NOAA Technical Memorandum NESDIS NGDC-30

DIGITAL ELEVATION MODEL OF PORTLAND, MAINE: PROCEDURES, DATA SOURCES AND ANALYSIS

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Also available from the National Technical Information Service (NTIS)
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1. Introduction

In December 2008, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed an integrated topographic-bathymetric digital elevation model (DEM) of Portland, Maine (Fig. 1) for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/). 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 designed to represent modern morphology. It will be used for tsunami forecasting as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a description of the data sources and methodology used in developing the Portland DEM.

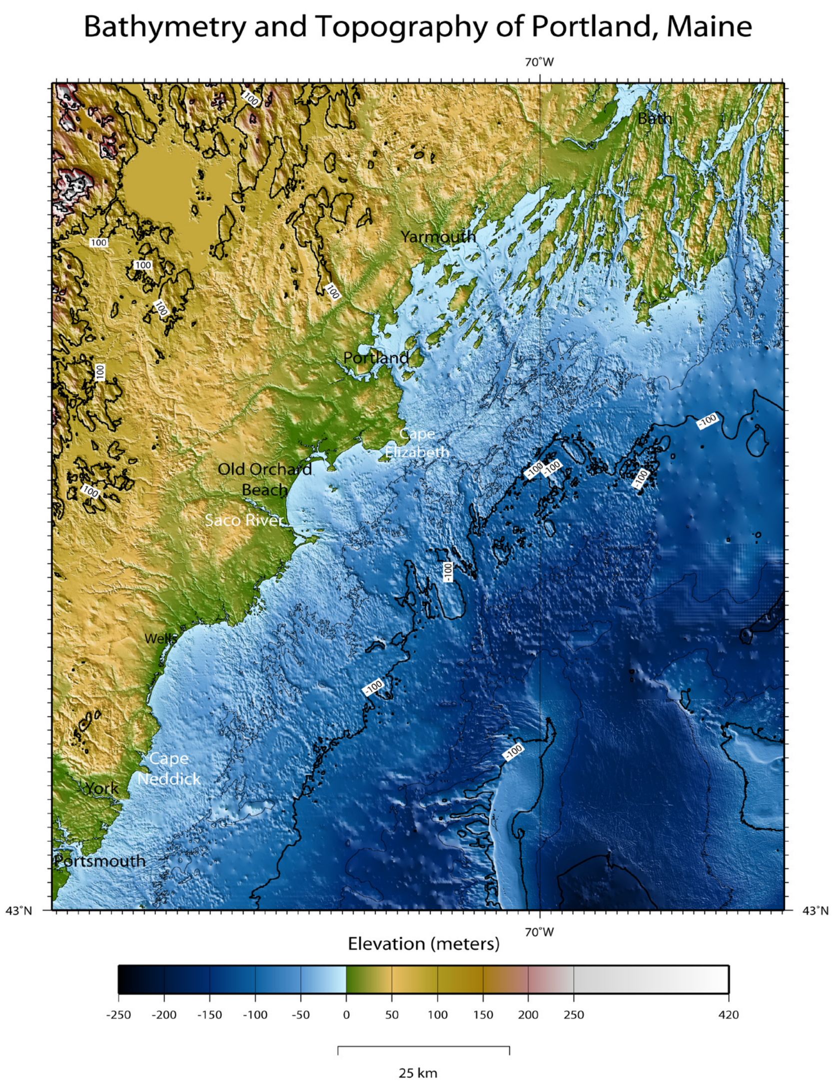

Figure 1. *Shaded-relief image of the Portland DEM. Contour intervals are 50 m for bathymetry, and 100 m for topography.*

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1. The Portland 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 Portland, Maine (43°39′54″N 70°16′9″W) 1/3 arc-second of latitude is equivalent to 10.288 meters; 1/3 arc-second of longitude equals 7.47 meters.

2. Study Area

The Portland DEM covers the coastal region surrounding the town of Portland, Maine. Included within the DEM boundary are the coastal communities of Portsmouth, York, Old Orchard Beach, Yarmouth, and Bath. Portland is located on Casco Bay about 50 miles north of the border with New Hampshire. As Maine's primary shipping and manufacturing center, petroleum accounts for much of the traffic through the port. In addition, the city produces paper, processed foods, leather, and machinery.

Maine is famous for its "rockbound coast" buttressed by rugged, unchanging cliffs of stone. Rocky points such as Portland Head, photographed a century ago, show little change after a hundred years of storms (Fig. 2). Maine's bedrock is very strong and consolidated and resists erosion from waves and weather. Other parts of Maine, however, have a "soft coast" of loose or unconsolidated materials that are subject to erosion. Although a slow, steady rise in sea-level is the underlying reason for modification of the coast, the noticeable erosion occurs quickly during individual storms or landslide events.

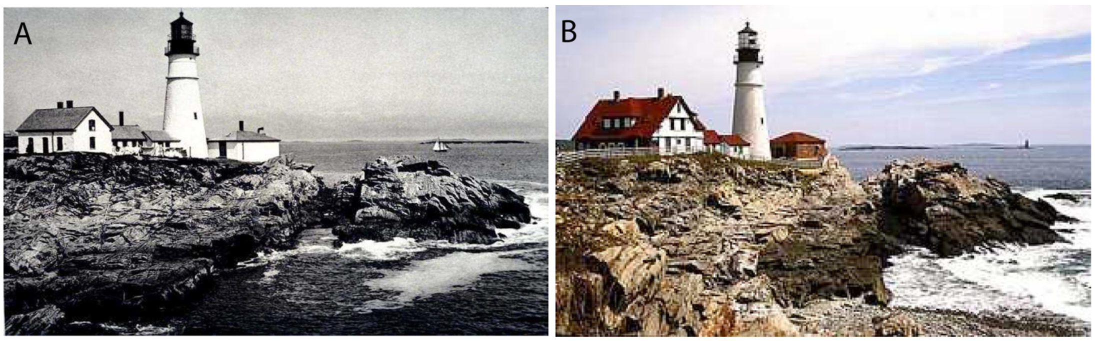

Figure 2. *Portland Head Light. A) Photographed around 1900. B) Photographed in 1998.*
[Photo credit: State of Maine, Department of Conservation; http://www.state.me.us/doc/nrimc/mgs/explore/marine/facts/jul99-1.htm]

3. Methodology

The Portland DEM was constructed to meet PMEL specifications (Table 1), based on input requirements for the development of reference inundation models (RIMs) and standby inundation models (SIMs) (*V. Titov, pers. comm.*) in support of NOAA's Tsunami Warning Centers use of SIFT to provide real-time tsunami forecasts in an operational environment. The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North America Datum of 1983 (NAD 83) and mean high water (MHW), for modeling of maximum flooding, respectively[2]. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1: PMEL specifications for the Portland DEM.

Grid Area	Portland, Maine
Coverage Area	70.74º to 69.63º W; 43.00º to 43.99º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	MHW
Vertical Units	Meters
Cell Size	1/3 arc-second
Grid Format	ESRI Arc ASCII grid

2. The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (WGS 84) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEM. Most GIS applications treat the two datums as identical, so do not actually transform data between them, and the error introduced by not converting between the datums is insignificant for our purposes. NAD 83 is restricted to North America, while WGS 84 is a global datum. As tsunamis may originate most anywhere around the world, tsunami modelers require a global datum, such as WGS 84 geographic, for their DEMs so that they can model the wave's passage across ocean basins. This DEM is identified as having a WGS 84 geographic horizontal datum even though the underlying elevation data were typically transformed to NAD 83 geographic. At the scale of the DEM, WGS 84 and NAD 83 geographic are identical and may be used interchangeably.

