second concern is that the data are not tide coordinated; when lidar data are acquired at varying tide stages, the amount of the shoreline exposed will differ.

4.2. Re-referencing the Bathymetric Data

Each bathymetric data point was adjusted to local MSL based on the tidal datums produced from the tidal model of the region (see Section 3). The model produced these tidal datums at all nodes in the finite element mesh. The datums for an element were determined by taking the average of the datums at the three nodes that compose an element. To adjust a bathymetric data point to MSL, first the data point was located within one of the grid elements. Next, the difference between MLW and MSL or MLLW and MSL for that element was applied to the bathymetric sounding point depending on the original sounding reference. For points where the metadata indicated that the data came from a LWD area, the bathymetry was adjusted 0.15 meters to MSL.

At some locations, data was available from several sources. Priority was given first to the POST-ISA data, then the PRE-ISA data, then the NOS soundings, then the CRM and finally the NOAA chart data. This means that all POST-ISA points within the DEM region were used. A tolerance distance of 0.0004 arc-degrees (~20.6 ft) was set. The PRE-ISA data was examined and any points that fell within the tolerance distance from any POST-ISA data point were eliminated. Points that were further by the tolerance distance from the PRE-ISA data were retained. Next, the NOS data points were compared to both the POST-ISA and PRE-ISA data points. Any NOS points closer than the predetermined tolerance were eliminated. The CRM data was compared to the PRE- and POST-ISA data as well as the NOS data to make sure the CRM data didn’t supercede data from any of those sources. Additionally, CRM data with 0.0 or –99999.0 depths were eliminated, since these two depths were only used in the CRM model as “placeholders”. Finally, the NOAA nautical chart data was compared to all previously mentioned data sources and was checked to make sure it was further than 0.0004° from any other points.

The final output files contain all saved points (i.e., those that were not eliminated in the process described above) adjusted to MSL. The files were constructed to contain data in a 1 arc-degree by 1 arc-degree area, and are labeled YY_XXX.xyz where the YY is the latitude and XXX is the longitude of the southeastern corner of the box. Each file lists the longitude in degrees, latitude in degrees, and bathymetric depth in meters relative to MSL. Negative bathymetry values indicate a depth below local MSL and positive bathymetry values indicate a height above local MSL. Additionally, there is a fourth column of data with an integer between 1 and 5 that corresponds to the source of the data where 1 = POST-ISA, 2 = PRE-ISA, 3 = NOS, 4=CRM, and 5 = NOAA paper nautical chart data.

4.3. Preliminary Merged Topographic/Bathymetric Dataset

A preliminary merge on a small portion of the topographic and bathymetric datasets was performed to work out the processing procedures that will be utilized when constructing the final combined topographic and bathymetric digital elevation model (Figure 11). This first run utilized only the North Carolina FEMA lidar bare-earth point data and the bathymetric point data. The bare-earth point data were in the appropriate format for processing in VDatum. The lidar point data also allow for a smoother workflow when they are ready to be merged with the bathymetric point data. The preliminary DEM has a horizontal spacing of 6.1 m and a vertical datum of NAVD 88.

In the future, in order to help fill the void in areas where lidar data were not made available, the other datasets that were acquired will be utilized. The priority will be to make use of the regular grid bare-earth data. The regular grids will be converted to point data and the water surfaces will be masked out. If the regular grid bare-earth data are not available, raw lidar will be used. A bare-earth routine will be used to remove features in the Digital Surface Model, an elevation model depicting buildings, trees, towers, etc., that are not representative of the ground surface. This data will then be integrated with the other datasets.

