NOAA Technical Memorandum NESDIS NGDC-7

DIGITAL ELEVATION MODEL OF VIRGINIA BEACH, VIRGINIA : PROCEDURES, DATA SOURCES AND ANALYSIS

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Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

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Also available from the National Technical Information Service (NTIS)
(http://www.ntis.gov)

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Digital Elevation Model of Virginia Beach, Virginia: Procedures, Data Sources and Analysis

1. Introduction

In January 2007, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed a bathymetric–topographic digital elevation model (DEM) of Virginia Beach, Virginia (Fig. 1) for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/). The DEM also spans the neighboring communities of Norfolk and Hampton, Virginia, which lie along southern Chesapeake Bay. The 1/3 arc-second[1] coastal DEM will be used as input for the Method of Splitting Tsunami (MOST) model developed by PMEL to simulate tsunami generation, propagation and inundation. The DEM was generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 3) and will be used for tsunami inundation modeling, as part of the tsunami forecast system SIFT (Short-term Inundation Forecasting for Tsunamis) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the Virginia Beach DEM.

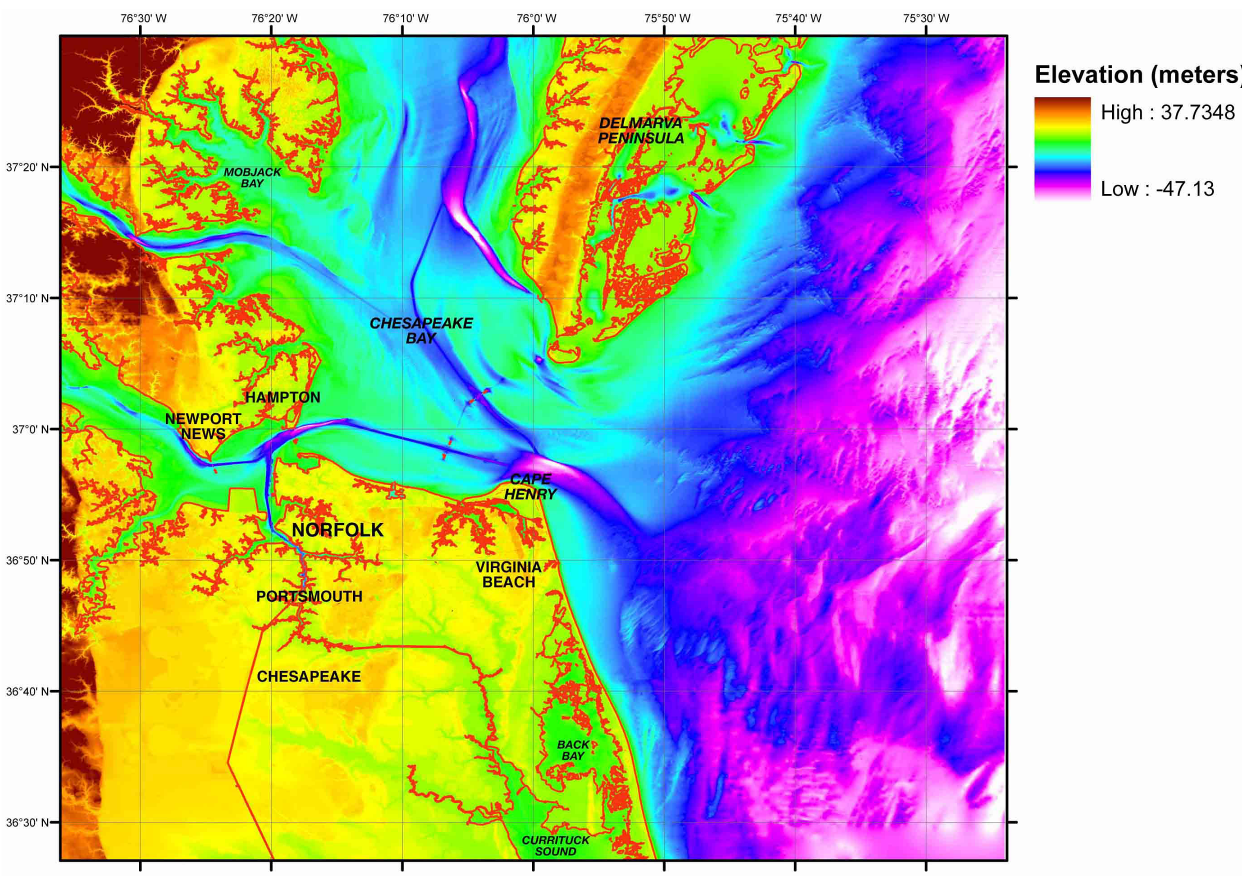

Figure 1. *Shaded-relief image of the Virginia Beach, Virginia region. Coastline in red.*

1. The Virginia Beach DEM is built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems, such as UTM zones (in meters). At the latitude of Virginia Beach, Virginia (36°51′ N, 76°00′ W) 1/3 arc-second of latitude is equivalent to 10.27 meters; 1/3 arc-second of longitude equals 8.26 meters.

2. Study Area

The Virginia Beach DEM covers the coastal area surrounding the city of Virginia Beach and the mouth of Chesapeake Bay. Besides a large tourism economy, the region also supports several significant military facilities, agricultural businesses, and serves as a main transportation hub based on its network of shipping and rail lines. Other communities located within the DEM include Norfolk, Portsmouth, Chesapeake, Hampton and Newport News (Fig. 1).

The DEM is located within the geologic region called the Atlantic Coastal Plain: a thick basement layer of igneous and metamorphic rock overlain with a thick wedge of sediments that increases in thickness and dips towards the eastern shoreline (Fig. 2). This sedimentary wedge consists primarily of eroded clays, sands, and gravel from the Appalachian mountains, covered with a thin layer of marine sands deposited in a series of sea level changes. Chesapeake Bay also contains an impact crater estimated to be 35 million years old, stretching 90 km in diameter. As the plain was uplifted, numerous peninsulas were incised by stream cutting, with the larger rivers forming tidal rivers. Examples of this include the Potomac, Rappahannock, York, and James Rivers, all of which empty into Chesapeake Bay.

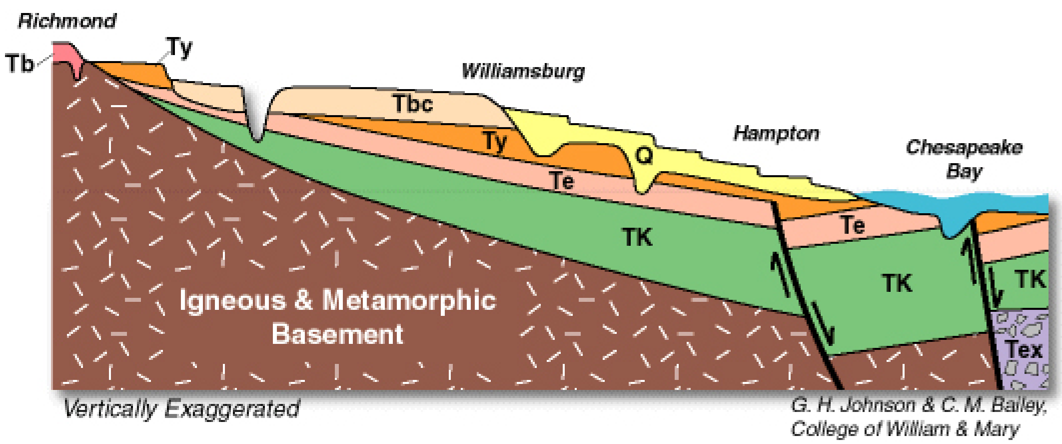

Figure 2. *Geologic cross-section showing stratigraphy of Atlantic Coastal Plain. (http://www.wm.edu/geology/virginia/coastal_plain_strat.html)*

3. Methodology

The Virginia Beach DEM was developed to meet PMEL specifications (Table 1), based on input requirements for the MOST inundation model. The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums: World Geodetic System 1984 (WGS84) and Mean High Water (MHW), for modeling of "worst-case scenario" flooding, respectively. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1. PMEL specifications for the Virginia Beach DEM.

Grid Area	Virginia Beach, Virginia
Coverage Area	75.4 º to 76.6º W; 36.45º to 37.5º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System 1984 (WGS84)
Vertical Datum	Mean High Water (MHW)
Vertical Units	Meters
Grid Spacing	1/3 arc-second
Grid Format	ESRI ASCII raster grid

3.1 Data Sources and Processing

Shoreline, bathymetric, topographic and combined topographic–bathymetric digital datasets (Fig. 3) were obtained from several U.S. federal and state agencies including: NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS), Coastal Services Center (CSC), Coast Survey Development Laboratory (CSDL), National Geodetic Survey (NGS), and NGDC; the U.S. Geological Survey (USGS); the U.S Army Corps of Engineers (USACE); Virginia Coast Reserve-Long Term Ecological Research (VCR/LTER), University of Virginia; and the cities of Norfolk, Virginia Beach, and Hampton, Virginia. Safe Software's (http://www.safe.com/) FME data translation tool package was used to shift datasets to WGS84 horizontal datum and to convert into ESRI (http://www.esri.com/) ArcGIS shape files. The shape files were then displayed with ArcGIS to assess data quality and manually edit datasets; NGDC's GEODAS software (http://www.ngdc.noaa.gov/mgg/geodas/) was used to manually edit large xyz datasets. Vertical datum transformations to MHW were accomplished using FME—based upon data from local NOAA tidal stations—and VDatum model software (http://vdatum.noaa.gov/).

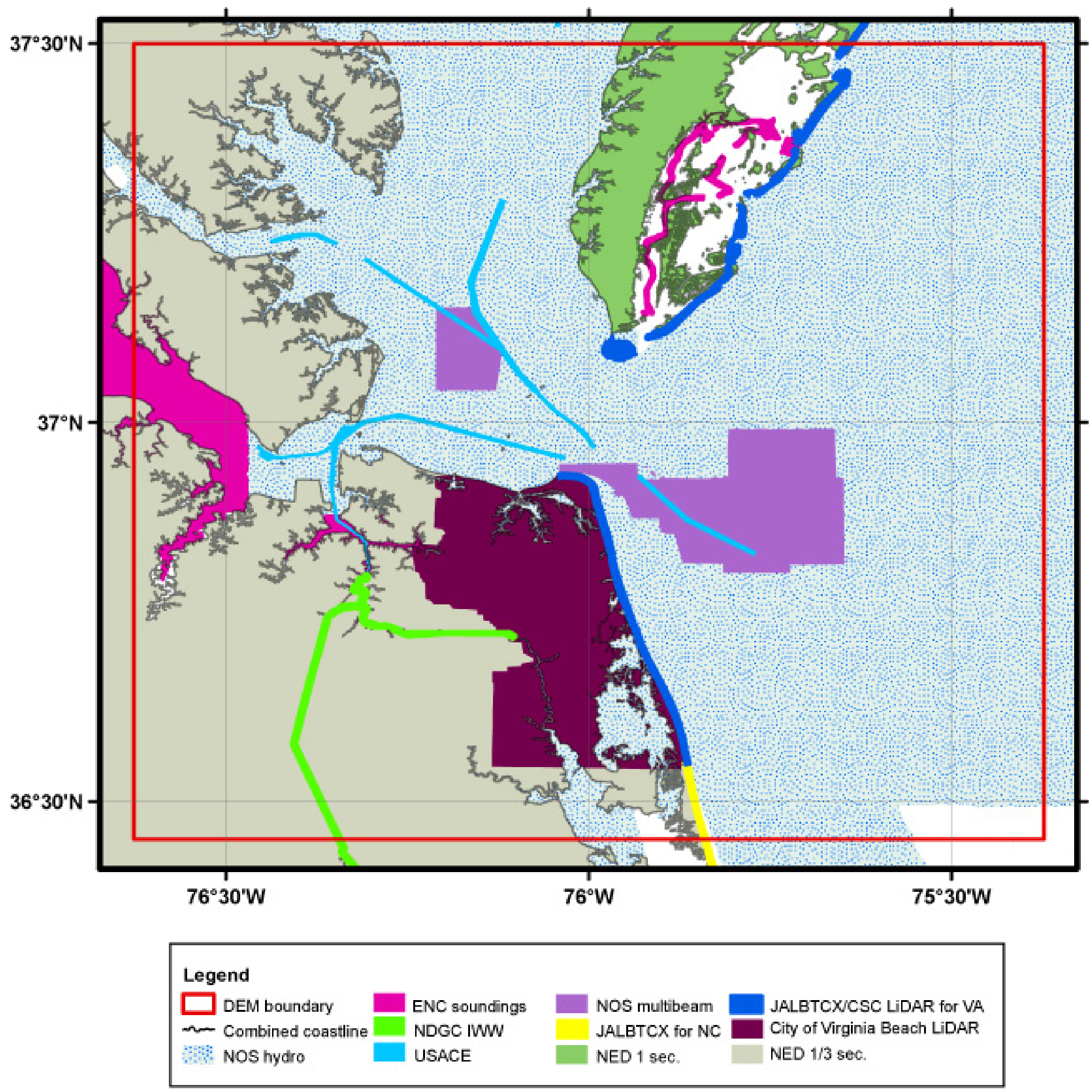

Figure 3. *Source and coverage of datasets used to compile the Virginia Beach DEM.*

3.1.1 Shoreline

Four digital coastline datasets of the Virginia Beach region were analyzed for inclusion in the Virginia Beach DEM: OCS electronic navigational charts, CSDL vector shoreline, NGS vector shoreline, and Northampton County, Virginia hydo-line (Table 2).

Table 2. Shoreline datasets used in compiling the Virginia Beach DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum*	*Original Vertical Datum*	*URL*
OCS Electronic Navigational Charts	2002 to 2006	MHW coastline	Digitized from 1:20,000 and 1:80,000 scale charts	WGS84 geographic	MHW	http://www.nauticalcharts.noaa.gov/mcd/enc/index.htm
CSDL	2001	U.S. Merged Vector shoreline	1:20,000	NAD83 geographic	MHW	http://nauticalcharts.noaa.gov/csdl/ctp/cm_vs.htm
National Geodetic Survey	2003	NGS Shoreline Mapping Program Vector shoreline		NAD83 geographic	MHW	http://www.ngs.noaa.gov/newsys_ims/shoreline/index.cfm
Virginia Coast Reserve – Long Term Ecological Research	1995	Northampton County Hydro-line	1:100,000 scale map	NAD83 State Plane Virginia South	MHW	http://atlantic.evsc.virginia.edu/
NGDC-digitized	2006	FWS wetlands maps and NOAA RNCs	1:24,000 scale topographic maps	WGS84 geographic	MHW	

1) OCS Electronic Navigational Charts

Eighteen NOAA nautical charts were available for the Virginia Beach region (Table 3) and were downloaded from NOAA's Office of Coast Survey (OCS) website (http://www.nauticalcharts.noaa.gov/). All of the nautical charts are available in raster nautical chart (RNC) format—georeferenced map imagery, which are frequently updated—with some also available as electronic navigation charts (ENCs)—digital GIS chart components (Fig. 4). The NOAA Coastal Services Center's 'Electronic Navigational Chart Data Handler for ArcView' extension (http://www.csc.noaa.gov/products/enc/) was used to import the ENCs into ArcGIS. The ENCs include coastline data files (MHW), which were compared with the other coastline datasets, high-resolution coastal LiDAR data, topographic data, and NOS hydrographic soundings. The ENCs also include soundings (extracted from NOS hydrographic surveys) and land elevations.

Eight of the ENCs were used in conjunction with other coastline datasets to build a 'combined coastline' (Fig. 5). Those nautical charts that exist only as RNCs were used to evaluate other coastline, bathymetric and topographic datasets and for digitization of coastal features not represented in any digital coastline dataset.

Table 3. NOAA nautical charts in the Virginia Beach, Virginia region.