3.1 Data Sources and Processing

Shoreline, bathymetric, topographic, and topographic-bathymetric digital datasets (Fig. 3) were obtained from U.S. federal and state agencies including: NOAA's Office of Coast Survey (OCS), Coastal Services Center (CSC) and NGDC; the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX); the University of New Hampshire (UNH); the U.S. Geological Survey (USGS); the U.S. Army Corps of Engineers (USACE); and the Maine Office of Geographic and Environmental Information (MEGIS). Safe Software's *FME* data translation tool package was used to shift datasets to NAD 83 geographic horizontal datum and to convert them into ESRI *ArcGIS* shapefiles[3]. The shapefiles were then displayed with *ArcGIS* to assess data quality and manually edit datasets. Vertical datum transformations to MHW were accomplished using *FME*, based upon data from the NOAA tide station in Portland. Applied Imagery's *Quick Terrain Modeler* software was used to evaluate processing and gridding techniques.

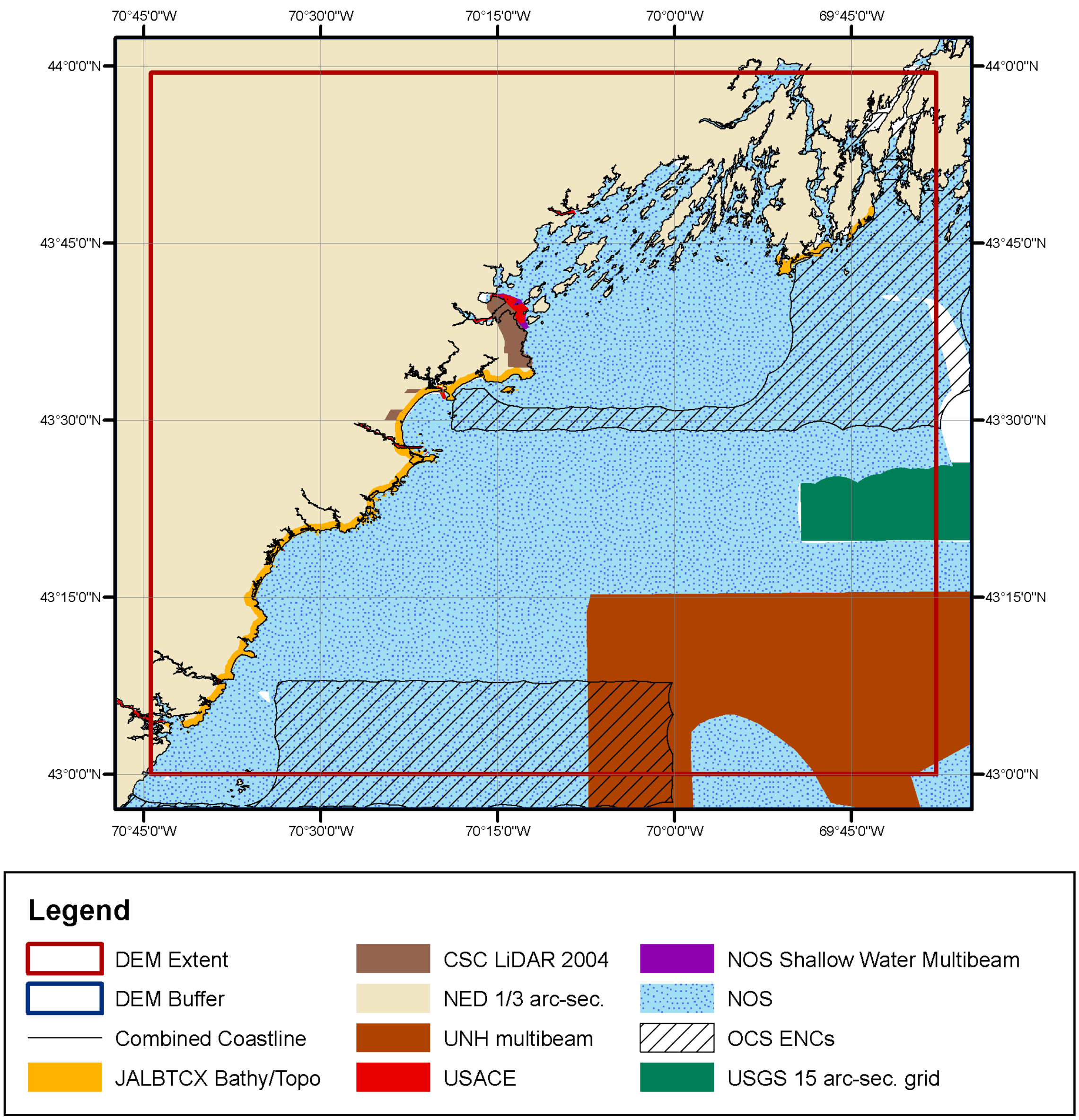

Figure 3. *Source and coverage of datasets used in compiling the Portland DEM.*

3. *FME* uses the North American Datum Conversion Utility (NADCON; http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.html) developed by NOAA's National Geodetic Survey (NGS) to convert data from NAD 27 to NAD 83. NADCON is the U.S. Federal Standard for NAD 27 to NAD 83 datum transformations.

3.1.1 Shoreline

Coastline datasets of the Portland region (Table 2) were obtained from OCS and MEGIS. The two datasets were used to develop a "combined coastline" of the Portland region.

Table 2: Shoreline datasets used in developing the Portland DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NOAA ENCs	2007	Digital Nautical Charts	1:40,000	WGS 84 geographic	MHW	http://nauticalcharts.noaa.gov/mcd/enc/
MEGIS	2004	Digitized 1:24,000 USGS DLG	1:24,000	NAD 83 Maine State Plane, UTM zone 19N	MHW	http://megis.maine.gov/catalog/

1) NOAA nautical charts

Ten NOAA nautical charts were available for the Portland area (Table 3), and were downloaded from NOAA's OCS web site (http://nauticalcharts.noaa.gov/mcd/enc/). All charts are available as georeferenced Raster Navigational Charts (RNCs; digital images of the charts), which were used to assess the quality of bathymetric datasets. The charts were also available as Electronic Navigational Charts (ENCs)[4] that represent chart features as individual digital objects. The ENCs are in S-57 format and include coastline data files referenced to MHW. The ENC digital coastlines were used as a secondary dataset to provide complete coverage of the DEM area (Fig. 4). This dataset contained many piers and other manmade structures that had to be removed when building the combined coastline.

Table 3: Nautical charts available in the Portland region.

Chart #	*Chart name*	*Scale*	*Format*	*ENC #*
13278	Portsmouth to Cape Ann	1:80,000	RNC, ENC	US4MA04M
13283	Portsmouth Harbor - Cape Neddick Harbor to Isles of Shoals	1:20,000; insets 1:10,000	RNC, ENC	US5NH02M
13285	Portsmouth to Dover and Exeter	1:20,000	RNC, ENC	US5NH01M
13286	Cape Elizabeth to Portsmouth	1:80,000; insets 1:10,000	RNC, ENC	US4ME01M
13288	Monhegan Island to Cape Elizabeth	1:80,000	RNC, ENC	US4ME03M
13290	Casco Bay B	1:40,000	RNC, ENC	US5ME13M
13292	Portland Harbor and Vicinity A	1:20,000	RNC, ENC	US5ME10M
13295	Kennebec and Sheepscot River Entrances	1:15,000	RNC, ENC	US5ME15M
13296	Boothbay Harbor to Bath Including Kennebec River	1:15,000	RNC, ENC	US5ME16M
13298	Kennebec River-Bath to Courthouse Point	1:15,000	RNC, ENC	US5ME18M

2) Maine GIS coastline

MEGIS modified the USGS 1:24,000 hydrography digital line graph (DLG) quadrangle files to produce the Maine coastline. MEGIS reformatted the DLG files into Arc/INFO coverages and projected them into the Maine State Plane Coordinate system, NAD 83. The coastline was then extracted from the files and edited. Polygon topology was also created for each quadrangle. The coverages were then projected into NAD 83 meters. This coastline contains many manmade features; NGDC removed piers and docks from the dataset.