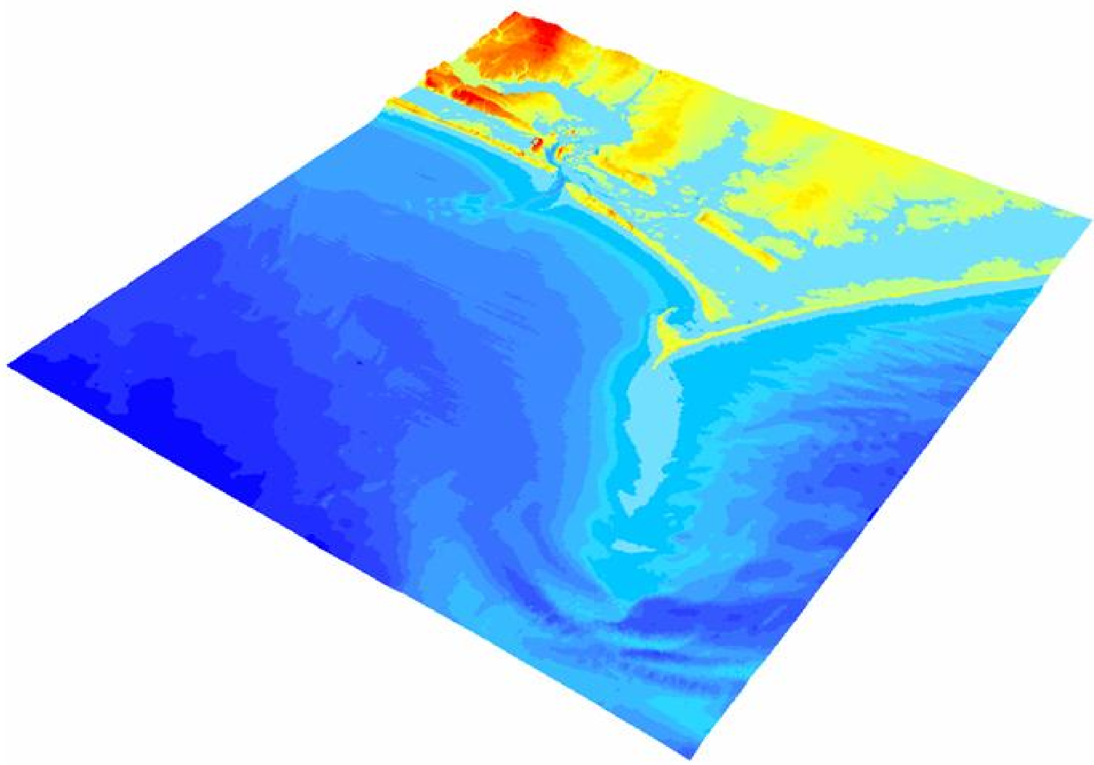


Figure 11. Isometric view of the preliminary topographic/bathymetric DEM created for designing the proper procedures for the merging of North Carolina elevation datasets.

5. FUTURE PLANS

The goal of the project is to predict and assess the impacts of rising sea level on coastal wetland and forest ecosystems in Pamlico, Core, Back, and Bogue Sounds and the adjacent lands in Pamlico, Craven, and Carteret Counties. Work on the physical aspects of sea level rise began in the first year of the study. The activities described below are planned for completion in the second year (May 2004 to May 2005).

The project staff will complete the task of applying VDatum for the selected geographic area so that the bathymetry can be re-referenced to a common vertical datum such as NAVD 88. VDatum is a NOS software application that converts among approximately 29 vertical datums, including tidal, orthometric, and three-dimensional datums, and is a prerequisite to creating the DEM. Tasks include generating the VDatum marine grid and populating the grid with tidal datum fields and sea surface topography.

The hydrodynamic model, which is substantially complete, will be used to simulate the influence of winds on water levels in the sounds. If time and resources permit, wind waves will be added to the model, and a three-dimensional version of the model that incorporates salinity and temperature will be tested.

The DEM will be completed when the bathymetry is combined with the land elevation data from the State's topographic lidar survey to produce the bathymetric/topographic elevation model, with a spatial resolution of 10 to 30 m in the horizontal. USGS personnel are also producing a DEM of the same area, possibly of higher spatial resolution, and the project staff plans to exchange data with them.

The coastal flooding model (CFM) combines the tide and water level model and the DEM. The CFM will be developed by expanding the existing tide model grid to cover low-lying land areas and then populating the grid's land cells with DEM-based elevation values. Elevations will be in a uniform vertical reference frame such as NAVD 88 or NAD 83 (86). The DEM will be revised to include roadways, drainages ditches, and other features affecting inundation. The CFM will then be used to assess land inundation due to storm surges and sea level rise. The CFM will be designed to be able to incorporate sub-models that will simulate surface and subsurface water flow, wetlands, and inter-tidal areas.

Management tools that include maps of inundated areas and other new information may be developed and accessed as work on the DEM and CFM progresses. The goal is to significantly improve the ability of coastal managers to assess the potential ecosystem changes due to rising sea levels.