Chart Number	*Title*	*Edition*	*Date*	*Scale*	*Available Format*	*Used in Combined Coastline*
12205	FOLIO SMALL-CRAFT CHART Cape Henry to Pamlico Sound, Including Albemarle Sound; Rudee Heights	30th	11/2005	various	ENC	yes
12206	Intracoastal Waterway Norfolk to Albemarle Sound via North Landing River or Great Dismal Swamp Canal	31st	4/2005	1:40,000	RNC	no
12207	Cape Henry to Currituck Beach Light	21st	3/2004	1:50,000	RNC	no
12208	Approaches to Chesapeake Bay	11th	5/2005	1:50,000	ENC	yes
12210	Chincoteague Inlet to Great Machipongo Inlet; Chincoteague Inlet	37th	1/2006	1:80,000	RNC	no

12221	Chesapeake Bay Entrance	78th	4/2006	1:80,000	ENC	no
12222	Chesapeake Bay Cape Charles to Norfolk Harbor	47th	11/2005	1:40,000	ENC	yes
12224	Chesapeake Bay Cape Charles to Wolf Trap	5th	11/2006	1:40,000	ENC	no
12225	Chesapeake Bay Wolf Trap to Smith Point	55th	8/2004	1:80,000	RNC	no
12226	Chesapeake Bay Wolf Trap to Pungoteague Creek	16th	11/2001	1:40,000	ENC	no
12235	Rappahannock River Entrance Piankatank and Great Wicomico Rivers	4th	10/2006	1:40,000	ENC	no
12238	Chesapeake Bay Mobjack Bay and York River Entrance	39th	1/2006	1:40,000	ENC	no
12241	York River Yorktown and Vicinity	21st	1/2002	1:20,000	ENC	yes
12245	Hampton Roads	65th	11/2005	1:20,000	ENC	yes
12248	James River Newport News to Jamestown Island; Back River and College Creek	41st	12/2005	1:40,000	ENC	yes
12253	Norfolk Harbor and Elizabeth River	44th	12/2004	1:20,000	ENC	yes
12254	Chesapeake Bay Cape Henry to Thimble Shoal Light	46th	2/2006	1:20,000	ENC	yes
12255	Little Creek Naval Amphibious Base	16th	9/2005	1:5,000	ENC	no

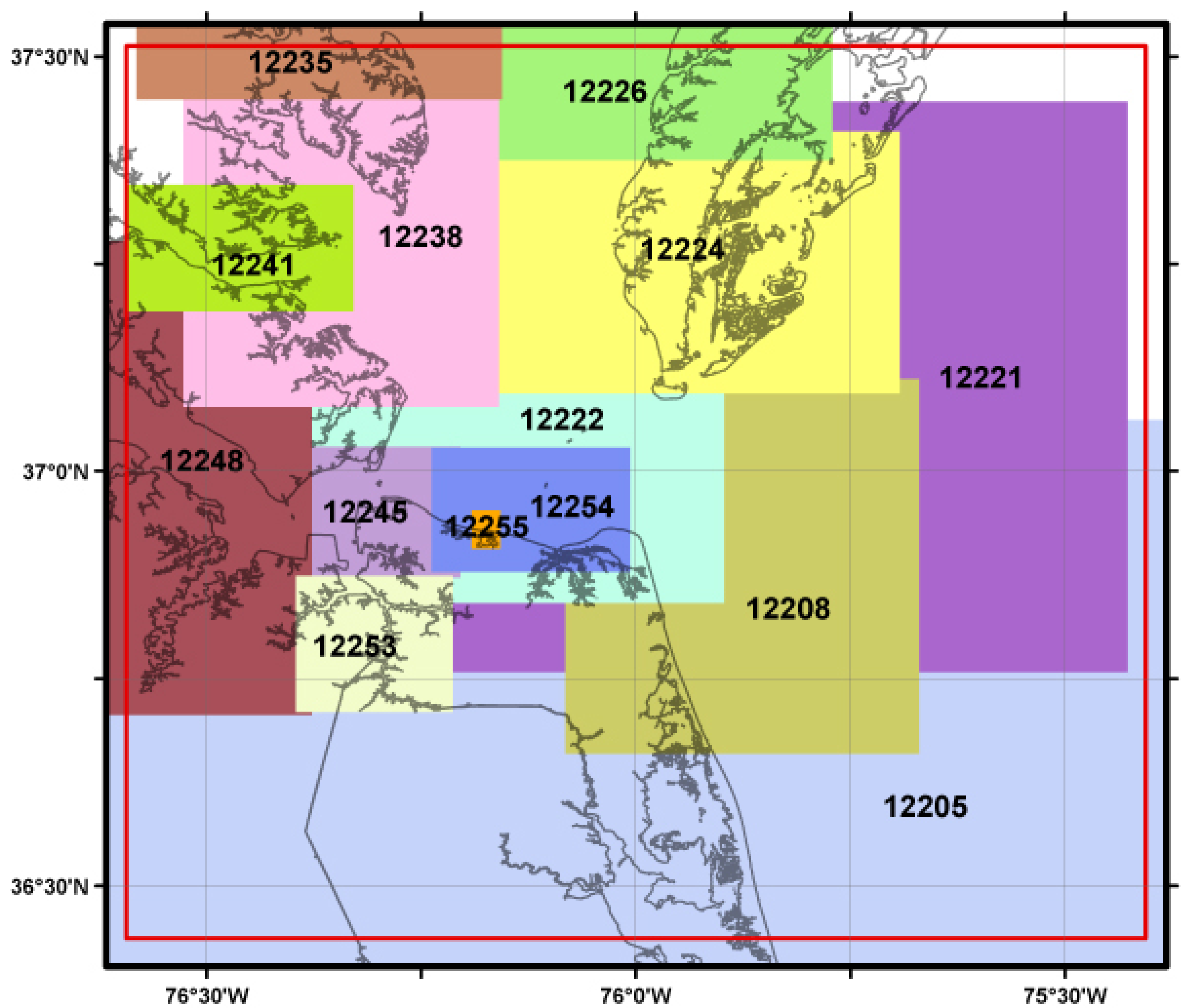

Figure 4. *Electronic Navigational Charts available for the Virginia Beach DEM.*

2) CSDL Merged Vector Shoreline Derived from NOAA Nautical Charts

A merged vector shoreline dataset of the U.S. was originally derived from NOAA Nautical Charts using a process and software developed by the CSDL Cartographic & Geospatial Technology Program. This dataset was used in building the combined coastline as it provides the most complete coverage within the Virginia Beach region.

3) NGS vector shoreline

The NGS high-resolution vector shoreline covers most of the territory of the United States, and was compiled by the NGS Remote Sensing Division. Five NGS datasets for the Virginia Beach were used: West Shore of Chesapeake Bay; Cape Henry to the Upper Part of Currituck Sound; Piankatank River to Cape Henry, North Landing, Northwest and North Rivers, North Carolina and Virginia; and Newport News–Norfolk. These vector data represent shoreline and associated data originating from current remote sensing production. The vector data files are seamless within the surveyed project area. These shoreline data represent a vector conversion of a set of NOS raster shoreline manuscript identified by t-sheet or tp-sheet numbers. These vector data were created by NOS contractors, who vectorized georeferenced raster shoreline manuscripts using ESRI ArcScan software to create individual ArcInfo coverages. The individual coverages were ultimately edge matched within a surveyed project area and appended together.

4) Northampton County hydro-line

This digital hydroline is a 1:100,000 scale digital map of hydrologic features for Northampton County, VA. It was created by the Virginia Coast Reserve – Long Term Ecological Research (VCR/LTER), University of Virginina in cooperation with Northampton County, Virginia. VCR/LTER built the map by linking 7 USGS 1:100,000 scale DLG files and eliminating all boundary lines. Minimal edge matching was done when necessary to correct for inconsistencies visible after the DLG sections were joined. Some attribute values were added and some were shifted to different attribute columns, to enable better use in ArcView without loss of original USGS data values.

5) NGDC digitized coastline segments

Several sections of coastline (Fig. 5) were not adequately represented in any digital coastline dataset, thus NGDC chose to digitize these segments, using ESRI ArcMap, based upon raster images and digital maps from the U.S. Fish and Wildlife Service (wetlands maps) and NOAA RNCs.

To obtain the best digital MHW coastline, NGDC combined the ENC, CSDL, NGS, and Northampton coastlines. This 'combined coastline' (Fig. 5) was manually adjusted in many places, using ArcGIS, to match the high-resolution coastal LiDAR data and RNC data. The combined coastline was sub sampled to 10-meter spacing and converted to point data for use in the gridding process. It was also used as a coastal buffer for the NOS pre-surfacing algorithm (see Section 3.3.3) to ensure that interpolated bathymetric values reached "zero" at the coast. The combined coastline was also used to clip the USGS NED topographic DEMs, which contain elevation values, typically zero, over the open ocean (Section 3.1.3).

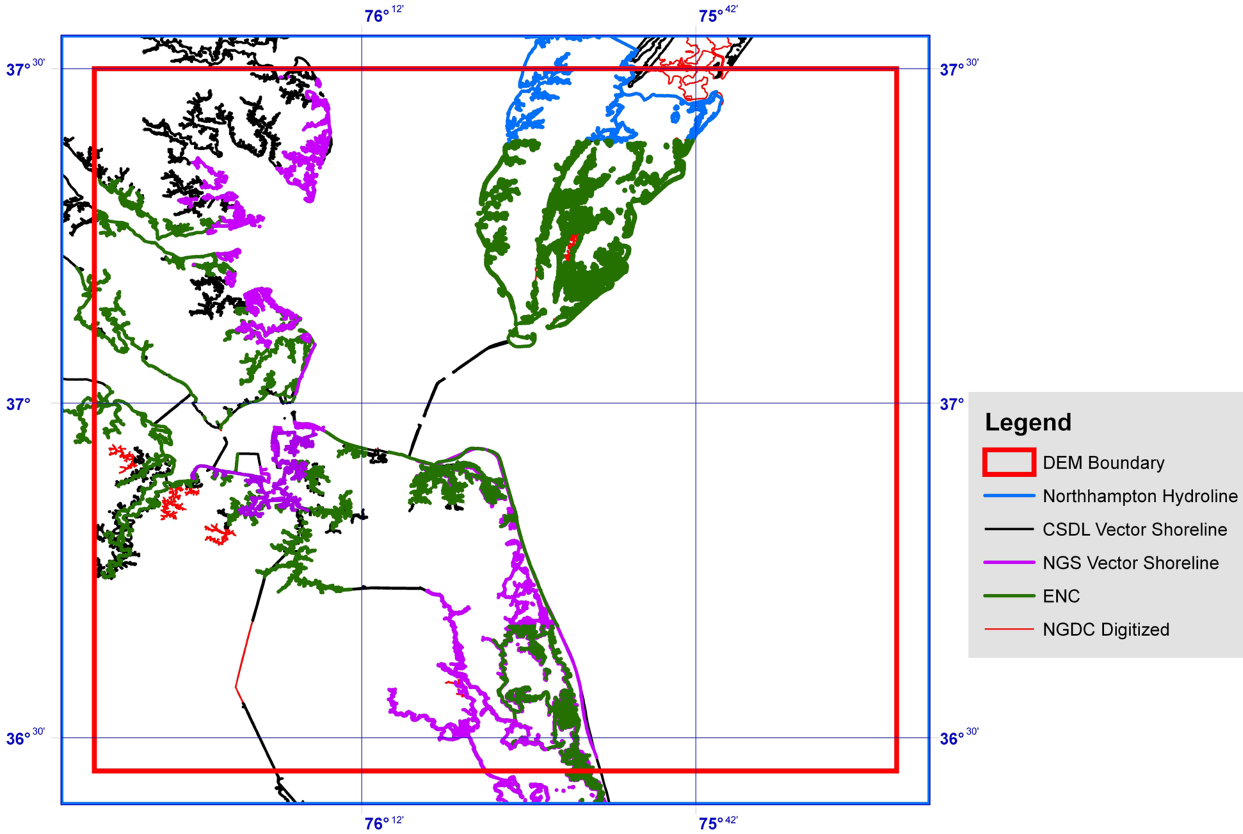

Figure 5. *Digital coastline segments used to create a 'combined coastline' for the Virginia Beach region.*

3.1.2 Bathymetry

Bathymetric datasets used in the compilation of the Virginia Beach DEM include: NOS hydrographic surveys, recent NOS shallow-water multibeam surveys, USACE surveys of dredged shipping channels, features digitized by NGDC, and soundings extracted from ENCs (Table 4).

Table 4. Bathymetric datasets used in compiling the Virginia Beach DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NOS	1868 to 1997	Hydrographic survey soundings	Ranges from 10 m to 4 km (varies with scale of survey, depth, traffic and probability of obstructions)	NAD27, NAD83	MLW or MLLW (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NOS	2001 to 2005	Shallow-water multibeam	1 to 10 meters	NAD 83 UTM Zone 18	MLLW (meters)	
USACE	2004 to 2006	Bathymetric surveys	Profiles 60 to 1100 m long, 30 to 130 m apart, with <1 m point spacing	NAD83 State Plane Virginia South	MLLW (meters)	
NGDC	2006	Digitized Intracoastal Waterway soundings	2 parallel track 10 to 20 m apart, with <10 m point spacing	WGS84	MLLW (feet)	
OCS ENCs	2006	Extracted ENC sounding data	1:20,000	WGS84	MLLW (meters)	http://www.nauticalcharts.noaa.gov/

1) NOS hydrographic survey data

A total of 107 NOS hydrographic surveys conducted between 1868 and 1997 were utilized in building the Virginia Beach DEM (Table 5; Fig. 6). 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. Numerous other NOS surveys that were older (i.e., superceded by subsequent surveys) or of low-resolution were not included in the DEM.

Data point spacing for the NOS surveys varied by collection date. In general, earlier surveys had greater point spacing than more recent surveys. All surveys were extracted from NGDC's online NOS hydrographic database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) in their original, digitized datums (Table 5). The data were then converted to WGS84 using FME software, an integrated collection of spatial extract, transform, and load tools for data transformation (http://www.safe.com). The surveys were subsequently clipped to a polygon 0.05 degree (~5%) larger than the Virginia Beach DEM area to support data interpolation along grid edges. Conversion to MHW was accomplished using VDatum, which has conversion grids for Chesapeake Bay and northern North Carolina (see Fig. 19), or by FME for areas outside VDatum coverage.

After converting all NOS survey data to MHW (see Section 3.2.1), the data were displayed in ESRI ArcMap and reviewed for digitizing errors against scanned original survey smooth sheets and compared to the recent NOS and USACE bathymetric surveys, coastal LiDAR data, topographic data sets, the combined coastline, RNCs, and *Google Earth* satellite imagery.