4. The Office of Coast Survey (OCS) produces NOAA Electronic Navigational Charts (NOAA ENC®) to support the marine transportation infrastructure and coastal management. NOAA ENC®s are in the International Hydrographic Office (IHO) S-57 international exchange format, comply with the IHO ENC Product Specification and are provided with incremental updates, which supply Notice to Mariners corrections and other critical changes. NOAA ENC®s are available for free download on the OCS web site. [Extracted from NOAA OCS web site: http://nauticalcharts.noaa.gov/mcd/enc/]

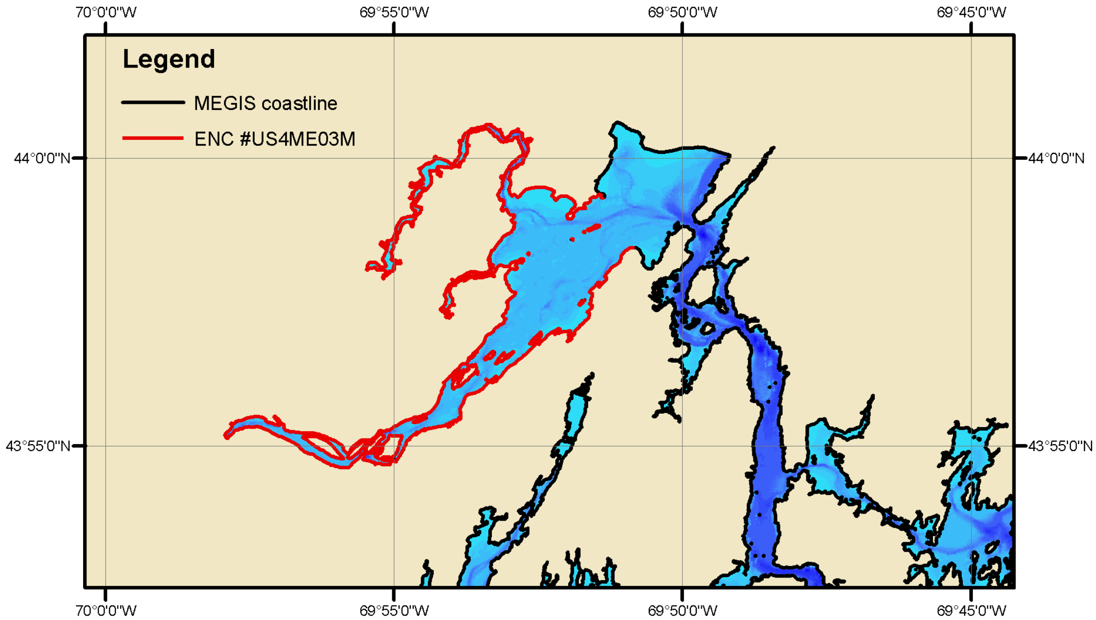

Figure 4. *MEGIS coastline gap.* The *ENC coastline (red) was used to connect broken segments in the MEGIS coastline (black).*

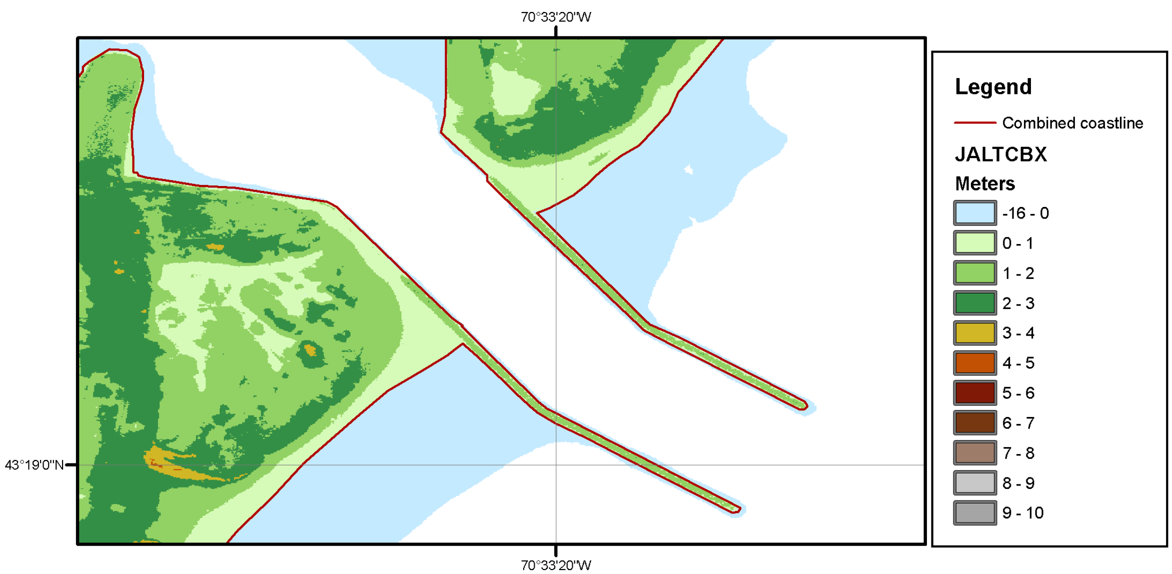

Figure 5. *Jetties at the entrance to Wells Harbor. The 'combined coastline' built by NGDC was adjusted to fit 5 meter resolution JALTCBX topographic-bathymetric coastal lidar data.*

The ENC and MEGIS coastlines were integrated into a combined coastline for the Portland DEM (Fig. 4), which was then adjusted to align with the large-scale RNCs, high-resolution coastal lidar data (e.g., Fig. 5), and satellite imagery extracted from *Google Earth*. Breakwaters, causeways, and large bridge columns were manually digitized by NGDC for representation in the combined coastline and the Portland DEM (Fig. 5). The combined coastline was converted to xyz data with 10 m point spacing using NGDC's *GEODAS* software for use in building a pre-surfaced bathymetric grid (see Sec. 3.3.2).

3.1.2 *Bathymetry*

Bathymetric datasets used in the compilation of the Portland DEM included 72 NOS hydrographic surveys, a 15 arc-second USGS grid, extracted NOAA ENC sounding data, USACE hydrographic harbor surveys, UNH multibeam swath sonar surveys, and two NOS shallow-water multibeam swath sonar surveys (Table 4; Fig. 3). Datasets were originally referenced to mean low water (MLW), mean lower low water (MLLW) or mean sea level (MSL).

Table 4: Bathymetric datasets used in compiling the Portland DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1861 to 2003	NOS hydrographic survey soundings	Ranges from 10 meters to 1 kilometer (varies with scale of survey, depth, traffic, and probability of obstructions)	NAD 83 geographic	MLW or MLLW (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
USGS	2001	Compiled Bathymetry Grid	~450 meters	NAD 83 geographic	MSL (meters)	http://pubs.usgs.gov/of/1998/of98-801/bathy/data.htm#Grids%20and%20Contours
NOAA ENC	2006 to 2007	Extracted soundings	1:10,000 to 1:80,000	WGS 84 geographic	MLLW (meters)	http://nauticalcharts.noaa.gov/mcd/enc/
USACE	1998 to 2007	Hydrographic surveys	Scattered soundings and channel profiles	NAD 27 Maine State Plane (feet)	NGVD29 (feet)	http://www.nae.usace.army.mil/navigation/navigation2.asp?mystate=ma
UNH	2007	Multibeam swath sonar	5 meters	WGS 84 UTM zone 19 (meters)	MLLW (meters)	http://www.gulfofmaine.org/gommi/coveragemap.php
NGDC	2000 to 2005	NOS shallow-water multibeam sonar	10 meters	NAD 83 UTM zone 19N (meters)	MLLW (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html

1) National Ocean Service hydrographic survey data

A total of 72 NOS hydrographic surveys conducted between 1861 and 2003 were available in digital form for use in developing the Portland DEM (Table 5; Fig. 6). The hydrographic survey data were originally vertically referenced to MLW or MLLW and horizontally referenced to the NAD 83 geographic datum. Two of the older surveys (H03033 and H04808) were not used in building the Portland DEM, as they have been superseded by more recent surveys.