ACKNOWLDEGEMENTS

The digital coastline data for North Carolina were extracted from the digital nautical charts and quality-controlled by CSDL's Anne Reymond. Maurice Hickson and George Myers of OCS' Hydrographic Surveys Division investigated the original hydrographic survey reports to verify the tidal datums. Rick Leuttick very kindly provided his model girds and bathymetry. CSDL's Edward Myers generated initial grid for the sounds and provided tidal harmonic constant data for the regional grid.

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APPENDIX A. PROJECT PERSONNEL

The following NOS personnel participated in the project. The initial planning was done by David Johnson of NCCOS, Bruce Parker and Kurt Hess of CSDL, Chris Zervas of CO-OPS, and Dennis Milbert of NGS.

Name	Organization	Activities
Kurt Hess	CSDL	Principal Investigator, VDatum marine grid
Dennis Milbert[1]	NGS	VDatum advisor
Emily Spargo	CSDL	Tide modeling
Adeline Wong	CSDL	Bathymetric data access
Jon Sellars	NGS	Land elevation data analysis, DEM
Stephen White	NGS	Land elevation data analysis, DEM
Stephen Gill	CO-OPS	Tidal data
Chris Zervas	CO-OPS	Sea Level Rise data analysis

1. Presently retired from federal service.

APPENDIX B. WATER LEVEL STATION DATA

Table B.1. Tidal and orthometric datums (meters) relative to mean sea level for NOS water level stations in North Carolina used in this study. –9.999 denotes a missing value. An * in the rightmost column indicates tidal datums from the 1983-2001 tidal datum epoch (see Fig. 4, red stations).

No.	Station	Latitude	Longitude	MHHW	MHW	MLW	MLLW	NAVD88	
1	8651370	36.1833	-75.7467	0.585	0.487	-0.495	-0.539	0.128	*
2	8652226	35.9100	-75.5917	0.609	0.518	-0.488	-0.549	-9.999	
3	8652232	35.9100	-75.6700	0.065	0.051	-0.045	-0.081	-9.999	
4	8652247	35.9033	-75.7700	0.061	0.049	-0.046	-0.061	-9.999	
5	8652437	35.8450	-75.6550	0.091	0.061	-0.061	-0.091	-9.999	
6	8652547	35.8117	-75.7000	0.088	0.061	-0.061	-0.088	-9.999	
7	8652587	35.7950	-75.5483	0.180	0.135	-0.137	-0.176	0.026	*
8	8652591	35.7983	-75.5833	0.092	0.061	-0.061	-0.091	-9.999	
9	8652648	35.7750	-75.5817	0.135	0.095	-0.102	-0.140	-9.999	
10	8652657	35.7733	-75.5583	0.214	0.183	-0.183	-0.213	-9.999	
11	8652659	35.7733	-75.5383	0.336	0.275	-0.305	-0.335	-9.999	
12	8652678	35.7683	-75.5267	0.366	0.305	-0.294	-0.321	0.158	*
13	8652715	35.7567	-75.5317	0.274	0.244	-0.275	-0.305	-9.999	
14	8652737	35.7483	-75.5533	0.153	0.122	-9.999	-0.152	-9.999	
15	8652905	35.6983	-75.7733	0.101	0.073	-0.070	-0.098	-9.999	
16	8653215	35.5950	-75.4717	0.168	0.115	-0.105	-0.131	0.009	*
17	8653305	35.5650	-75.7350	0.091	0.061	-0.058	-0.091	-9.999	
18	8654400	35.2233	-75.6350	0.564	0.455	-0.456	-0.492	0.135	*
19	8654792	35.1150	-75.9883	0.204	0.158	-0.141	-0.162	0.027	*
20	8655151	35.0200	-76.3100	0.082	0.071	-0.042	-0.045	-0.003	*
21	8656084	34.8233	-76.6900	0.407	0.336	-0.308	-0.334	-9.999	
22	8656225	34.7917	-76.6083	0.330	0.284	-0.256	-0.280	-9.999	
23	8656298	34.7667	-76.6867	0.606	0.515	-0.430	-0.491	-9.999	
24	8656306	34.7683	-76.6717	0.560	0.472	-0.467	-0.505	-9.999	*
25	8656451	34.7283	-76.6683	0.531	0.451	-0.472	-0.518	-9.999	
26	8656467	34.7250	-76.8033	0.229	0.195	-0.021	-0.204	-9.999	
27	8656483	34.7200	-76.6700	0.558	0.470	-0.477	-0.521	0.112	*
28	8656485	34.7217	-76.7517	0.354	0.302	-0.302	-0.332	-9.999	
29	8656486	34.7200	-76.7550	0.354	0.302	-0.302	-0.332	-9.999	
30	8656487	34.7167	-76.6717	0.551	0.475	-0.461	-0.491	-9.999	
31	8656495	34.7200	-76.6950	0.552	0.470	-0.487	-0.533	-9.999	
32	8656499	34.7183	-76.7367	0.457	0.396	-0.336	-0.366	-9.999	
33	8656502	34.7200	-76.7267	0.541	0.458	-0.481	-0.524	0.118	*
34	8656503	34.7150	-76.5783	0.145	0.095	-0.224	-0.248	0.066	*
35	8656518	34.7117	-76.6450	0.496	0.419	-0.440	-0.483	-9.999	*
36	8656539	34.7083	-76.6200	0.428	0.356	-0.365	-0.402	-9.999	*
37	8656554	34.7033	-76.6200	0.360	0.299	-0.311	-0.341	-9.999	
38	8656566	34.7000	-76.7683	0.268	0.225	-0.257	-0.287	-9.999	
39	8656569	34.6983	-76.6650	0.634	0.542	-0.433	-0.494	-9.999	
40	8656571	34.6983	-76.6817	0.546	0.464	-0.487	-0.533	-9.999	
41	8656590	34.6933	-76.7117	0.696	0.587	-0.584	-0.628	0.133	*
42	8656612	34.6867	-76.5333	0.318	0.257	-0.266	-0.295	0.094	*
43	8656841	34.6133	-76.5383	0.722	0.614	-0.620	-0.669	-9.999	*
44	8656937	34.6067	-76.5283	0.600	0.500	-0.500	-0.570	-9.999	
45	8657419	34.4517	-77.4950	0.710	0.615	-0.616	-0.668	-9.999	