Table 5. Digital NOS hydrographic surveys used in compiling the Virginia Beach DEM.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum*	*Vertical translation tool*
F00294	1987	5,000	mean lower low water	NAD27	CB VDatum
F00336	1989	5,000	mean lower low water	NAD83	CB VDatum
F00369	1991/92	5,000	mean lower low water	NAD83	CB VDatum
F00408	1995	10,000	mean lower low water	NAD83	CB VDatum
H00965	1868	40,000	mean low water	NAD27	NC VDatum/FME
H01583	1884	20,000	mean low water	NAD27	FME
H03311	1911	20,000	mean low water	NAD27	FME
H03532	1913	5,000	mean low water	NAD27	CB VDatum

H03533	1933	5,000	mean low water	NAD27	CB VDatum
H04084	1919	10,000	mean low water	NAD27	CB VDatum
H04286	1922	40,000	mean low water	NAD27	NC VDatum/CB VDatum
H04962	1930	10,000	mean low water	NAD27	CB VDatum
H05000	1929	10,000	mean low water	NAD27	CB VDatum
H05201	1932	10,000	mean low water	NAD27	CB VDatum
H05704	1934	20,000	mean low water	NAD27	FME
H05895	1935	10,000	mean low water	NAD27	FME
H05896	1935	10,000	mean low water	NAD27	FME
H05897	1935	10,000	mean low water	NAD27	FME
H05898	1935	10,000	local low water	NAD27	FME
H05899	1935	10,000	local low water	NAD27	FME
H05968	1934	10,000	mean low water	NAD27	CB VDatum
H05969	1934	10,000	mean low water	NAD27	CB VDatum/FME
H05990	1935	40,000	mean low water	NAD27	NC VDatum/CB VDatum
H05991	1935	40,000	mean low water	NAD27	CB VDatum
H05992	1935	40,000	mean low water	NAD27	NC VDatum/CB VDatum
H05993	1935	40,000	mean low water	NAD27	NC VDatum/CB VDatum
H06595	1940	40,000	mean low water	NAD27	CB VDatum
H06729	1942	10,000	mean low water	NAD27	CB VDatum
H06812	1943	10,000	mean low water	NAD27	CB VDatum
H06815	1943	2,500	mean low water	NAD27	CB VDatum
H06832	1943	10,000	mean low water	NAD27	CB VDatum
H06833	1943	2,500	mean low water	NAD27	CB VDatum
H06928	1944	10,000	mean low water	NAD27	CB VDatum
H06930	1944	5,000	mean low water	NAD27	CB VDatum
H07022	1945	10,000	mean low water	NAD27	CB VDatum
H07025	1945	10,000	mean low water	NAD27	CB VDatum
H07087	1946	10,000	mean low water	NAD27	CB VDatum
H07160	1947	10,000	mean low water	NAD27	CB VDatum
H07162	1944/47	10,000	mean low water	NAD27	CB VDatum
H07171	1947	10,000	mean low water	NAD27	CB VDatum
H07174	1948	10,000	mean low water	NAD27	CB VDatum
H07175	1947	5,000	mean low water	NAD27	CB VDatum
H07181	1947	5,000	mean low water	NAD27	CB VDatum
H07184	1947	5,000	mean low water	NAD27	CB VDatum/FME
H07185	1947	5,000	mean low water	NAD27	CB VDatum
H07703	1948	10,000	mean low water	NAD27	CB VDatum
H07750	1949/50	40,000	mean low water	NAD27	CB VDatum
H07783	1949	10,000	mean low water	NAD27	CB VDatum
H07791	1949	10,000	mean low water	NAD27	CB VDatum
H07823	1950	10,000	mean low water	NAD27	CB VDatum
H07824	1948/50	10,000	mean low water	NAD27	CB VDatum
H07894	1951	10,000	mean low water	NAD27	CB VDatum
H07910	1950	10,000	mean low water	NAD27	CB VDatum
H07911	1950/54	10,000	mean low water	NAD27	CB VDatum
H07952	1952/53	10,000	mean low water	NAD27	CB VDatum
H07953	1952/53	10,000	mean low water	NAD27	CB VDatum
H07954	1952/53	10,000	mean low water	NAD27	CB VDatum
H07955	1952	10,000	mean low water	NAD27	CB VDatum
H07956	1952	10,000	mean low water	NAD27	CB VDatum
H07957	1952	10,000	mean low water	NAD27	CB VDatum

H07958	1952	10,000	mean low water	NAD27	CB VDatum
H07959	1952	10,000	mean low water	NAD27	FME
H07960	1952	20,000	mean low water	NAD27	CB VDatum
H08012	1952	40,000	mean low water	NAD27	CB VDatum
H08078	1953	10,000	mean low water	NAD27	CB VDatum
H08079	1953	10,000	mean low water	NAD27	CB VDatum
H08080	1953	10,000	mean low water	NAD27	CB VDatum
H08081	1953	10,000	mean low water	NAD27	CB VDatum
H08083	1953	20,000	mean low water	NAD27	CB VDatum
H08217	1954	10,000	mean low water	NAD27	CB VDatum
H08447	1958	10,000	mean low water	NAD27	CB VDatum
H08448	1958	20,000	mean low water	NAD27	CB VDatum
H08505	1959	10,000	mean low water	NAD27	CB VDatum
H08506	1959	10,000	mean low water	NAD27	CB VDatum
H08507	1959	10,000	mean low water	NAD27	CB VDatum
H08724	1962/63	10,000	mean low water	NAD27	CB VDatum
H08725	1963	5,000	mean low water	NAD27	CB VDatum
H08878	1966	10,000	mean low water	NAD27	CB VDatum
H09693	1977	10,000	mean low water	NAD27	CB VDatum
H09701	1977	5,000	mean low water	NAD27	CB VDatum
H09814	1980	10,000	mean low water	NAD27	CB VDatum
H09880	1980	10,000	mean low water	NAD27	CB VDatum
H09901	1980	10,000	mean low water	NAD27	CB VDatum
H09904	1980	10,000	mean low water	NAD27	CB VDatum
H09905	1980	10,000	mean low water	NAD27	CB VDatum
H09910	1980	10,000	mean low water	NAD27	CB VDatum
H09919	1980/81	20,000	mean lower low water	NAD27	CB VDatum
H09922	1980	20,000	mean lower low water	NAD27	CB VDatum
H09923	1980	5,000	mean lower low water	NAD27	CB VDatum
H09948	1981	20,000	mean low water	NAD27	NC VDatum/CB VDatum
H09955	1981	20,000	mean lower low water	NAD27	CB VDatum
H09959	1981	20,000	mean low water	NAD27	CB VDatum
H09961	1981	20,000	mean lower low water	NAD27	CB VDatum
H09962	1981	20,000	mean lower low water	NAD27	CB VDatum
H09969	1981	20,000	mean lower low water	NAD27	CB VDatum/FME
H09970	1981	20,000	mean lower low water	NAD27	CB VDatum/FME
H09972	1981	20,000	mean low water	NAD27	NC VDatum/CB VDatum
H09978	1981	20,000	mean low water	NAD27	CB VDatum
H09980	1981	20,000	mean low water	NAD27	FME
H09981	1981/82	20,000	mean lower low water	NAD27	FME
H10034	1982	20,000	mean lower low water	NAD27	FME
H10066	1982	20,000	mean lower low water	NAD27	FME
H10116	1983	10,000	mean lower low water	NAD27	CB VDatum
H10127	1984	10,000	mean lower low water	NAD27	CB VDatum
H10275	1988	5,000	mean lower low water	NAD83	CB VDatum
H10529	1994	5,000	mean lower low water	NAD83	CB VDatum
H10745	1997	10,000	mean lower low water	NAD83	CB VDatum

* NC–North Carolina; CB–Chesapeake Bay; FME–translated using FME and constant offset from neighboring tide station.

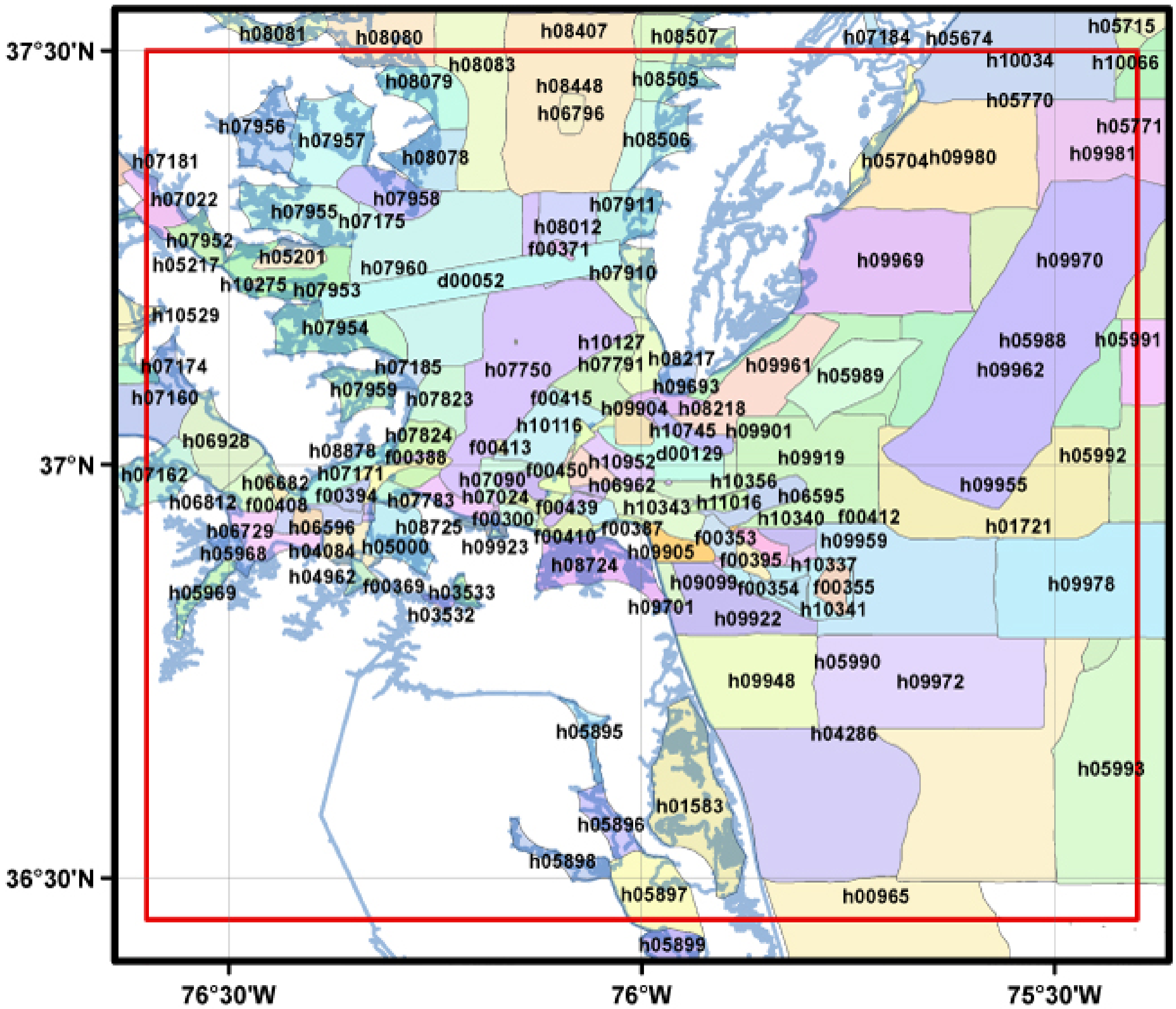

Figure 6. Digital NOS hydrographic survey coverage in the Virginia Beach region. Not all surveys were used as some fall outside the DEM region, while others have been fully superceded by subsequent surveys. Red denotes boundary of Virginia Beach DEM; combined coastline in light blue.

2) Recent NOS shallow-water multibeam surveys

The NOS Atlantic Hydrographic Branch (AHB) provided 6 shallow-water, "not fully reviewed" NOS multibeam surveys for inclusion in the Virginia Beach DEM (Table 6); these surveys have not yet been submitted to NGDC's NOS hydrographic database. The surveys cover the southern portion of the entrance to Chesapeake Bay, near Cape Henry (Fig. 7). All of the surveys were conducted recently and are of high resolution. Survey H11303 was found to contain north–south lineations (e.g., Fig. 8) over its whole coverage area. NGDC was unable to correct the errors and therefore deleted the soundings along the lineations. AHB is re-processing this survey to correct for the lineations.

Table 6. Recent NOS shallow-water multibeam surveys used in compiling the Virginia Beach DEM.

Survey	*Date*	*Resolution*	*Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
H11028	2001 to 2002	1 meter	1:10,000	NAD83 UTM Zone 18	MLLW
H11301	2005	10 meters	1:10,000	NAD83 UTM Zone 18	MLLW
H11302	2003	5 meters	1:10,000	NAD83 UTM Zone 18	MLLW
H11303	2004	5 meters	1:10,000	NAD83 UTM Zone 18	MLLW
H11401	2005	5 meters	1:10,000	NAD83 UTM Zone 18	MLLW
H11402	2005	10 meters	1:10,000	NAD83 UTM Zone 18	MLLW

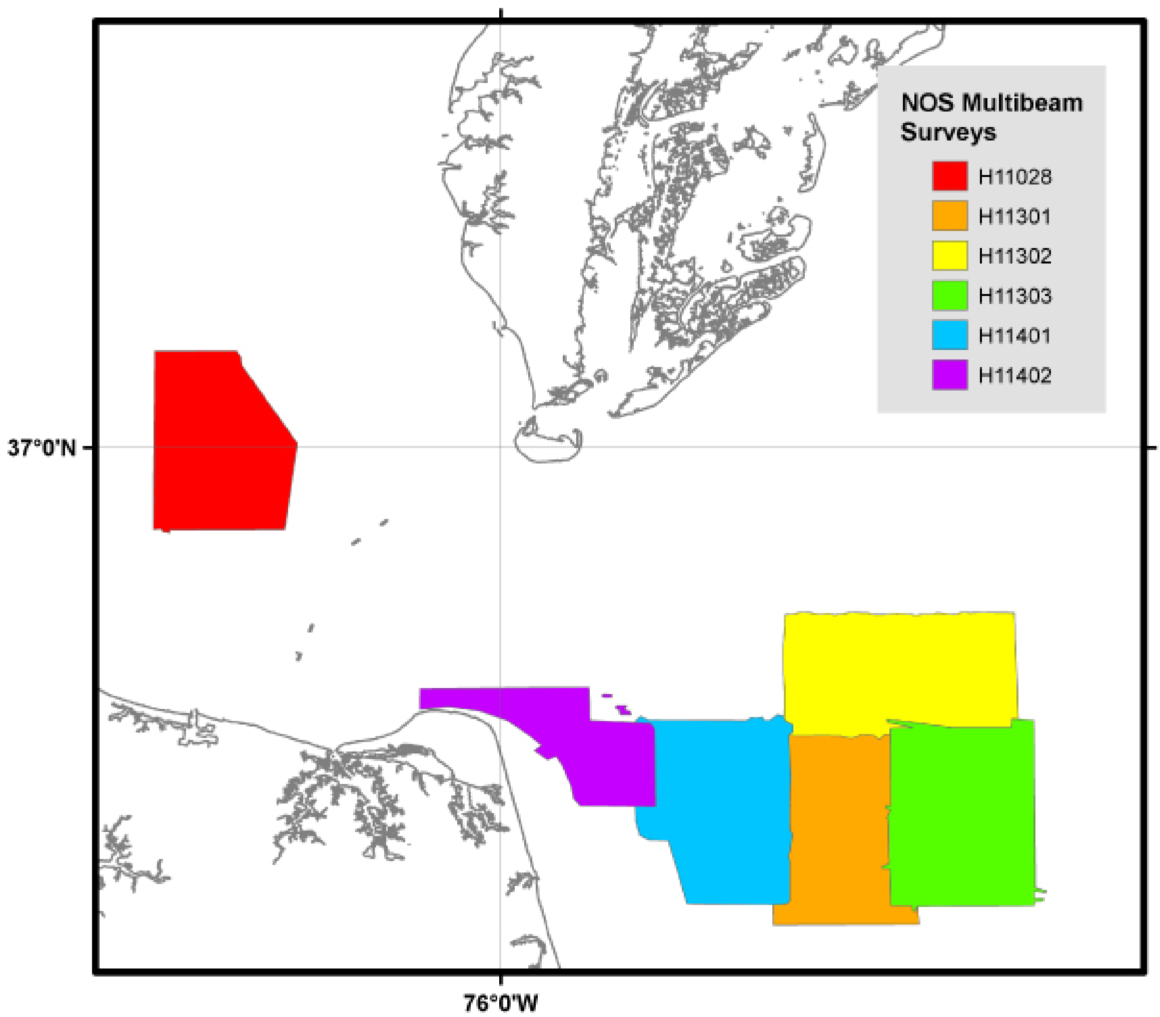

Figure 7. *Spatial coverage of NOS shallow-water multibeam swath sonar surveys in the vicinity of Virginia Beach that were utilized in DEM development.*