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 NOS Hydrographic Survey Database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) referenced to NAD 83. The surveys were subsequently clipped to a polygon 0.05 degrees (~5%) larger than the Portland DEM area to support data interpolation along grid edges.

After converting all NOS survey data to MHW using *FME* (see Sec. 3.2.1), the data were displayed in ESRI *ArcMap* and reviewed for digitizing errors against scanned original survey smooth sheets and edited as necessary. The surveys were also compared to the topographic, bathymetric, and topographic-bathymetric datasets, the combined coastline, and NOAA RNCs. The surveys were clipped to remove soundings that overlap more recent NOS and USACE bathymetric surveys.

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

NOS Survey ID	*Year Of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum of survey*
H06959	1944	5,000	MLW	NAD 27
H06960	1944	5,000	MLW	NAD 27
H06961	1944	5,000	MLW	NAD 27
H06661	1941	20,000	MLW	NAD 27
H06857	1943	10,000	MLW	NAD 27
H08090	1953/55	5,000	MLW	NAD 27
H08091	1953	10,000	MLW	NAD 27
H08092	1954	10,000	MLW	NAD 27
H08160	1954/55	10,000	MLW	NAD 27
H08161	1954/55	10,000	MLW	NAD 27
H08162	1954	5,000	MLW	NAD 27
H08254	1955	10,000	MLW	NAD 27
H08256	1955	10,000	MLW	NAD 27
H08257	1955	5,000	MLW	NAD 27
H08258	1955	5,000	MLW	NAD 27
H10830	1998	10,000	MLLW	NAD 83
H07795	1950	5,000	MLW	NAD 27
H06808	1942	10,000	MLW	NAD 27
H06809	1942	10,000	MLW	NAD 27
H06810	1942/43	20,000	MLW	NAD 27
H06837	1943	10,000	MLW	NAD 27
H06839	1943	10,000	MLW	NAD 27
H06840	1943	10,000	MLW	NAD 27
H06841	1943	10,000	MLW	NAD 27
H06842	1943	10,000	MLW	NAD 27
H06843	1943	10,000	MLW	NAD 27
H06844	1943	10,000	MLW	NAD 27
H06858	1943	20,000	MLW	NAD 27
H07127	1947	40,000	MLW	NAD 27
H07140	1947	40,000	MLLW	NAD 27
H07147	1946	40,000	MLW	NAD 27
H07148	1946	40,000	MLW	NAD 27
H07149	1946	20,000	MLW	NAD 27
H06564	1940	120,000	MLW	NAD 27
H06672	1941	5,000	MLW	NAD 27
H06673	1941	5,000	MLW	NAD 27
H06675	1941	10,000	MLW	NAD 27
H06677	1941	10,000	MLW	NAD 27
H06716	1941	20,000	MLW	NAD 27
H06708	1941	10,000	MLW	NAD 27
H06728	1941	10,000	MLW	NAD 27
H06730	1941	20,000	MLW	NAD 27
H06731	1941	10,000	MLW	NAD 27
H06732	1941	10,000	MLW	NAD 27
H08163	1953/54	5,000	MLW	NAD 27
F00445	1998	10,000	MLLW	NAD 83
F00460	2000	10,000	MLLW	NAD 83
H10763	1997	10,000	MLLW	NAD 83

NOS Survey ID	*Year Of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum of survey*
H10771	1997	10,000	MLLW	NAD 83
H10831	1998	10,000	MLLW	NAD 83
H10963	1999/2000	10,000	MLLW	NAD 83
H00741A	1859/1902	10,000	MLW	NAD1913
H00741B	1874/1902	10,000	MLW	NAD1913
H00790	1861	10,000	MLW	United States Standard Datum 1901
H00933	1867	40,000	MLW	NAD 27
H01064	1869/1903	10,000	MLW	Unknown Horizontal Datum
H01836	1888	40,000	MLW	Unknown Horizontal Datum
H03032	1909	20,000	MLW	United States Standard Datum 1901
H04303	1923	20,000	MLW	NAD1913
H04805	1927/28	40,000	MLW	NAD1913
H04808	1928	10,000	MLW	NAD1913
H06800	1942	5,000	MLW	NAD 27
H06801	1942	5,000	MLW	NAD 27
H06802	1942	5,000	MLW	NAD 27
H06803	1942	5,000	MLW	NAD 27
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H06805	1942	10,000	MLW	NAD 27
H06806	1942	10,000	MLW	NAD 27
H06807	1942	10,000	MLW	NAD 27
H08255	1955/58	10,000	MLW	NAD 27
H10646	2000/03	10,000	MLLW	NAD 83