Table B.2. NOS water level station names.

No.	Station	Name
1	8651370	DUCK FRF PIER NC
2	8652226	JEANETTES PIER NC
3	8652232	MANTEO SHALLOWBAG BAY NC
4	8652247	MANNS HARBOR CROATAN SOUND
5	8652437	OYSTER CREEK CROATAN SOUND
6	8652547	ROANOKE MARSH CROATAN SOUND
7	8652587	OREGON INLET MARINA NC
8	8652591	ROANOKE SOUND CHANNEL NC
9	8652648	OLD HOUSE CHANNEL NC
10	8652657	OREGON INLET CHANNEL NC
11	8652659	OREGON INLET BRIDGE NC
12	8652678	USCG LIFEBOAT STATION ORE
13	8652715	PEA ISLAND #2 NC
14	8652737	DAVIS SLOUGH NC
15	8652905	LAKE WORTH, STUMPY POINT BAY
16	8653215	RODANTHE PAMLICO SOUND NC
17	8653305	LONG SHOAL LT.
18	8654400	CAPE HATTERAS FISHING PIER
19	8654792	OCRACOKE ISLAND NC
20	8655151	CEDAR ISLAND NC
21	8656084	CORE CREEK BRIDGE NC
22	8656225	NORTH RIVER BRIDGE BETTIE
23	8656298	NEWPORT RIVER NC
24	8656306	MOREHEAD-BEAUFORT Y C NEW
25	8656451	GALLANT CHANNEL NC
26	8656467	SPOONERS CREEK NC
27	8656483	BEAUFORT DUKE MARINE LAB
28	8656485	N C A R STATE FISHERIES N
29	8656486	N C A R STATE FISHERIES N
30	8656487	DUKE MARINE LA (MOD BUB)
31	8656495	PORT TERMINAL NC
32	8656499	ATLANTIC BEACH BRIDGE NC
33	8656502	MOREHEAD CITY HARBOR HARB
34	8656503	HARKERS ISLAND BRIDGE NC
35	8656518	BEAUFORT TAYLOR CREEK NC
36	8656539	LENOXVILLE POINT NORTH RI
37	8656554	CHANNEL MARKER LIGHT #59
38	8656566	CORAL BAY ATLANTIC BEACH
39	8656569	BEAUFORT INLET CHANNEL RA
40	8656571	FORT MACON NC
41	8656590	ATLANTIC BEACH TRIPLE S P
42	8656612	CALICO JACKS MARINA NC
43	8656841	CAPE LOOKOUT (INSIDE) NC
44	8656937	CAPE LOOKOUT (OUTSIDE) NC
45	8657419	OCEAN CITY FISHING PIER N