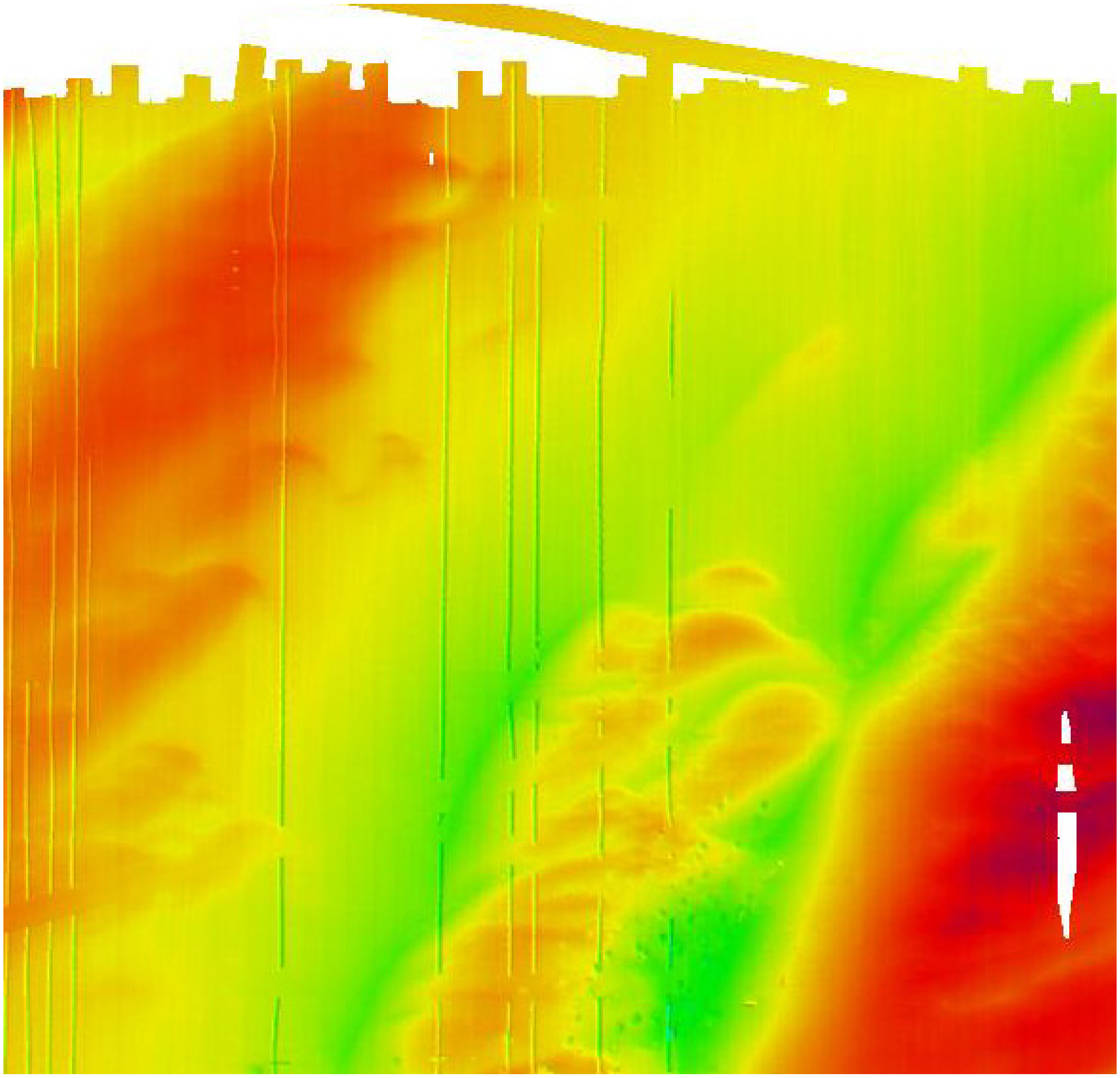

Figure 8. *Detail of NOS multibeam survey H11303. Prominent lineations were excised by deleting corresponding data values from the survey.*

3) USACE surveys of dredged shipping channels and the Intracoastal Waterway

The USACE Hydrographic Surveys Division, Virginia Beach District provided NGDC with recent survey data in dredged shipping channels and the Atlantic Intracoastal Waterway. All data were originally in NAD83 State Plane Virginia South horizontal datum and MLLW vertical datum (Table 7). Surveys consist of numerous, parallel, across-channel profiles, spaced 30 to 130 meters apart, with point soundings <1m apart.

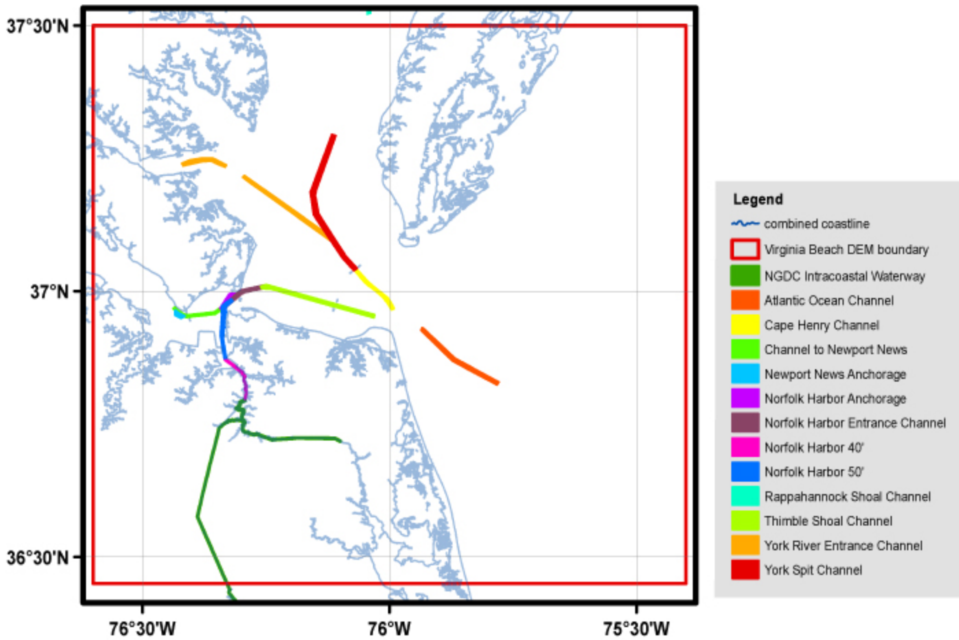

Figure 9. *Spatial coverage of USACE surveys of dredged shipping channels and the Atlantic Intracoastal Waterway in the vicinity of Virginia Beach.*

Table 7. Recent USACE surveys used in compiling the Virginia Beach, Virginia.

Region	*Original horizontal datum*	*Original vertical datum*	*Spatial resolution*	*Year*
Atlantic Ocean Channel	NAD83 State Plane Virginia South	MLLW	Profiles ~600 to 700m long, spaced 30m apart, with point spacing <1m.	2006
Cape Henry Channel	NAD83 State Plane Virginia South	MLLW	Profiles 500 to 600m long, spaced 60m apart, with point spacing <1m.	2006
Channel to Newport News	NAD83 State Plane Virginia South	MLLW	Profiles 500m long, spaced 30 to 60m apart, with <1m point spacing.	2006
Newport News Anchorage	NAD83 State Plane Virginia South	MLLW	Profiles 900m long, spaced 60m apart, with <1m point spacing.	2006
Norfolk Harbor Anchorage	NAD83 State Plane Virginia South	MLLW	Profiles 60 to 1100m long, spaced 60m apart, with <1m point spacing.	2005
Norfolk Harbor 40' Channel	NAD83 State Plane Virginia South	MLLW	Profiles 300 to 400m long, spaced 30m apart, with <1m point spacing	2006
Norfolk Harbor 50' Channel	NAD83 State Plane Virginia South	MLLW	Profiles 350 to 700m long, spaced 30m apart, with <1m point spacing.	2006
Norfolk Harbor Entrance Channel	NAD83 State Plane Virginia South	MLLW	Profiles 600 to 700m long, spaced 30 to 60m apart, with <1m point spacing	2004
Rappahannock Shoal Channel	NAD83 State Plane Virginia South	MLLW	Profiles 500m long, spaced 100m apart, with <1m point spacing.	2005
Thimble Shoal Channel	NAD83 State Plane Virginia South	MLLW	Profiles 500 to 750m long, spaced 60m apart, with <1m point spacing	2006
York River Entrance Channel	NAD83 State Plane Virginia South	MLLW	Profiles 500m long, spaced 60m apart, with <1m point spacing.	2005
York Spit Channel	NAD83 State Plane Virginia South	MLLW	Profiles 800m long, spaced 60 to 130m apart, with point spacing of <1m.	2005

4) NGDC-digitized Atlantic Intracoastal Waterway

The continuation of the Atlantic Intracoastal Waterway southward from the Elizabeth River to Currituck Sound (Figs. 9 and 10) was digitized by NGDC in ESRI ArcMap, referencing NOAA nautical chart #12206 and Coast Pilot 4. NGDC defined the soundings at 12 feet below MLLW (the minimum dredged depth in the waterway) for Route 1, Albemarle and Chesapeake Canal to North River, and 9 feet for Route 2, Great Dismal Swamp Canal to Albemarle Sound (Fig. 10). Additional information on project depths and locations can be found in Coast Pilot 4, chapter 12 (http://www.nauticalcharts.noaa.gov/nsd/coastpilot_w.php?book=4).

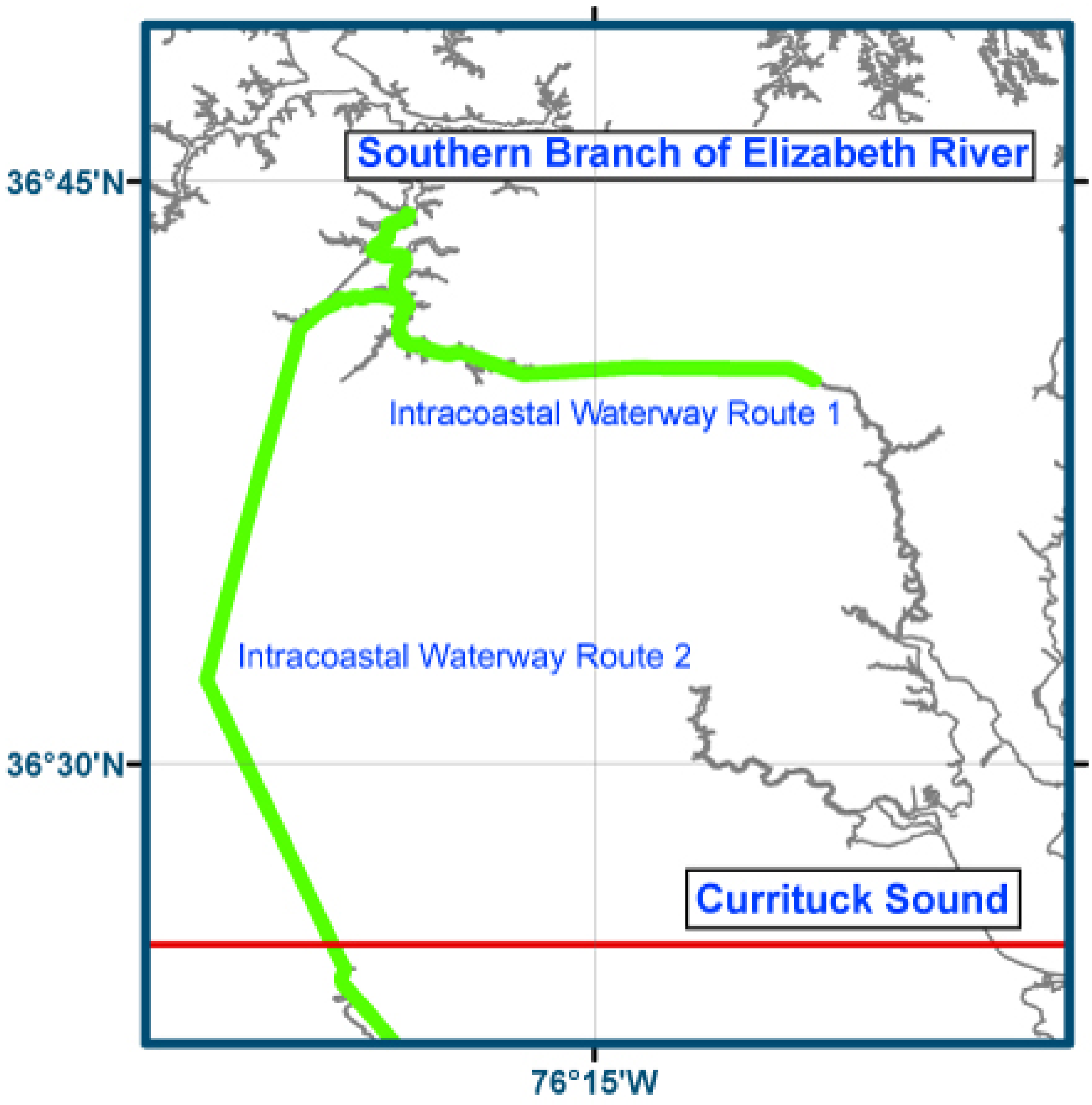

Figure 10. Spatial coverage of NGDC-digitized sections of the Atlantic Intracoastal Waterway. Depths were defined based upon minimum dredge depths reported in Coast Pilot 4.

5) ENC-extracted sounding data

Sounding data from four ENCs (Table 8) were extracted to fill in gaps in NOS bathymetric coverage: #12253 in the southern branch of the Elizabeth River (Fig. 11), #12224 and #12221 in the Delmarva Peninsula region (Fig. 12), and #12248 in the James River from Newport News to Tribell Shoal. The sounding files were extracted from the ENCs in S-57 geodatabase format using CSC's ENC data handler extension for ArcGIS 9.x (http://www.csc.noaa.gov/products/enc/arcgis9x.html) and then exported to ESRI shapefiles. Charts #12221 and #12224 were then edited to include only those which lie inside the peninsula and eliminate those on the eastern shoreline and in Chesapeake Bay where NOS bathymetric coverage was available. Soundings were shifted from MLLW to MHW using FME and applying a conversion constant derived from the local tide station (see Table 11).

Table 8. Constants applied to ENC-extracted soundings.

Chart #	*MLLW to MHW constant applied*	*Tide Station #*
12221	-.827 meters	8632200
12224	-.827 meters	8632200
12253	-.778 meters	8638610
12248	-.778 meters	8638610

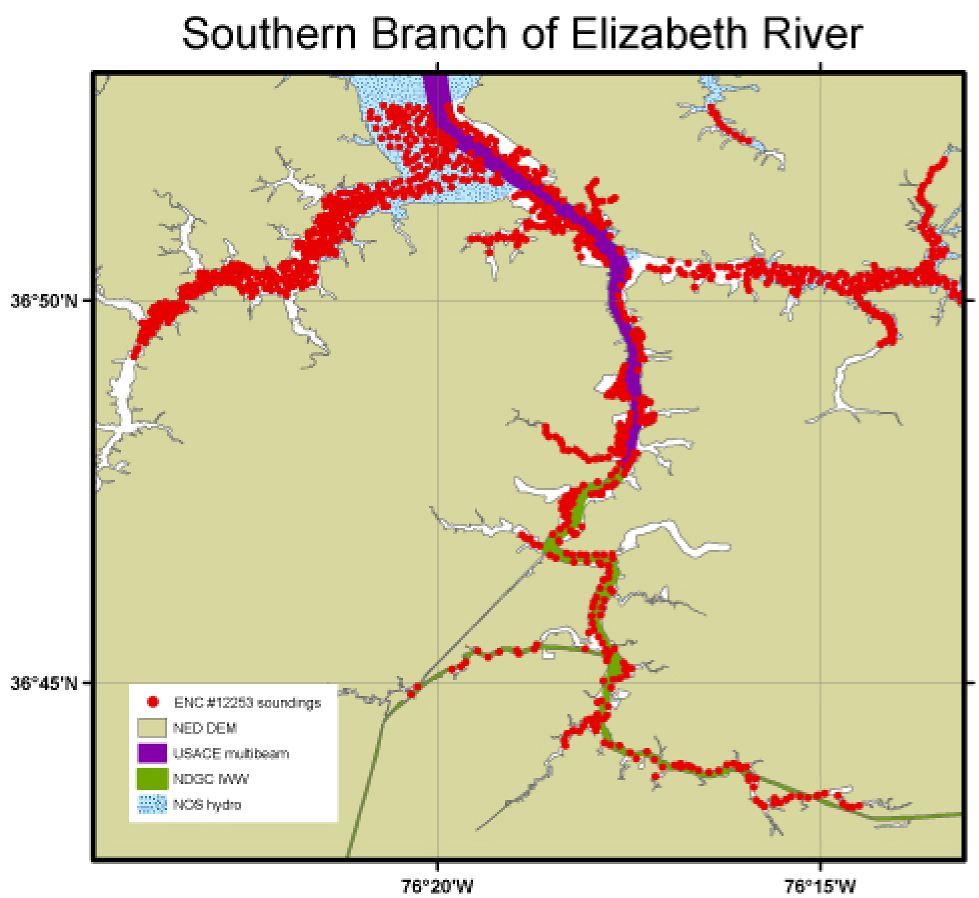

Figure 11. *Spatial coverage of soundings extracted from ENC #12253. ENC data shown with USACE and NOS surveys and NGDC-digitized Atlantic Intracoastal Waterway.*