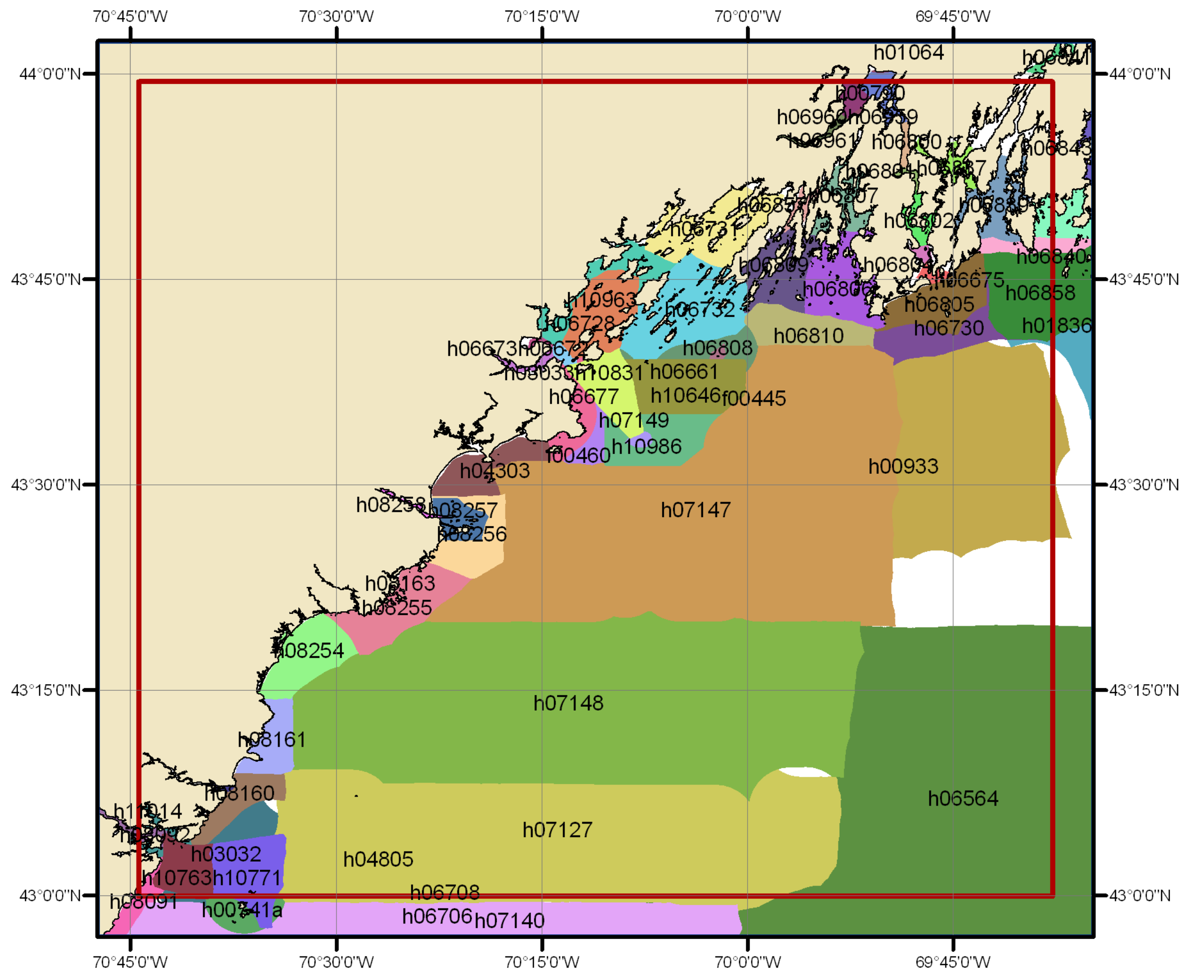

Figure 6. Digital NOS hydrographic survey coverage in the Portland DEM. Some older surveys were not used as they have been superseded by more recent surveys. DEM boundary in red; combined coastline in brown.

2) U.S. Geological Survey Gulf of Maine grid

A 15 arc-second grid of the Gulf of Maine, built by the USGS in 2001, was used in the development of the Portland DEM. The grid was originally vertically referenced to MLLW and horizontally referenced to the NAD 83 geographic datum. Due to its coarse resolution the data were only used in areas where no other bathymetric data were available (Fig. 7).

Table 6: USGS 15 arc-second grid used in compiling the Portland DEM.

Dataset	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Resolution*
USGS Gulf of Maine Gridding Project	2001	MLLW	NAD 83 geographic	~450 meters

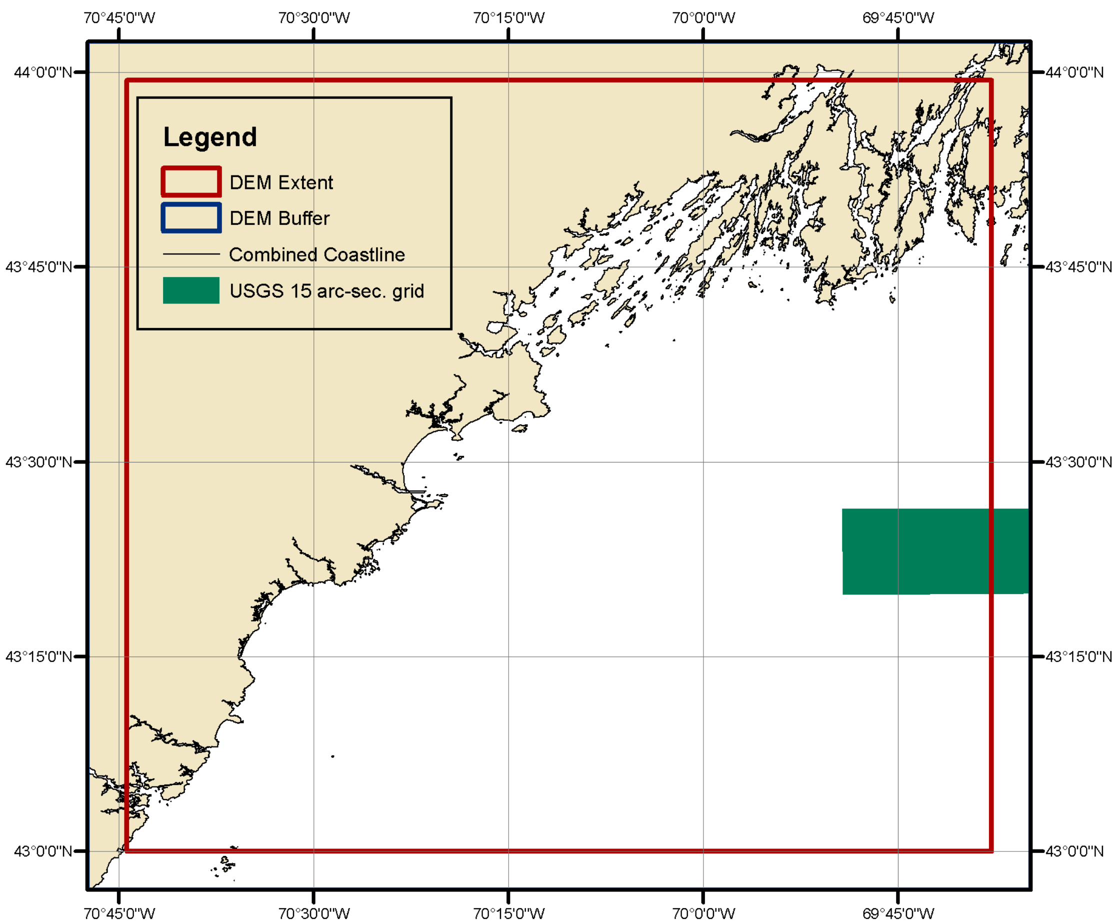

Figure 7. *Coverage of the part of the USGS 15 arc-second grid used in developing the Portland DEM. DEM boundary in red; combined coastline in black.*

3) NOAA Electronic Navigational Chart soundings

NOAA ENC sounding data were extracted from charts #13278, 13288, and 13296. The ENCs provided sounding data where bathymetric coverage was very sparse or not available. Sounding data from these charts were extracted using *FME*.

ENC Chart #13278 covers the area from Portsmouth to Cape Ann. Soundings range from ~250 meters to ~1 kilometer apart, and depths range from 3.48 meters to 203.68 meters. The scale for this dataset is 1:80,000.

ENC Chart #13288 covers the area from Monhegan Island to Cape Elizabeth. Soundings range from ~300 meters to 2.5 kilometers apart, and depths range from 3.18 meters to 169.28 meters. The scale for this dataset is 1:80,000.

ENC Chart #13296 covers the area from Boothbay Harbor to Bath, including the Kennebec River. Soundings range from ~35 meters to ~120 meters, and depths range from 2.58 meters to 52.48 meters. The scale for this dataset is 1:15,000.

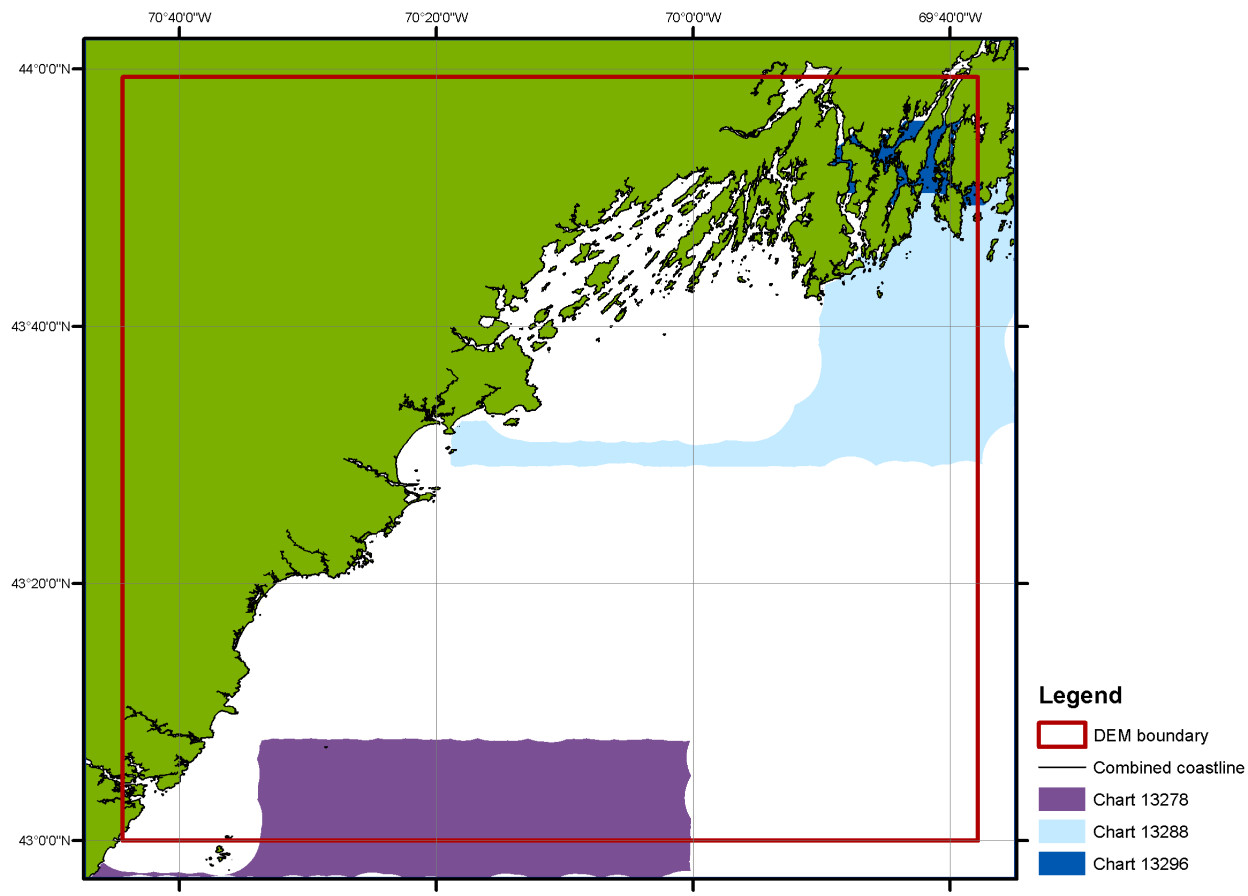

Figure 8. *Coverage of ENCs in the Portland region. DEM boundary in red; combined coastline in black.*

4) U.S. Army Corps of Engineers hydrographic surveys of harbor channels

USACE conducted ten surveys at the entrance of harbors in the Portland region (Table 7; Fig. 9). All data were originally in Maine State Plane coordinates NAD 27 horizontal datum. Depths were in feet relative to NGVD29.

Table 7: USACE hydrographic sonar surveys used in compiling the Portland DEM.

Location	*Year*	*Original Vertical Datum (feet)*	*Original Horizontal Datum (feet)*	*Spatial Resolution*
Portland	2004	NGVD29	NAD 27 Maine State Plane	Profiles 130-1700 meters long, spaced 15-20 meters apart, with ~2 meter point spacing
Kennebunk River	2004	NGVD29	NAD 27 Maine State Plane	Profiles 10-100 meters long, spaced 10-15 meters apart, with <1 meter point spacing
Royal River	2007	NGVD29	NAD 27 Maine State Plane	Profiles 75-100 meters long, spaced 10-20 meters apart, with <1 meter point spacing
Saco River	1999	NGVD29	NAD 27 Maine State Plane	Profiles 350-2000 meters long, spaced 8–12 meters apart, with <1 meter point spacing
Scarborough River	2004	NGVD29	NAD 27 Maine State Plane	Profiles 100 to 150 meters long, spaced 8–10 meters apart, with <1 meter point spacing
Biddeford	1998	NGVD29	NAD 27 Maine State Plane	Profiles 600 to 700 meters long, spaced 5-10 meters apart, with ~1 meter point spacing
Josias River	2007	NGVD29	NAD 27 Maine State Plane	Profiles 100 to 200 meters long, spaced 2-10 meters apart, with ~2 meter point spacing
Portsmouth	2005	NGVD29	NAD 27 Maine State Plane	Profiles 200-300 meters long, spaced ~30 meters apart, with ~2 meter point spacing
Wells Harbor	2007	NGVD29	NAD 27 Maine State Plane	Profiles 200-350 meters long, spaced ~8 meters apart, with ~2 meter point spacing
York Harbor	2005	NGVD29	NAD 27 Maine State Plane	Profiles 100-600 meters long, spaced 10-20 meters apart, with ~5 meter point spacing

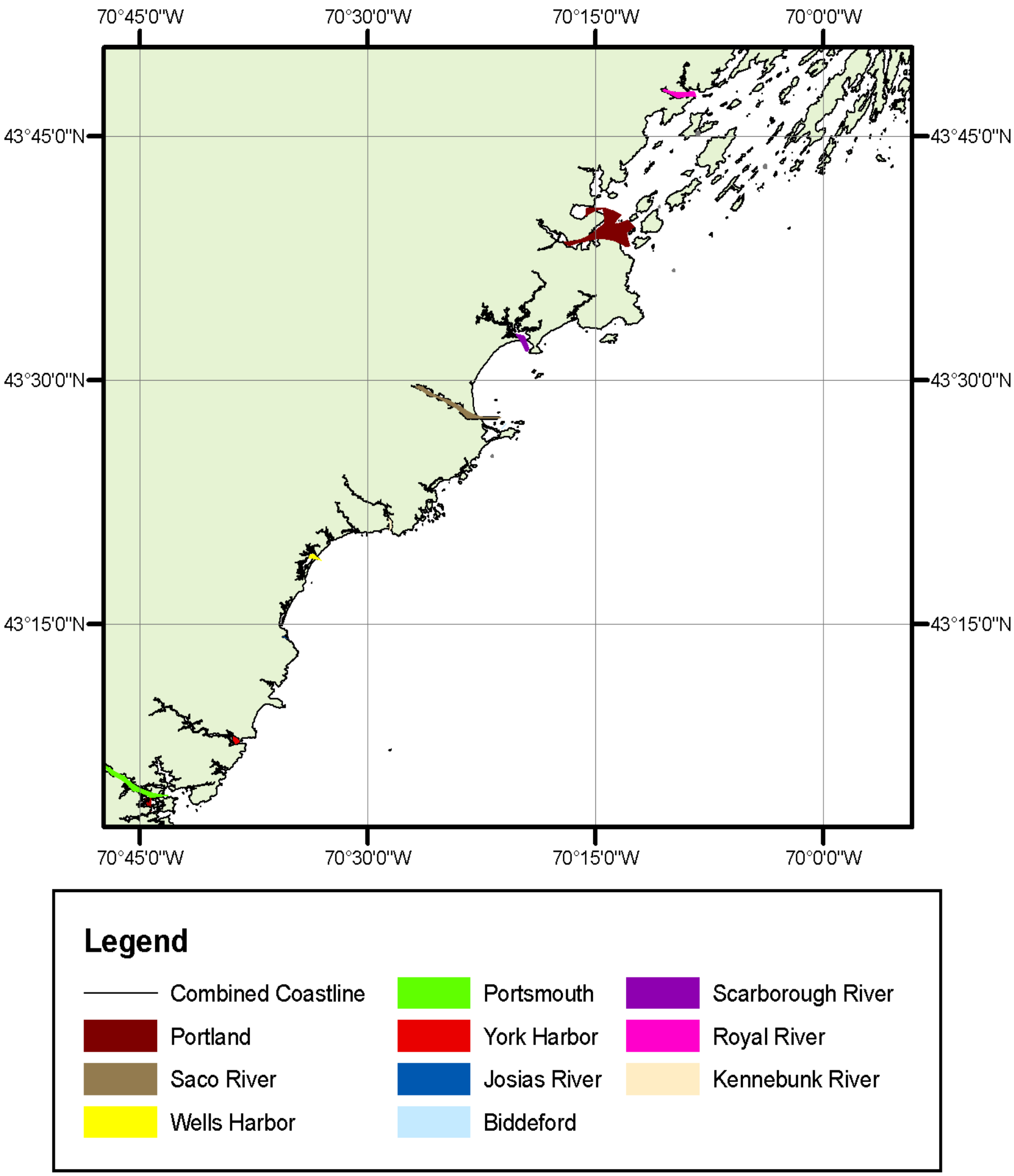

Figure 9. Coverage of USACE hydrographic surveys in the Portland region. Combined coastline in black.