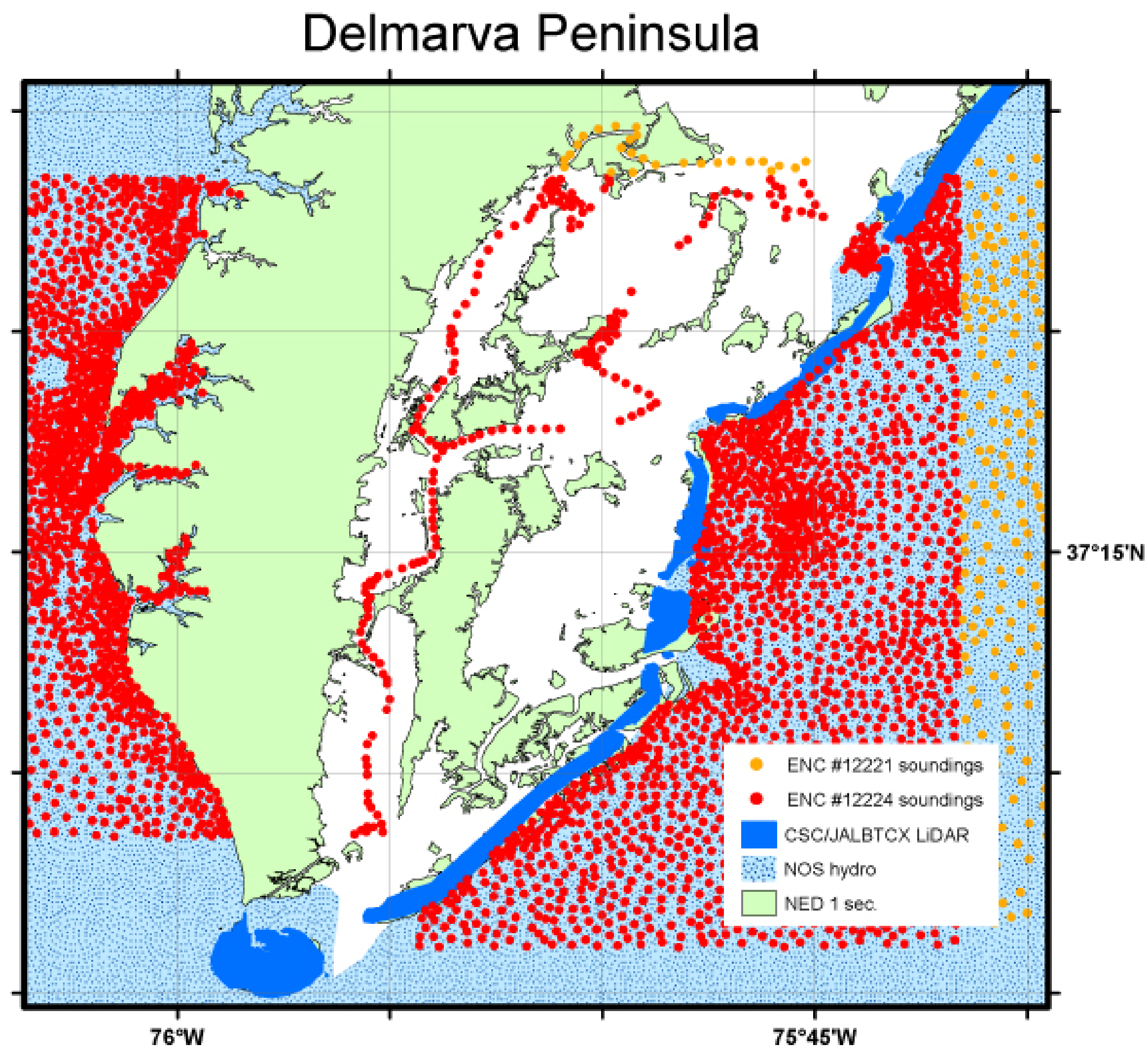

Figure 12. *Spatial coverage of soundings extracted from ENCs in the Delmarva Peninsula region. Extensive gaps (white areas) between the ENC soundings and NOS hydrographic soundings were filled by interpolation (see Section 3.3.3)*

3.1.3 Topography

Topographic datasets in the Virginia Beach region were obtained from the U.S. Geological Survey and the cities of Virginia Beach, Norfolk, and Hampton, Virginia (Table 9).

Table 9. Topographic datasets used in compiling the Virginia Beach DEM.

Source	*Data*	*Date*	*Resolution*	*Original horizontal datum*	*Original vertical datum*
USGS	NED	1999	1/3 to 1 arc-second (~ 10 to 30 m)	NAD83 geographic	NAVD88
City of Virginia Beach	LiDAR	2004	~2 m point spacing	NAD83 HARN State Plane Virginia South	NAVD88

1) **USGS NED topography**

The U.S. Geological Survey's (USGS) National Elevation Dataset (NED; http://ned.usgs.gov/) provides complete 1 arc-second coverage of the contiguous lower 48 states, as well as some areas at 1/3 arc-second[2]. Data are in NAD83 geographic coordinates and NAVD88 vertical datum (meters), and are available for download as raster DEMs. The extracted bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution. See the USGS *Seamless* web site for specific source information (http://seamless.usgs.gov/). The dataset was derived from contours on USGS topographic quadrangle maps and aerial photos, based on surveys conducted in the 1970s and 1980s.

NED 1/3 arc-second topographic data is available for most of the Virginia Beach region, with the exception of the Delmarva Peninsula, for which 1 arc-second data was downloaded (see Fig. 3). One problem identified with the NED 1/3 arc-second data, near Hampton, is artifacts representing an approximate one half meter elevation change, which are present at 7.5 minute intervals (Fig. 13). NGDC was unable to make corrections and the artifacts are present in the DEM. Also recognizable are "steps" in the topographic, presumably derived from the digitization of contours. These features are also present in the Virginia Beach DEM (see Fig. 21). NED 1 arc-second data the in Delmarva Peninsula also exhibited some problems (e.g., Fig. 14), which could not be rectified.

The NED data also included "zero" elevation values over the open ocean, which were removed from the dataset before gridding by clipping to the combined coastline, with ArcCatalog, and deleting of all values equal or less than zero, with FME.

2. The USGS National Elevation Dataset (NED) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for Georgia. The dataset provides seamless coverage of the United States, HI, AK, and the island territories. NED has a consistent projection (Geographic), resolution (1 arc second), and elevation units (meters). The horizontal datum is NAD83, except for AK, which is NAD27. The vertical datum is NAVD88, except for AK, which is NGVD29. NED is a living dataset that is updated bimonthly to incorporate the "best available" DEM data. As more 1/3 arc second (10 m) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED website]

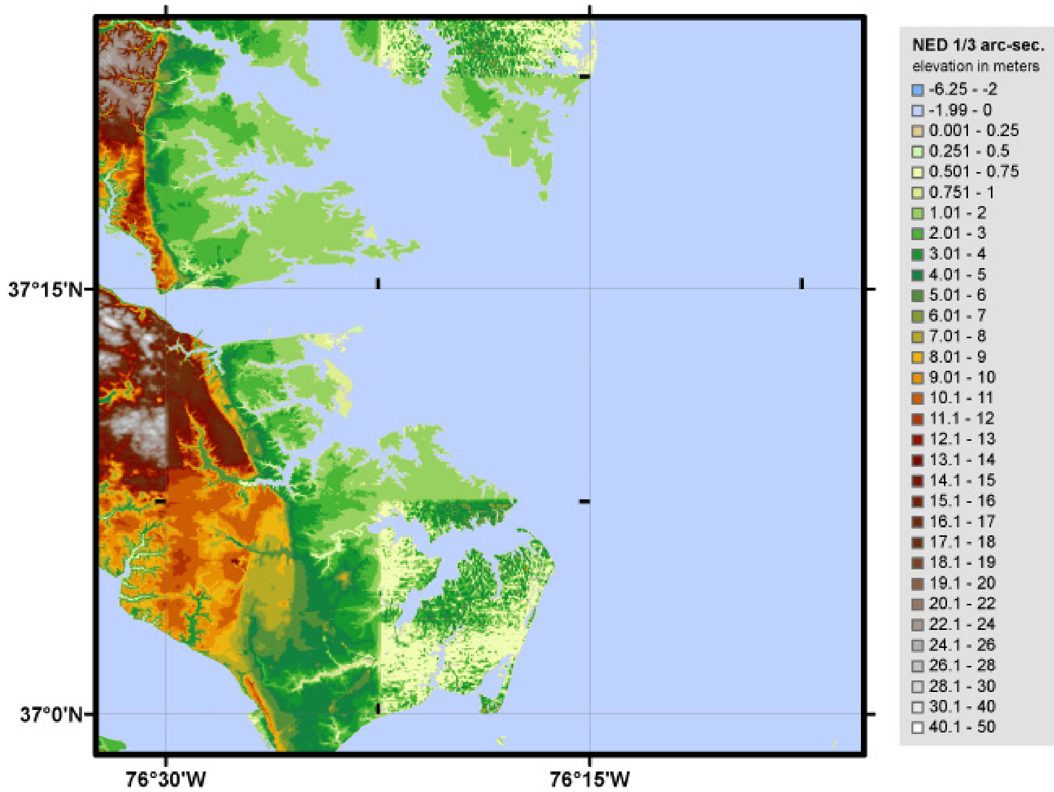

Figure 13. *Color image of the NED 1/3 arc-second DEM in the Hampton, Virginia area. Tick marks show artificial elevation changes within the DEM that roughly correspond to 7.5 minute quadrangle boundaries.*

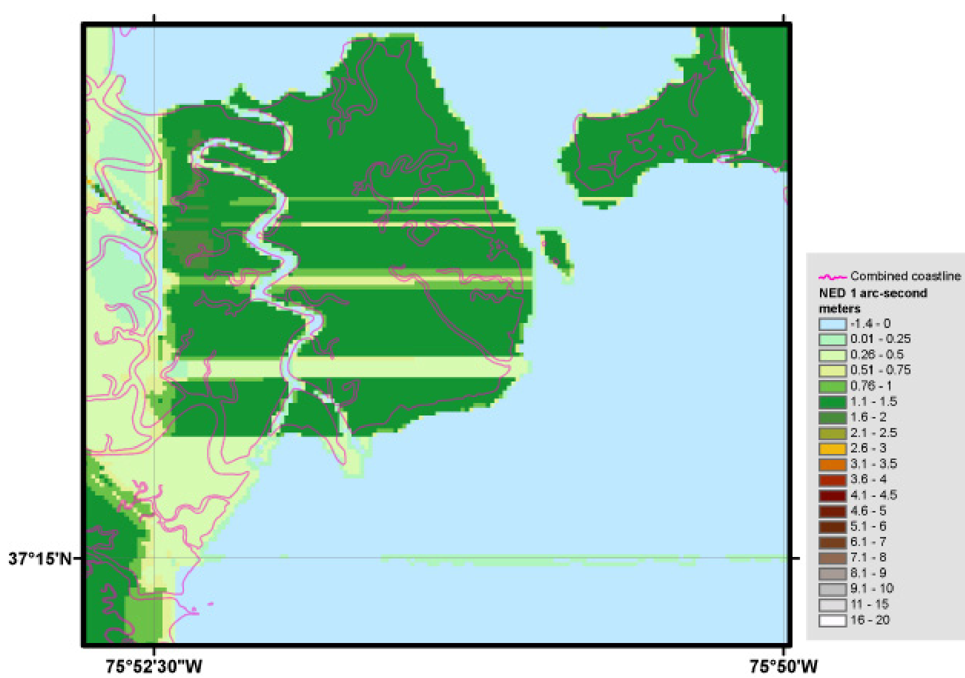

Figure 14. *Color image of striations within the NED 1 arc-second data in the Delmarva Peninsula. Striation elevations are within a 1 meter of surrounding topography. Combined coastline in red.*

2) NASA Shuttle Radar Topography Mission

The NASA Shuttle Radar Topography Mission (SRTM) obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth[3]. The SRTM consisted of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000. Data from this mission have been processed into 1 degree × 1 degree tiles that have been edited to define the coastline, and are available from the USGS *Seamless* web site (http://seamless.usgs.gov/) as raster DEMs. The data have not been processed to bare earth, but meet absolute horizontal and vertical accuracies of 20 and 16 meters, respectively.

The SRTM dataset was downloaded for use in the Delmarva Peninsula region, for areas not covered by the 1/3 arc-second NED data. This area consists of western lowlands and eastern marshlands. The SRTM data reflects little topography variation on the eastern side of the peninsula but has a range of elevation values—from -47 meters to 78 meters, MHW—on the western and southernmost tip, at Fishermans Island (Fig. 15); USGS quadrangles Cheriton, Fishermans Island, and Franktown have maximum elevation values of ~30 m. The SRTM DEM also contains positive elevation values over the open ocean. Analysis of this dataset, compared to overlapping NED 1 arc-second data and USGS quadrangles, showed the SRTM data to have less accurate elevation values in general, thus, this dataset was not used in building the Virginia Beach DEM.

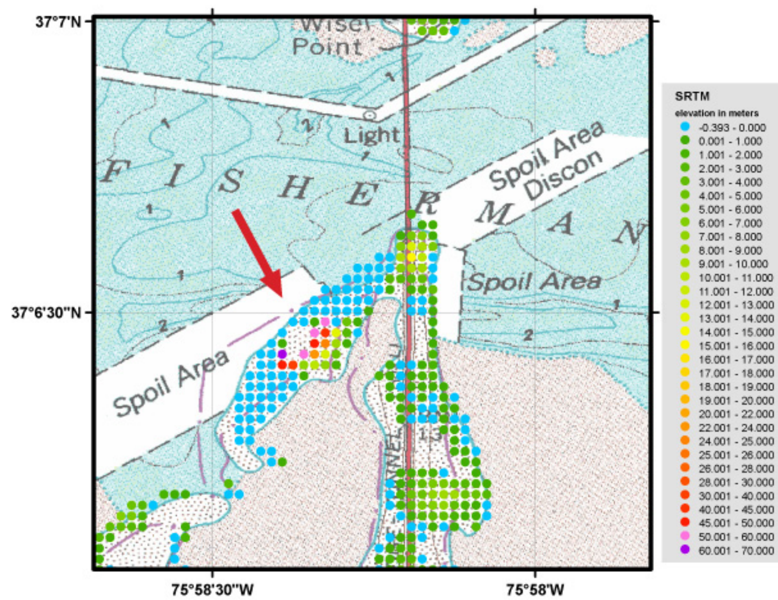

Figure 15. *SRTM data in the vicinity of Fishermans Island. Some SRTM elevation values are greater than 50 meters: high data points are located on land "exposed at low tide" (from underlying USGS quadrangle 'Fishermans Island').*

3. The SRTM data sets result from a collaborative effort by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA – previously known as the National Imagery and Mapping Agency, or NIMA), as well as the participation of the German and Italian space agencies, to generate a near-global digital elevation model (DEM) of the Earth using radar interferometry. The SRTM instrument consisted of the Spaceborne Imaging Radar-C (SIR-C) hardware set modified with a Space Station-derived mast and additional antennae to form an interferometer with a 60 meter long baseline. A description of the SRTM mission can be found in Farr and Kobrick (2000). Synthetic aperture radars are side-looking instruments and acquire data along continuous swaths. The SRTM swaths extended from about 30 degrees off-nadir to about 58 degrees off-nadir from an altitude of 233 km, and thus were about 225 km wide. During the data flight the instrument was operated at all times the orbiter was over land and about 1000 individual swaths were acquired over the ten days of mapping operations. Length of the acquired swaths range from a few hundred to several thousand km. Each individual data acquisition is referred to as a "data take." SRTM was the primary (and pretty much only) payload on the STS-99 mission of the Space Shuttle Endeavour, which launched February 11, 2000 and flew for 11 days. Following several hours for instrument deployment, activation and checkout, systematic interferometric data were collected for 222.4 consecutive hours. The instrument operated almost flawlessly and imaged 99.96% of the targeted landmass at least one time, 94.59% at least twice and about 50% at least three or more times. The goal was to image each terrain segment at least twice from different angles (on ascending, or north-going, and descending orbit passes) to fill in areas shadowed from the radar beam by terrain. This 'targeted landmass' consisted of all land between 56 degrees south and 60 degrees north latitude, which comprises almost exactly 80% of Earth's total landmass. [Extracted from SRTM online documentation]

3) City of Virginia Beach LiDAR

The City of Virginia Beach provided NGDC with a topographic LiDAR dataset consisting of 1517 tiles covering the region around Virginia Beach and Cape Henry[4]. The tiles are approximately 775 meters square and have average point spacing of two meters—significantly higher-resolution than overlapping NED 1/3 arc-second topography. The dataset was originally in NAD83 HARN State Plane Virginia South horizontal datum, and NAVD88 vertical datum. This dataset had been processed to bare earth, but also contained elevation values over water, which were removed using FME software by deleting all values less than 0.2 meters below MHW. The massive quantity of elevation points (170 million) required surfacing of the entire dataset (see Section 3.3.2) for proper evaluation. The bare-earth processing done by Sanborn, contractor for the City of Virginia Beach, removed most elevated structures, however, some features, such as freeway overpasses, bridges and piers, remained in the dataset, requiring editing by NGDC (e.g., Figs. 16 and 17). The bare-earth processing also left "shadows" in the data: low-relief (<1 m) features reminiscent of the original man-made structures, such as roads and airport runways.