5) University of New Hampshire multibeam swath sonar survey

UNH with the Center of Coastal and Ocean Mapping (CCOM) conducted a high-resolution multibeam swath sonar survey in the Three Dory Ledge region in the southeast portion of the Portland DEM (Fig. 11). Data were provided to NGDC by Larry Mayer of CCOM. Original data were in ASCII xyz gridded format in WGS 84, UTM zone 19 at 5-meter resolution and referenced to MLLW. This dataset provided dense bathymetric coverage in deeper water in the southeast portion of the Portland DEM.

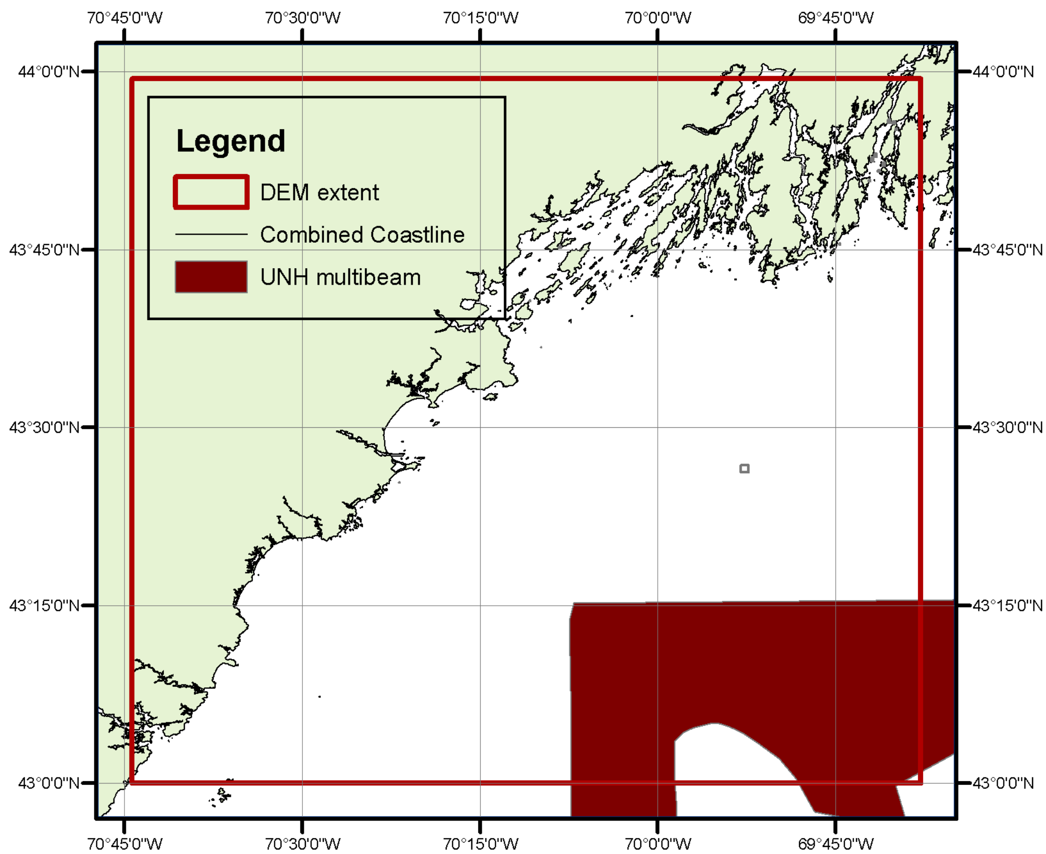

Figure 10. *Coverage of the UNH multibeam swath sonar survey. Combined coastline in black.*

6) National Ocean Service shallow-water multibeam survey

NOAA's NOS conducted two recent shallow-water multibeam swath sonar surveys at the entrances to Portland Harbor and Back Bay (Fig. 11). The surveys were downloaded from NGDC's NOS Hydrographic Survey Database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) in ASCII xyz gridded format in NAD 83, UTM zone 19 at 10-meter resolution and referenced to MLLW. This dataset provided dense bathymetric coverage in Portland Harbor and the entrance to Back Bay.

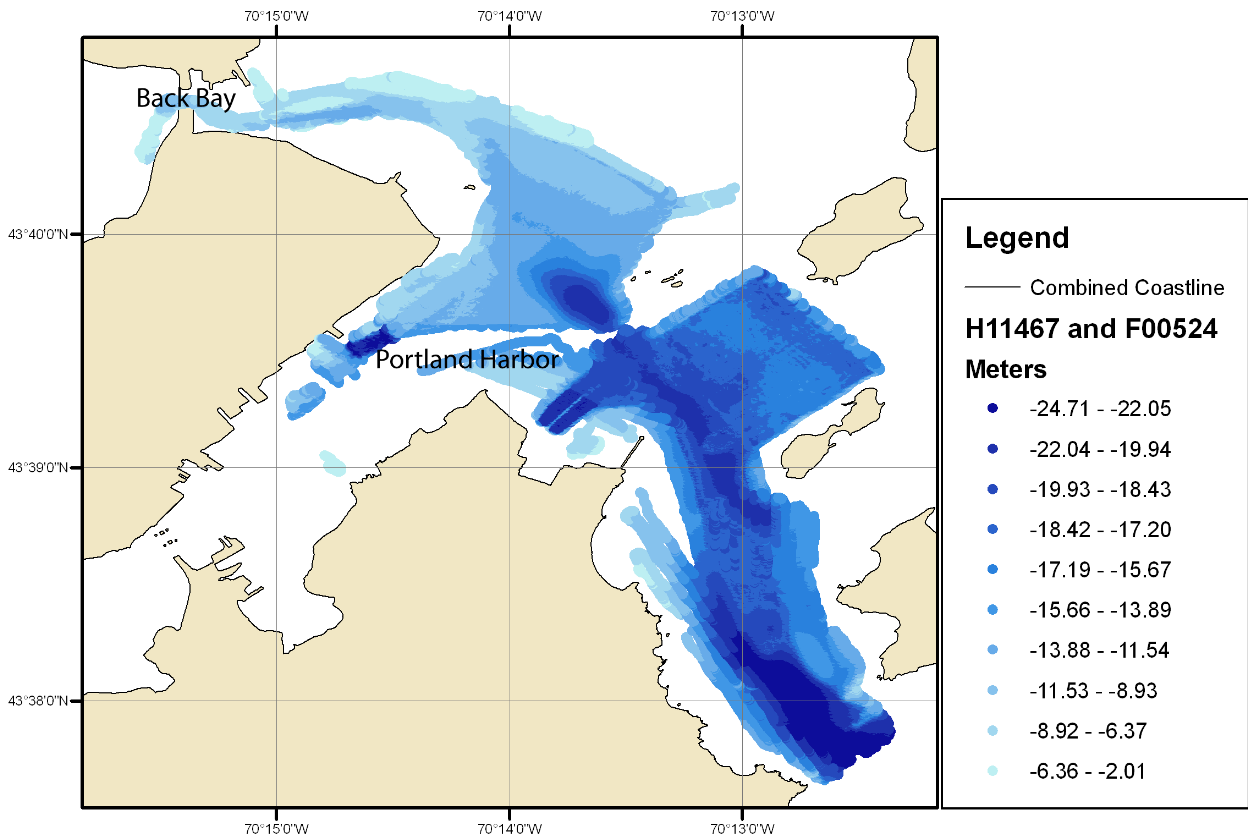

Figure 11. *Coverage of the NOS shallow-water multibeam swath sonar surveys H11467 and F00524. Combined coastline in black.*

3.1.3 *Topography*

Two topographic datasets were used to build the Portland DEM: one from USGS and one from NOAA CSC (Table 8; Fig. 3). NGDC also digitized values for breakwaters and jetties prevalent in areas near estuaries.