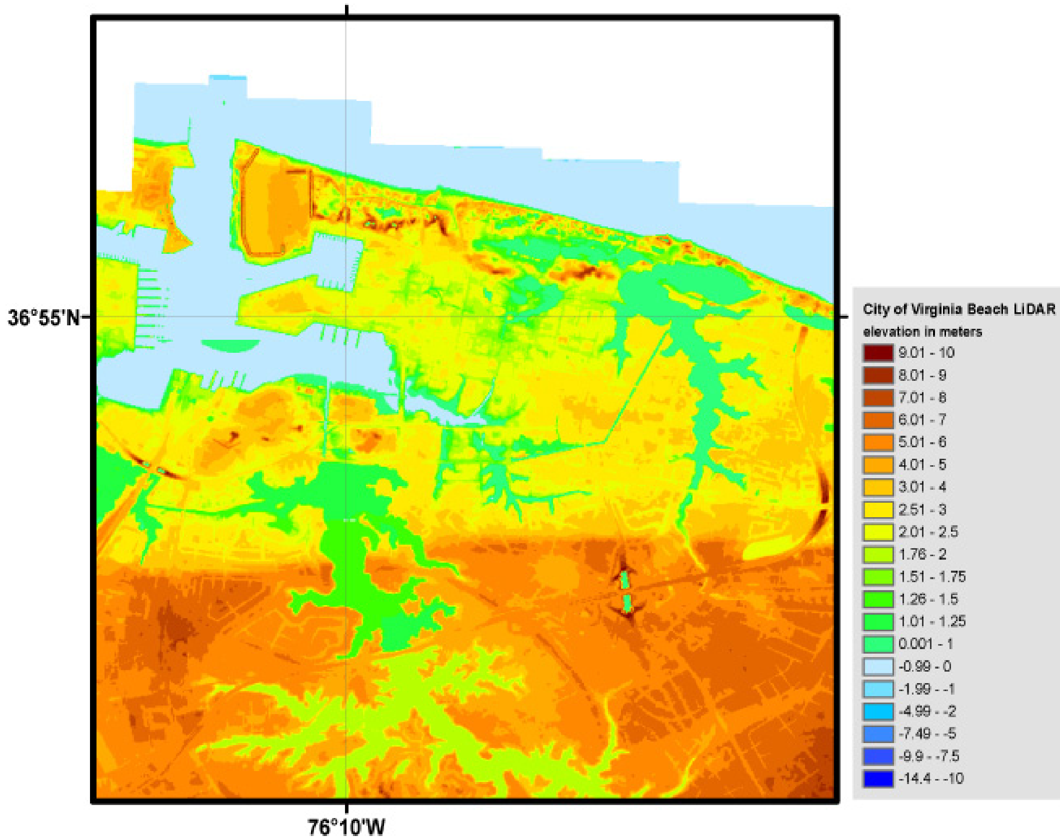

Figure 16. *Color image of City of Virginia Beach LiDAR data in the vicinity of Little Creek Channel. Image shows freeway routes, piers, docks, and portion of jetty at entrance to channel. Also at entrance is low retaining wall surrounding amphibious vehicle parking area. Building at the site was removed during processing to bare earth by contractor.*

4. Utilizing Sanborn's Optech ALTM 2050 system, the Light Detection and Ranging (LIDAR) data was for use in the development of a very dense and highly accurate digital elevation model that will be used in the generation of digital orthophoto imagery and subsequent development of 2' contours. The system consisted of geodetic GPS positioning, orientation derived from high-end inertial sensors and a powerful laser. The sensor was attached to an airplane's underside and emits rapid pulses of light that are used to determine distances between the plane and terrain below. The 50kHz Optech 2050 provide up to 50,000 light impulses per second. The 2050 allows for faster flight speeds, higher altitude of data collection, larger swath width of the sensor, and most importantly a denser point spacing of 1 meter which results in improved surface definition and better penetration of vegetation. After the acquisition, the data were "filtered" using automatic routines, which recognize trees, buildings, cars, etc. and are able to delete these items from the DTM. [Extracted from metadata.]

Figure 17. *Google Earth image of Little Creek Channel. Numerous man-made structures—piers and docks—had to be removed from the City of Virginia Beach LiDAR data. Note jetty at channel entrance that was retained.*

4) City of Norfolk SPOT data

SPOT data (topographic elevations derived from imagery taken by the Spot 1 satellite) for Norfolk was provided to NGDC by the GIS Team, eAccess Bureau, Department of Information Technology for the City of Norfolk without associated metadata confirming vertical datum. NGDC assumed that it is referenced to NAVD88, which is typical of U.S. topographic datasets. The dataset covers the metropolitan area of Norfolk and is not processed to bare earth; elevation values were compared to USGS topographic quadrangles, and points corresponding to features such as bridges and freeway overpasses exist within the data. As bare-earth 1/3 arc-second NED topography exists for this area, this dataset was not used in the development of the Virginia Beach DEM.

5) City of Hampton SPOT data

This data set consists of SPOT elevation data acquired in 1999 from Air Survey Corp. original aerial photos at 1:400. The dataset covers the metropolitan region of Hampton and the surrounding coastal areas and is not processed to bare earth. NED 1/3 arc-second topography exists for this region, so this dataset was also not used in the development of the Virginia Beach DEM.

3.1.4 Topography–Bathymetry

Combined topographic–bathymetric surveys of the Atlantic coast of Virginia and North Carolina (Fig. 18) were performed in 2005 by the Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX; Table 10). The data were collected using the CHARTS (Compact Hydrographic Airborne Rapid Total Survey) system to depict elevations above and below water along the immediate coastal zone. The surveys generally have a swath width approaching 1 km, most of which, in the Virginia Beach region, covers onshore areas: 700–800 m inland, and 100–150 m offshore. Data points are spaced approximately every 1 to 5 meters, and have an accuracy better than 3.0 meters horizontally and 0.3 meters vertically.

Table 10. Combined topographic–bathymetric datasets used in compiling the Virginia Beach DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*
JALBTCX (USACE)	2005	Bare-earth coastal topographic and bathymetric LiDAR	1-meter DEM	NAD83 UTM Zone 18 (meters)	NAVD88 (meters)
JALBTCX (CSC)	2005	Raw coastal topographic and bathymetric LiDAR	5-meter point data	NAD83 geographic	NAVD88 (meters)

1) **JALBTCX bare-earth DEM for NC**

   USACE provided to NGDC JALBTCX bathymetric–topographic LiDAR data along the Atlantic coast of North Carolina that had been processed to bare earth[5]. Data were provided as DEMs, with 1-meter grid spacing.

2) **JALBTCX data available through CSC**

   Unprocessed JALBTCX bathymetric–topographic LiDAR data[6] for the Atlantic coast of Virginia are available for download from the NOAA CSC website (http://maps.csc.noaa.gov/TCM/). Data along the southern coast of Virginia, south of Cape Henry, were overlapped by topographic LiDAR data from the City of Virginia Beach, which had been processed to bare earth. JALBTCX LiDAR data in this region were therefore clipped to exclude values greater than 1 meter above MHW. Data along the northern coast (Delmarva Peninsula) were not overlapped by any other high-resolution dataset, though few man-made structures exist in that largely undeveloped area.

5. Acquisition Data were acquired using a SHOALS-1000T. Sensor orientation was measured using a POS AV 410, while images were acquired at 1Hz using a Duncantech DT4000 digital camera. Prior to survey PDOP was checked and missions planned to avoid PDOP greater than 3.5. During survey the plane was always within 30km of a GPS ground control point, to provide a good quality position solution. Final positions were determined using a post-processed inertially aided Kinematic GPS (KGPS) solution. GPS ground control data were acquired at 1Hz. Data received by the airborne system were continually monitored for data quality during acquisition operations. Display windows showed coverage and information about the system status. In addition, center waveforms at 5Hz were shown. All of this information allowed the airborne operator to assess the quality of data being collected. Data were processed in the field to very coverage and data quality. Processing Data were processed using the SHOALS Ground Control System (GCS). The GCS includes links to Applanix POSPac software for GPS and inertial processing, and IVS Fledermaus software for data visualization, 3D editing and tie-line analysis. Data were processed in NAD83 horizontal and vertical datum. Data were later converted to the NAVD88 vertical datum using the GEOID03 model. Fugro in-house utilities were used to extract XYZ data from the native LIDAR files and split the data in to pre-defined boxes, each covering approximately 5km of shoreline. ASCII files include Longitude Latitude Elevation Date Time Intensity (Topo) or Depth Confidence (Hydro). The bare earth model was created using Terrascan to define ground points. The ground points were then gridded using QT Modeler, to create a seamless model. The final Bare Earth Model is a 1m resolution GeoTIFF file. [Extracted from metadata.]

6. These data were collected using a SHOALS-1000T system. It is owned and operated by Fugro Pelagos performing contract survey services for the US Army Corps of Engineers. The system collects topographic lidar data at 10kHz and hydrographic data at 1kHz. The system also collects RGB imagery at 1Hz. Aircraft position, velocity and acceleration information are collected through a combination of Novatel and POS A/V equipment. Raw data are collected and transferred to the office for downloading and processing in SHOALS GCS software. GPS data are processed using POSPac software and the results are combined with the lidar data to produce 3-D positions for each lidar shot. These data are edited using Fledermaus software where anomalous data are removed from the dataset. The edited data are unloaded from SHOALS GCS, converted from ellipsoid to orthometric heights, based on the GEOID03 model, and split into geographic tiles covering approximately 5km each. [Extracted from metadata.]

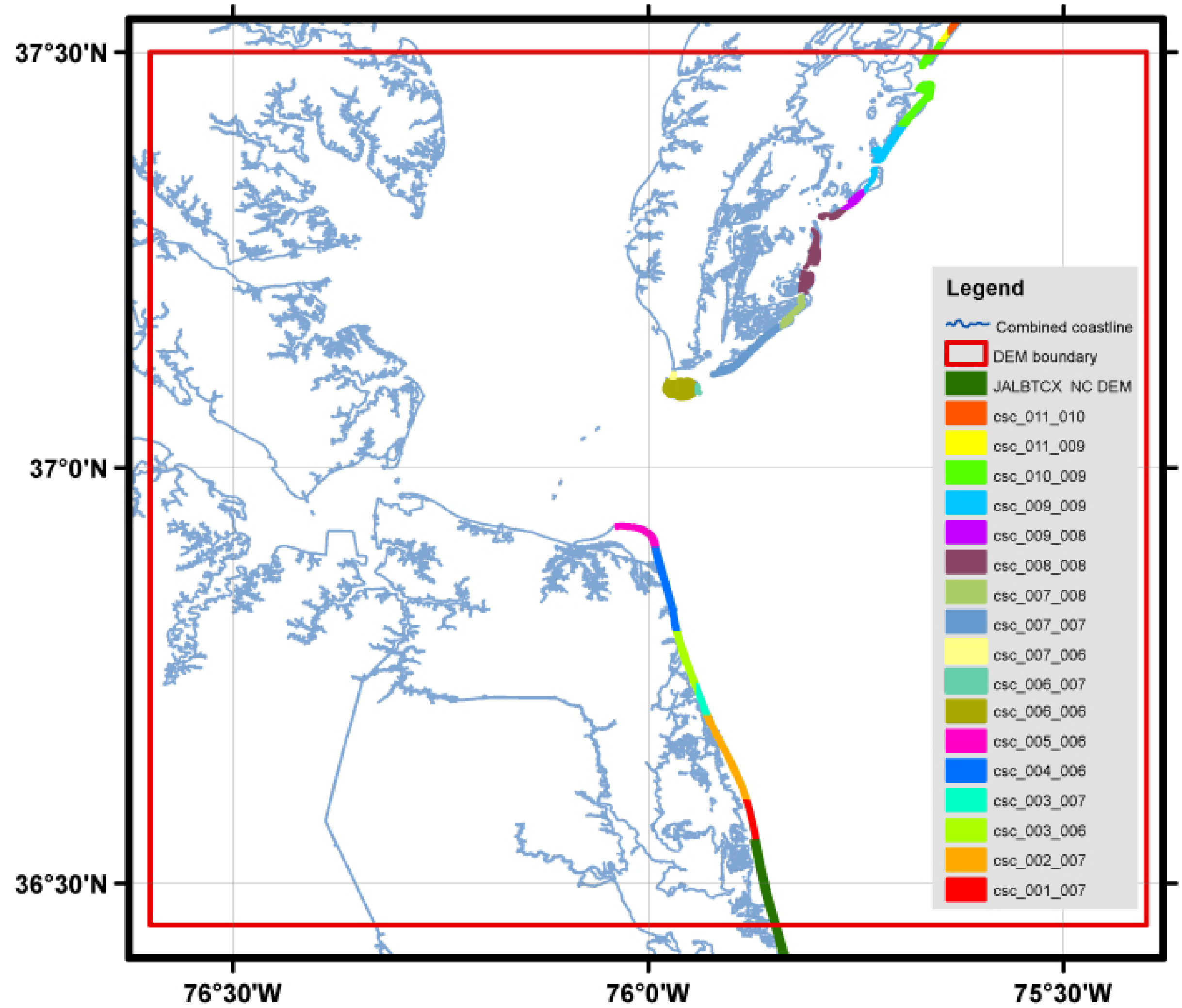

Figure 18. *Spatial coverage of JALBTCX high-resolution, combined bathymetric–topographic, coastal LiDAR surveys in the vicinity of Virginia Beach that were utilized in DEM development.*

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Virginia Beach DEM were originally referenced to a number of vertical datums including: Mean Lower Low Water (MLLW), Mean Low Water (MLW), and North American Vertical Datum of 1988 (NAVD88). All datasets were transformed to MHW to provide the worst-case scenario for inundation modeling.

1) **Bathymetric data**

The NOS hydrographic and multibeam survey data were transformed from original vertical datum to MHW using the VDatum Transformation Tool developed by OCS and NGS. VDatum was only available for a portion of the DEM (Fig. 19), so where unavailable, FME software was used to apply a constant value based on both tidal benchmark values (Table 11) and the difference in value before and after VDatum was used on nearby data. The ENC sounding data used in Delmarva Peninsula and in the Elizabeth River were transformed to MHW from MLLW by applying a constant value based on the nearest tide station. For the Atlantic Intracoastal Waterway digitized by NGDC, Coast Pilot 4 provided project depths at MLLW and a constant was applied to the value to transform to MHW.

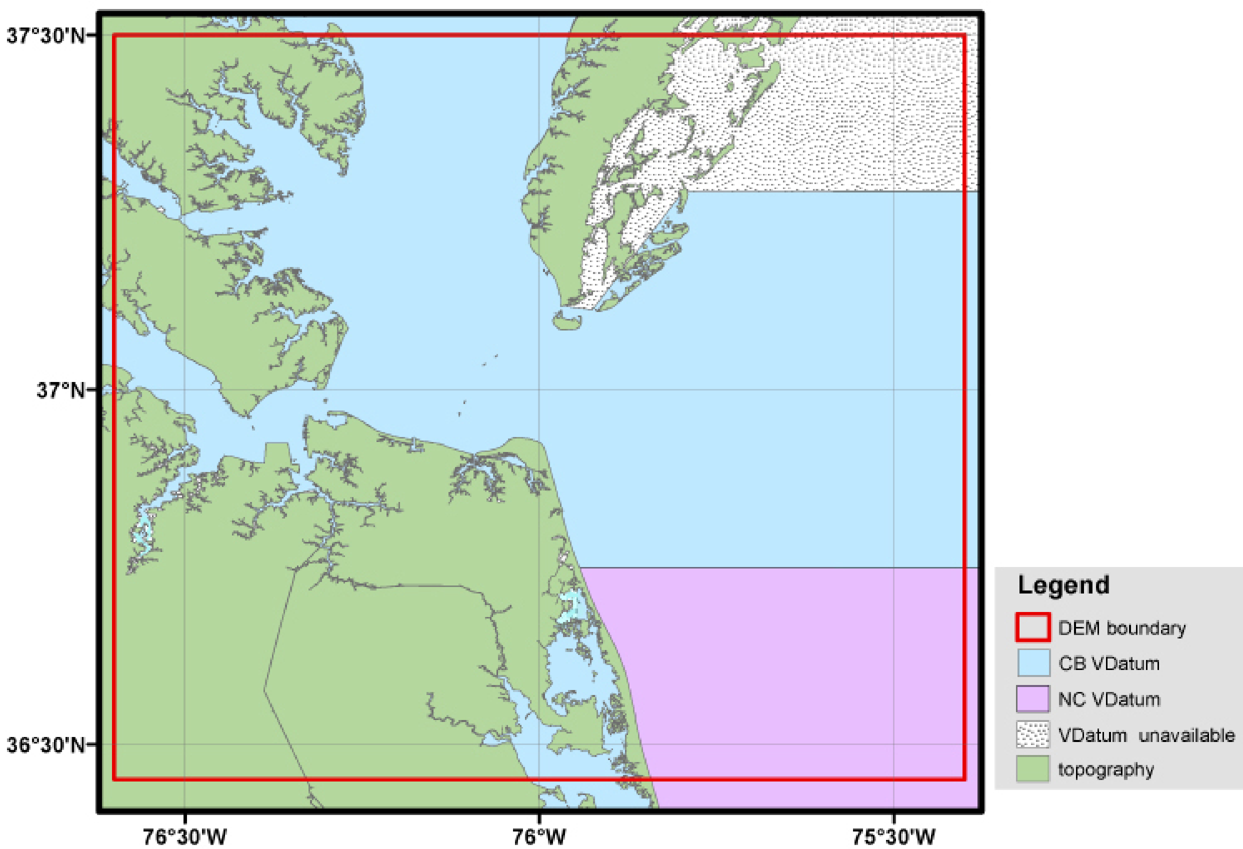

Figure 19. *Spatial coverage of VDatum transformation tools within Virginia Beach DEM boundary.*

2) **Topographic data**

The NED DEM and City of Virginia Beach LiDAR data were originally in NAVD88 and converted to MHW using FME software by adding a constant value based on closest tidal benchmark (Table 11).

3) Topographic–bathymetric data

The JALBTCX coastal LiDAR survey data and the NC DEM were transformed from NAVD88 to MHW using FME and closest tide station values.

Table 11. Relationships between Mean High Water and other vertical datums in the Virginia Beach region.*

Tide Station #	*Station Name*	*MLLW to MHW*	*MLW to MHW*	*NAVD88 to MHW*
8632200	Kiptopeke, Chesapeake Bay	-0.827	-0.793	-0.247
8638610	Sewells Point	-0.778	-0.740	-0.277
8638863	Chesapeake Bay Bridge Tunnel	-0.814	-0.777	N/A
8639208	Virginia Beach	-1.038	-1.001	-0.281
8639348	Money Point	-0.914	-0.872	-0.357

* Tide station locations shown in Figure 24.

3.2.2 Horizontal datum transformations

Datasets used to compile the Virginia Beach DEM were originally referenced to State Plane Virginia South, UTM Zone 18, NAD83, and WGS84 horizontal datums. The relationships and transformational equations between these horizontal datums are well established. All data were converted to a horizontal datum of WGS84 using FME software.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting ESRI shape files were checked in ESRI ArcMap for inter-dataset consistency. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shape files were then converted to xyz files in preparation for gridding. Problems included:

- Presence of man-made structures and river banks in most coastline datasets, which had to be removed.
- Data values over the open ocean in the NED 1 arc-second and 1/3 arc-second topographic DEMs, and in the City of Virginia Beach LiDAR data. Each dataset required automated clipping to the combined coastline and removal of "zero" values.
- Artifacts present in the NED DEMs, such as elevation changes at the apparent boundaries of USGS topographic quadrangles, and lineations in the Delmarva Peninsula. Other discrepancies included artificial "steps" in the NED DEMs, which presumably result from the digitization of USGS topographic contours (see Fig. 21).
- Presence of man-made structures (e.g., Fig 16) in the City of Virginia Beach LiDAR data, which had been processed to bare earth by the city's contractor. Such features, where they could be confidently identified, were removed from coastal areas.
- Presence of some buildings and other man-made structures, as well as trees, in the JALBTCX coastal LiDAR topographic–bathymetric datasets along the southern Virginia coastline. As these datasets were principally along the immediate coastline, were not processed to bare earth, and were overlapped by the City of Virginia Beach topographic LiDAR data, NGDC eliminated elevations greater than 1 meter above MHW to crudely remove such features while retaining the beach morphology.
- Bare-earth processing of the City of Virginia Beach LiDAR data left "shadows" in the data: low-relief (<1 m) features reminiscent of the original man-made structures, such as roads and airport runways. These features are retained in the DEM.
- Digital, measured bathymetric values from NOS surveys date back over 140 years. More recent data, such as USACE surveys in dredged shipping channels and the multibeam sonar surveys, differed from older, pre-dredging NOS data by as much as 10 meters. The older NOS survey data were excised where more recent bathymetric data exists.

3.3.2 Averaging of City of Virginia Beach LiDAR data

The massive number of points (170 million) in the City of Virginia Beach LiDAR data, as well as their small point-spacing (~2 meters), and the fact that the dataset contained returns from the surface of water bodies, necessitated averaging the data to a more manageable 1/3 arc-second spacing (~10 m). This was accomplished by generating a 'pre-surface' or grid using MB-System, an NSF-funded share-ware software application designed to manipulate multibeam sonar data for mapping purposes (http://www.ldeo.columbia.edu/res/pi/MB-System/). Data were gridded using 'mbgrid', which applied a tight spline algorithm to generate a "weighted-mean" grid without interpolation into empty cells. Output grid was in ESRI Arc ASCII format, which was evaluated in ArcMap. The resulting surface was compared with the original soundings to ensure grid accuracy, converted to a shape file, and then exported as an xyz file for use in the final gridding process (see Table 12).

3.3.3 Smoothing of bathymetric data

The NOS hydrographic surveys are generally sparse at the resolution of the 1/3 arc-second Virginia Beach DEM: in deep water, the NOS survey data have point spacing up to 4 kilometers apart. In order to reduce the effect of artifacts in the form of lines of "pimples" in the DEM due to this low resolution dataset, and to provide effective interpolation into the coastal zone, a 1 arc-second-spacing 'pre-surface' or grid was generated using GMT, an NSF-funded share-ware software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/).

The NOS hydrographic point data, in xyz format, were combined with the recent high-resolution NOS multibeam, NGDC and USACE channel data, and ENC soundings into a single file, along with points extracted every 10 meters from the combined coastline—to provide a "zero" buffer along the entire coastline. These point data were then smoothed using the GMT tool 'blockmedian' onto a 1 arc-second grid 0.05 degrees (~5%) larger than the Virginia Beach DEM gridding region. The GMT tool 'surface' then applied a tight spline tension to interpolate cells without data values. The GMT grid created by 'surface' was converted into an ESRI Arc ASCII grid file using the MB-System tool 'mbm_grd2arc'. Conversion of this Arc ASCII grid file into an Arc raster permitted clipping of the grid by the combined coastline (to eliminate data interpolation into land areas). The resulting surface was compared with the original soundings to ensure grid accuracy (e.g., Fig. 20), converted to a shape file, and then exported as an xyz file for use in the final gridding process (see Table 12).

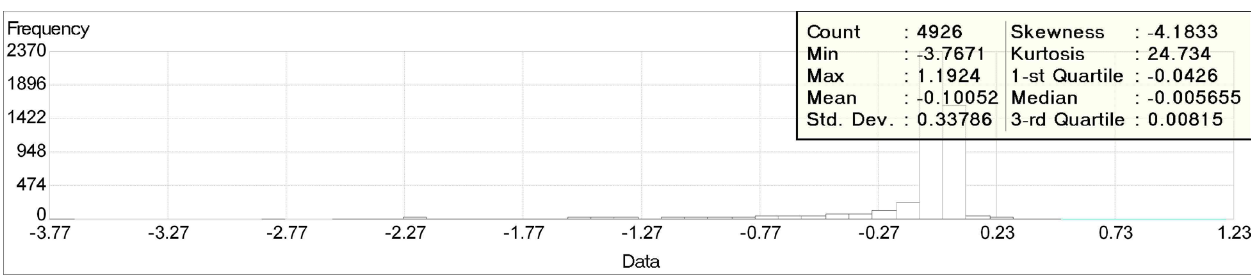

Figure 20. *Histogram of the difference between NOS hydrographic survey H10745 (relatively dense survey at mouth of Chesapeake Bay) and the 1 arc-second NOS pre-surfaced bathymetric grid. The greatest differences derive from the averaging of several closely spaced soundings from overlapping surveys, including recent NOS multibeam surveys.*

3.3.4 Gridding the data with MB-System

MB-System (http://www.ldeo.columbia.edu/res/pi/MB-System/) was used to create the 1/3 arc-second Virginia Beach DEM. MB-System is an NSF-funded share-ware software application specifically designed to manipulate submarine multibeam sonar data, though it can utilize a wide variety of data types, including generic xyz data. The MB-System tool 'mbgrid' applied a tight spline tension to the xyz data, and interpolated values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 12. Greatest weight was given to the high-resolution NOS multibeam and coastal LiDAR survey data. Least weight was given to the pre-surfaced 1 arc-second NOS bathymetric grid. Gridding was performed in quadrants, each with a

5% data overlap buffer. The resulting Arc ASCII grids were seamlessly merged in ArcCatalog to create the final 1/3 arc-second Virginia Beach DEM.

Table 12. Data hierarchy used to assign gridding weight in MB-System.

Dataset	*Relative Gridding Weight*
USACE bathymetry	100
JALBTCX coastal LiDAR bathymetry–topography	100
NGDC-digitized intracoastal waterway	100
NOS multibeam surveys	100
City of VB pre-surfaced LiDAR grid	10
USGS NED topographic DEM	1
NOS hydrographic surveys	1
NOAA nautical chart soundings	1
Pre-surfaced bathymetric grid	0.1

3.4 Quality Assessment of the DEMs

3.4.1. Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Virginia Beach DEM is dependent upon the datasets used to determine corresponding DEM cell values. Topographic features have an estimated accuracy of 10 to 15 meters: City of Virginia Beach and coastal LiDAR have an accuracy of between 1 and 3 meters, NED topography is accurate to within about 15 meters. Bathymetric features are resolved only to within a few tens of meters in deep-water areas, larger in the southeast corner of the DEM. Shallow, near-coastal regions, rivers, and dredged shipping channels have an accuracy approaching that of subaerial topographic features. Positional accuracy is limited by: the sparseness of deep-water soundings, and potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the Virginia Beach DEM is also highly dependent upon the source datasets contributing to DEM cell values. Topographic areas have an estimated vertical accuracy between 0.15 (for City of Virginia Beach and coastal LiDAR data) and up to 7 meters (for NED topography). Bathymetric areas have an estimated accuracy of between 0.1 meters and 5% of water depth (~2.5 meters in the southeast corner of the DEM). Those values were derived from the wide range of input data sounding measurements from the late 19^{th} century to recent, GPS-navigated sonar surveys. Gridding interpolation to determine values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations in deep water.

3.4.3 Slope maps and 3-D perspectives

ESRI ArcCatalog was used to generate a slope grid from the Virginia Beach DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (e.g., Fig. 21). The DEM was transformed to NAD83 UTM Zone 18 coordinates (horizontal units in meters) in ArcCatalog for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Three-dimensional viewing of the UTM-transformed DEM (e.g., Fig. 22) was accomplished using ESRI ArcScene. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 1 shows a color image of the Virginia Beach DEM in its final version.

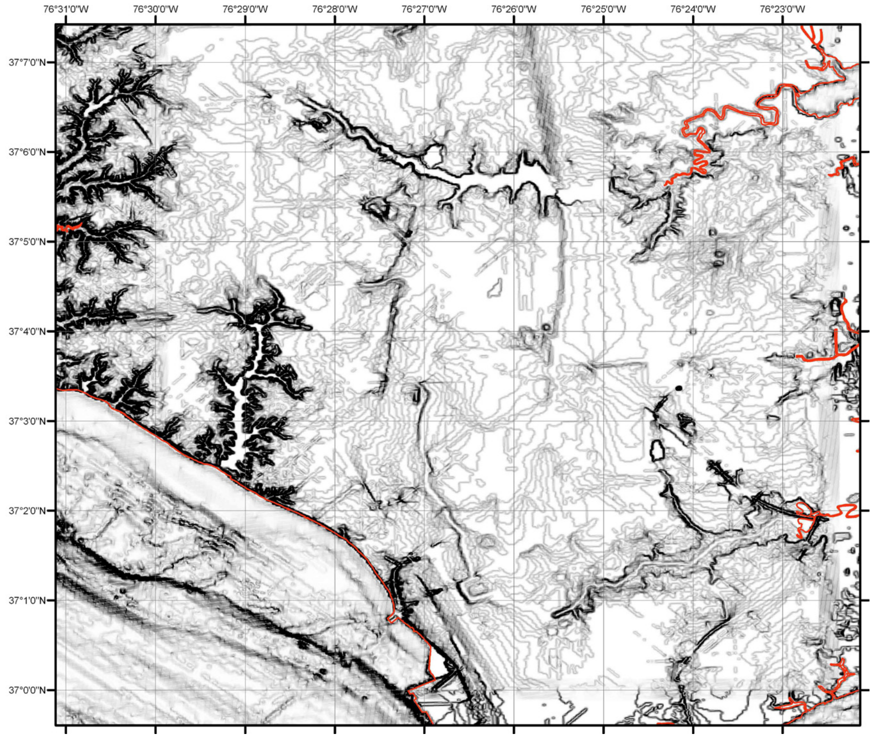

Figure 21. *Slope map of the Virginia Beach DEM in the vicinity of Newport News. Flat-lying slopes are white; dark shading denotes steep slopes; combined coastline in red. Note the "steps" in the DEM, resulting from the NED 1/3 arc-second DEM in this region. The steps are presumably the result of digitization of USGS topographic contours.*

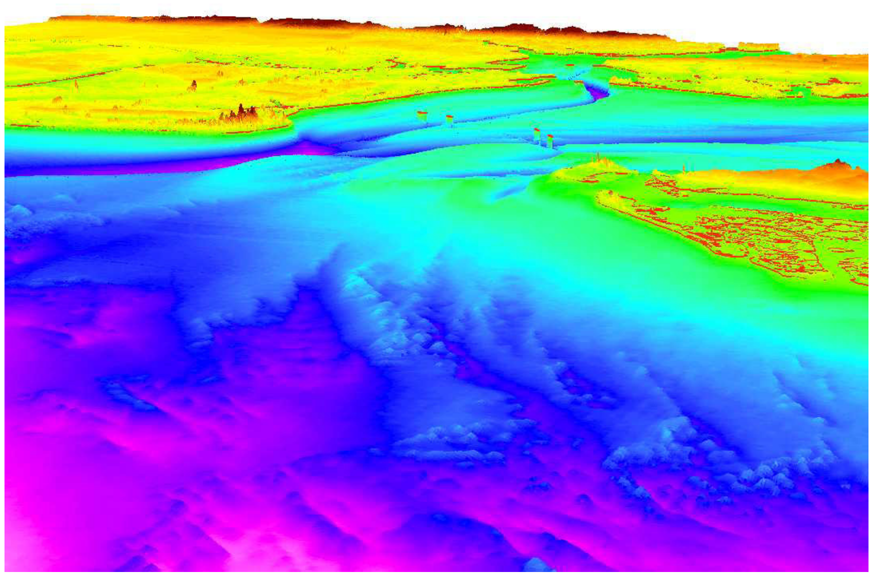

Figure 22. *Perspective view from the east of the Virginia Beach DEM. Combined coastline in red; vertical exaggeration–times 50.*

3.4.4 Comparison with source data files

To ensure grid accuracy, the Virginia Beach DEM was compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas (i.e., had the greatest weight and did not significantly overlap other data files with comparable weight). A histogram of the difference between a JALBTCX coastal bathymetric–topographic LiDAR survey file and the Virginia Beach DEM is shown in Figure 23. The largest differences occur in areas of highly variable relief, where the 5-meter point spacing of the LiDAR survey results in multiple elevation values contributing to one cell value in the DEM.

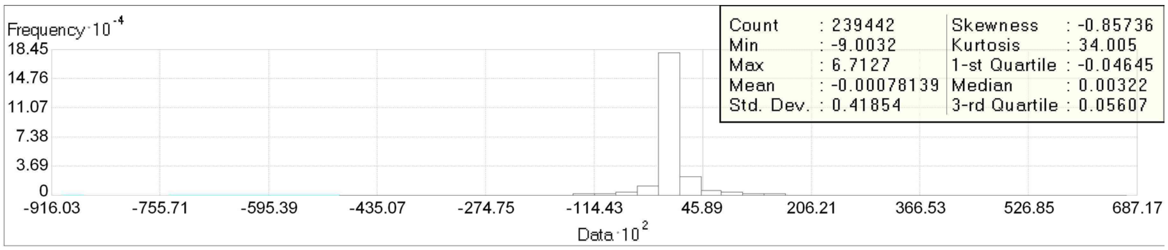

Figure 23. *Histogram of the difference between one JALBTCX coastal bathymetric–topographic LiDAR survey file (239,442 points) and the Virginia Beach DEM.*

3.4.5 Comparison with NOAA tidal stations

The National Geodetic Survey (NGS) data sheets for U.S. tidal stations (http://tidesandcurrents.noaa.gov/) document benchmark elevations, in meters above MHW, allowing for direct comparison with DEM values at those locations. Tidal station within the Virginia Beach study area were compared with the value taken at the same locale from the 1/3 arc-second Virginia Beach DEM (see Fig. 24 and Table 13 for station location). Each station has multiple benchmark stampings, all of which have the same geographic position, recorded to within 6 arc-seconds (~180 meters). This results in significant error in station position, which can cause significant difference with the DEM. Of particular note is the Sewells Point station, whose benchmark is located on a pier that is not represented in the DEM.

Table 13. Comparison of NOAA tidal benchmark elevation, in meters above MHW, with the Virginia Beach DEM.

Station number	*Station name*	*Year*	*Longitude*	*Latitude*	*Bench mark*	*DEM*	*Difference*
8639208	Virginia Beach	2006	-75.971389	36.835833	2.991	3.22	0.23
8639219	South End Lake Rudee	2006	-75.981389	36.819722	6.919	3.76	-3.14
8638863	Chesapeake Bay Bridge Tunnel	1975	-76.112956	36.966303	7.396	0.94	-6.44
8638610	Sewells Point	1985	-76.331111	36.957500	2.012	-11.14	-13.15
8632200	Kiptopeke	1958	-75.985278	37.168333	2.476	1.54	-0.92
8639214	Rudee Heights	1967	-75.975000	36.819722	10.385	1.94	-8.43
8639348	Money Point	1959	-76.293611	36.775833	4.154	0.91	-3.23
8638660	Portsmouth	1971	-76.295000	36.819722	2.167	0.21	-1.94
8638999	Cape Henry	1982	-76.006667	36.930000	3.869	-2.96	-6.82
8637624	Gloucester Point	1971	-76.501111	37.248611	7.972	6.50	-1.46
8631591	Oyster Harbor	1980	-75.925000	37.288333	2.347	0.55	-1.78
8631542	Sand Shoal Inlet, Cobb Island	1979	-75.778333	37.301667	-0.107	-0.34	-0.24

3.4.6 Comparison with NGS geodetic monuments

The elevations of NOAA NGS geodetic monuments were extracted from online monument datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), which give position in NAD83 (sub-mm accuracy) and elevation in NAVD88 (in meters). Elevations were shifted to MHW vertical datum (see Table 11) for comparison with the Virginia Beach DEM (see Fig. 24 for monument locations). Differences between the Virginia Beach DEM and the

NGS geodetic monument elevations range from -9.6 to 6.7 meters, with a negative value indicating that the DEM is less than the monument elevation (e.g., Fig. 25). Examination of the monuments with the largest differences from the DEM revealed that most are located along steep topographic features whose relief cannot be adequately captured at the 1/3 arc-second resolution of the Virginia Beach DEM.

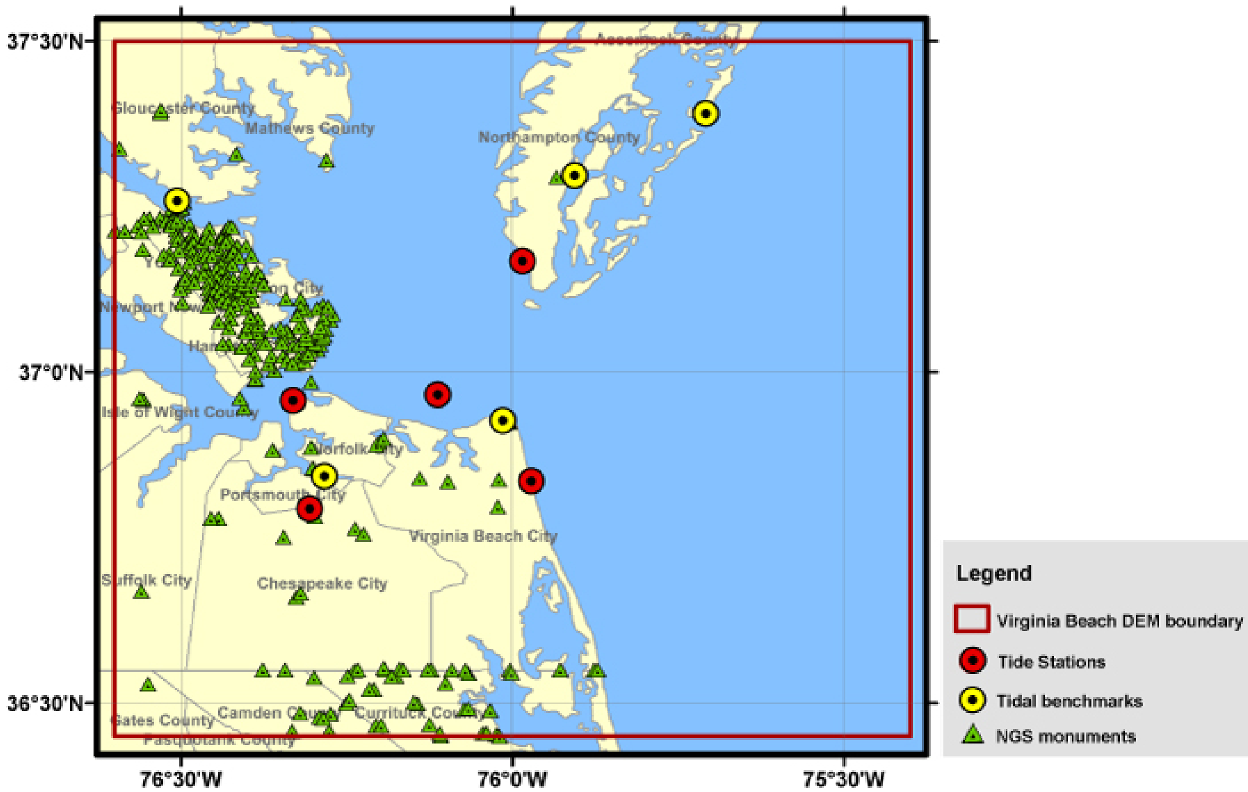

Figure 24. *Location of NGS monuments and NOAA tide stations in the vicinity of Virginia Beach. NOAA tide stations identified in red were used for shifting datasets to MHW. NGS monuments and tide stations with benchmarks (yellow and red) were used for evaluating the Virginia Beach DEM.*

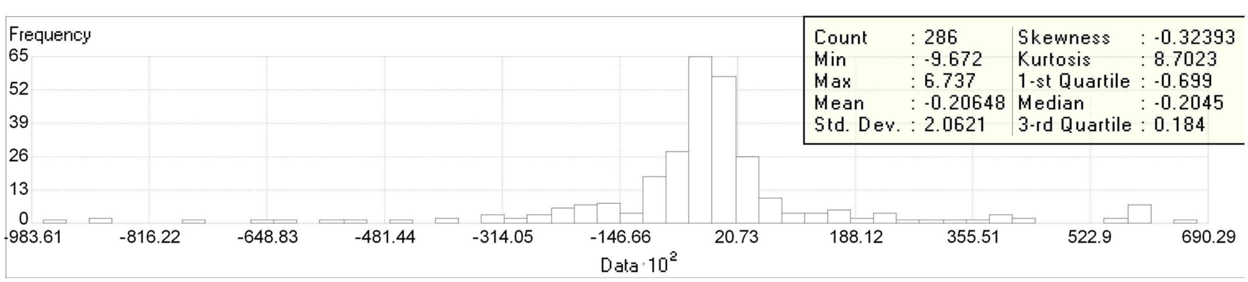

Figure 25. *Histogram of the differences between NGS geodetic monument elevations and the Virginia Beach DEM.*

4. Summary and Conclusions

A topographic–bathymetric digital elevation model of the Virginia Beach, Virginia area, with cell spacing of 1/3 arc-seconds, was developed for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research. The best available digital data from U.S. federal, state and local agencies, as well as academic institutions, were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI ArcGIS, FME, GMT, and MB-System software.

Recommendations to improve the DEM, based on NGDC's research and analysis, are listed below:

- Process coastal JALBTCX LiDAR data to bare earth.
- Obtain digital versions of several NOAA nautical charts (#12206, 12207, 12210, 12225) that have not yet been digitized.
- Improve topography in the regions currently covered by NED 1/3 and 1 arc-second data (especially in the Delmarva Peninsula).
- NGDC digitized the southern routes of the Atlantic Intracoastal Waterway, based upon minimum depths reported in Coast Pilot 4, as no digital data existed for these channels. The channels are frequently deeper along much of their lengths than their representation in the DEM, which could be remedied with further survey work.

5. Acknowledgments

The creation of these DEMs was funded by the NOAA, Pacific Marine Environmental Laboratory (PMEL). The authors thank Chris Chamberlin and Vasily Titov (PMEL), Allan Lambert (City of Hampton, Virginia GIS Dept), Fraser Pichard (City of Norfolk, Virginia GIS Dept), Susan O'Neill and Jules Robichaud (City of Virginia Beach, Virginia GIS Dept), Michael Kay (City of Virginia Beach, Virginia Coastal Engineering), Eric Legaspi (U.S. Army Corp of Engineers, Norfolk District Office), Jeff Lillycrop, (JALBTCX), and Donna Milligan (Virginia Institute of Marine Science).

6. References

Coast Pilot 4, 38th Edition, 2006. Atlantic Coast: Cape Henry to Key West, FL. U.S. Department of Commerce, NOAA, National Ocean Service.

Nautical Chart #12205, 30th Edition, 2005. FOLIO SMALL-CRAFT CHART Cape Henry to Pamlico Sound, Including Albemarle Sound; Rudee Heights. Scale various. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12206, 31st Edition, 2005. Intracoastal Waterway Norfolk to Albemarle Sound via North Landing River or Great Dismal Swamp Canal. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12207, 21st Edition, 2004. Cape Henry to Currituck Beach Light. Scale 1:50,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12208, 11th Edition, 2005. Approaches to Chesapeake Bay. Scale 1:50,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12210, 37th Edition, 2006. Chincoteague Inlet to Great Machipongo Inlet; Chincoteague Inlet. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12221, 78th Edition, 2006. Chesapeake Bay Entrance. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12222, 47th Edition, 2005. Chesapeake Bay Cape Charles to Norfolk Harbor. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12224, 5th Edition, 2006. Chesapeake Bay Cape Charles to Wolf Trap. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12225, 55th Edition, 2004. Chesapeake Bay Wolf Trap to Smith Point. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12226, 16th Edition, 2001. Chesapeake Bay Wolf Trap to Pungoteague Creek. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12235, 4th Edition, 2006. Rappahannock River Entrance Piankatank and Great Wicomico Rivers. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12238, 39th Edition, 2006. Chesapeake Bay Mobjack Bay and York River Entrance. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12241, 21st Edition, 2002. York River Yorktown and Vicinity. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12245, 65th Edition, 2005. Hampton Roads. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12248, 41st Edition, 2005. James River Newport News to Jamestown Island; Back River and College Creek. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12253, 44th Edition, 2004. Norfolk Harbor and Elizabeth River. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12254, 46th Edition, 2006. Chesapeake Bay Cape Henry to Thimble Shoal Light. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12255, 16th Edition, 2005. Little Creek Naval Amphibious Base. Scale 1:5,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

U.S. Geological Survey Quad #O37075A8, 1996, Fishermans Island, Scale 1:24,000. U.S. Department of Interior, U.S. Geological Survey, Earth Sciences Information Center. Data downloaded from University of Virginia Library Geospatial and Statistical Center. (http://fisher.lib.virginia.edu/collections/gis/data/va_drg/)

U.S. Geological Survey Quad #O36076G2, 1996, Kempsville, Scale 1:24,000. U.S. Department of Interior, U.S. Geological Survey, Earth Sciences Information Center. Data downloaded from University of Virginia Library Geospatial and Statistical Center. (http://fisher.lib.virginia.edu/collections/gis/data/va_drg/)

U.S. Geological Survey Quad #O36076G3, 1996, Norfolk South, Scale 1:24,000. U.S. Department of Interior, U.S. Geological Survey, Earth Sciences Information Center. Data downloaded from University of Virginia Library Geospatial and Statistical Center. (http://fisher.lib.virginia.edu/collections/gis/data/va_drg/)

U.S. Geological Survey Quad #O36076H3, 1996, Norfolk North, Scale 1:24,000. U.S. Department of Interior, U.S. Geological Survey, Earth Sciences Information Center. Data downloaded from University of Virginia Library Geospatial and Statistical Center. (http://fisher.lib.virginia.edu/collections/gis/data/va_drg/)

U.S. Geological Survey Quad #O37075C8, 1996, Cheriton, Scale 1:24,000. U.S. Department of Interior, U.S. Geological Survey, Earth Sciences Information Center. Data downloaded from University of Virginia Library Geospatial and Statistical Center. (http://fisher.lib.virginia.edu/collections/gis/data/va_drg/)

U.S. Geological Survey Quad #O37075D8, 1996, Franktown, Scale 1:24,000. U.S. Department of Interior, U.S. Geological Survey, Earth Sciences Information Center. Data downloaded from University of Virginia Library Geospatial and Statistical Center. (http://fisher.lib.virginia.edu/collections/gis/data/va_drg/)

7. Data Processing Software

ArcGIS v. 9.1, developed and licensed by ESRI, Redlands, California, http://www.esri.com/

Electronic Navigational Chart Data Handler for ArcView, developed by NOAA Coastal Services Center, http://www.csc.noaa.gov/products/enc/

FME 2006 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/

GEODAS v. 5 – Geophysical Data System, shareware developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas/

GMT v. 4.1.1 – Generic Mapping Tools, shareware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/

MB-System v. 5.0.9, shareware developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System/