Table 8: Topographic datasets used in compiling the Portland DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum (meters)*	*URL*
USGS	1999-2006	NED DEM	1/3 arc-second	NAD 83 geographic	Mixed	http://ned.usgs.gov/
NOAA CSC	2004	Coastal topographic lidar	1 to 3 meters	NAD 83 geographic	NAVD88	http://www.csc.noaa.gov/digitalcoast/
NGDC		Digitized elevation points	~2.5 meters	WGS 84 geographic	MHW	

1) U.S. Geological Survey NED topographic DEM

USGS National Elevation Dataset (NED) provides complete 1/3 arc-second coverage of the Portland region[5]. The dataset is available for download as raster DEMs in NAD 83 geographic horizontal datum and NAVD88 vertical datum (meters). The 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 USGS quadrangle maps and aerial photographs based on topographic surveys.

NGDC visually compared georeferenced images (TIFFs) of USGS topographic quadrangles in the Portland area with the NED dataset before and after its conversion to MHW (Figs. 12 and 13). The 20-ft contours on the quadrangles are referenced to vertical datums of either National Geodetic Vertical Datum of 1929 (NGVD29) or MSL; the coastlines are relative to MHW. NGDC generated 20-foot contours from the original "NAVD88" NED dataset using *ArcGIS*, which were then draped over the USGS topographic quadrangle images for comparison (e.g., Fig. 12). The NED data were also converted from NAVD88 to MHW: the resulting NED "zero" contour (e.g., Fig. 13) is significantly inland of the actual MHW coastline, which, if accurate, would produce coastal flooding with each tidal cycle.

NGDC has concluded that the NED DEMs in the Portland region are actually in a mixed vertical datum, with values above 20 feet (6 meters) in either NGVD29 or MSL (depending upon quadrangle), and the coastal "zero" value being relative to MHW; the original NED data also contain "zero" elevation values over the open ocean, which were removed from the dataset by clipping to the combined coastline. Values between zero (MHW) and 20 feet (NGVD29/MSL) are not consistent with either datum. Note that in the Portland region, the MHW coastline is at approximately the 5-foot (1.5 meter) NGVD 29/MSL contour (see Table 9).

In an effort to overcome this mixing of vertical datums in the NED DEMs, NGDC converted the NED dataset from NGVD29/MSL (see Table 10) to MHW using *ArcGIS*. Elevations in the converted data that were greater than or equal to 0.5 meters were extracted directly from the grids. Elevations that were less than 0.5 meters were set to an assigned value of 0.5 meters above MHW to prevent inappropriate coastal flooding, though fortunately, there is significant coastal lidar data in the Portland region. The resulting NED data were clipped to the lidar coverage areas (Figs. 14 and 16) to limit the effects of this approximate NED vertical datum conversion.

5. The USGS National Elevation Dataset (NED; http://ned.usgs.gov/) 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 NAD 83, except for AK, which is NAD 27. The vertical datum is NAVD88. 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 web site]

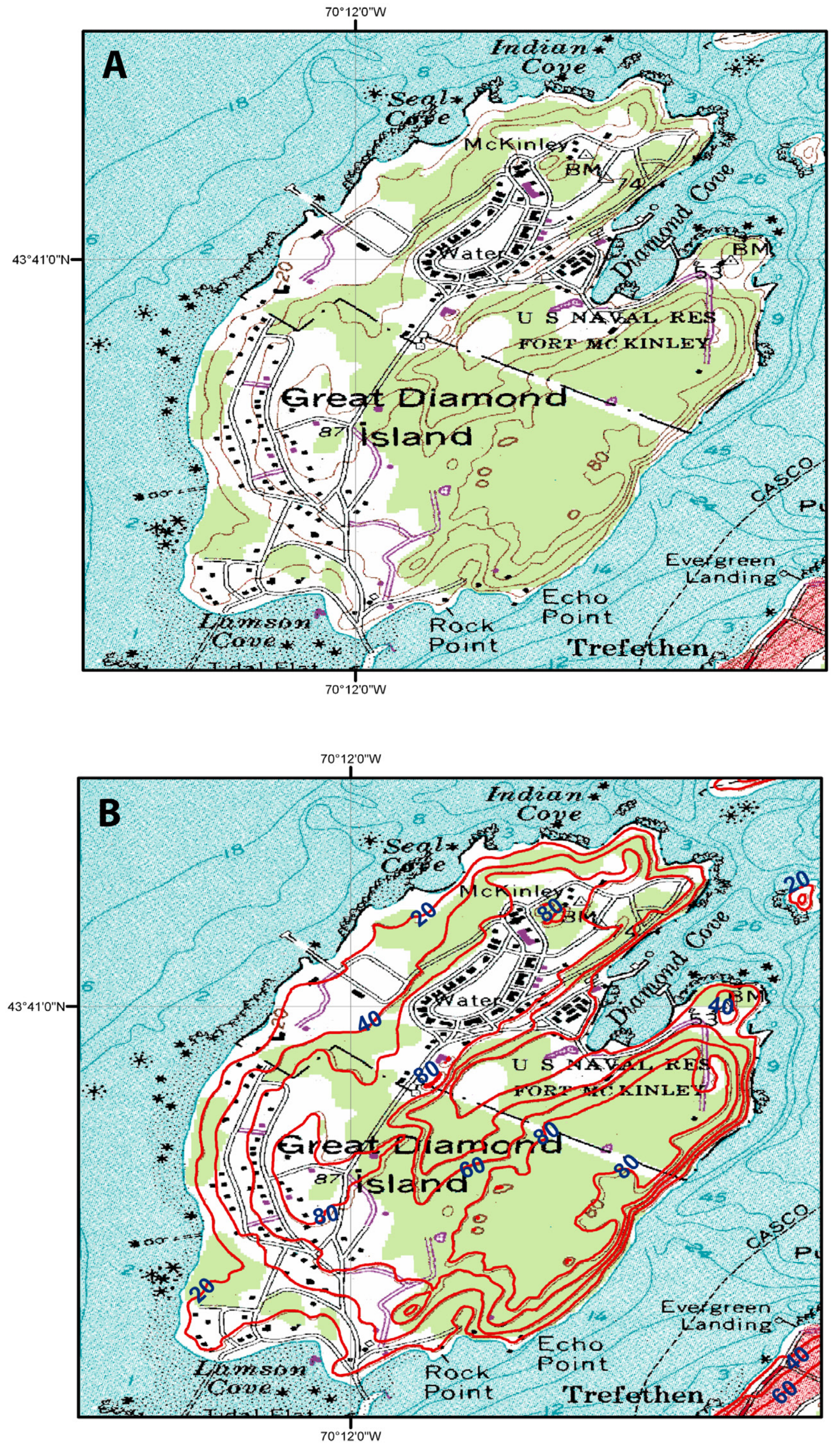

Figure 12. *Comparison between USGS topographic quadrangle contours and the original NED data. A) Color image of USGS topographic quadrangle centered on Great Diamond Island. Brown lines and numbers denote 20 ft. topographic contours relative to NGVD29 vertical datum. B) 20 ft. contours (red) generated from the original NED data (converted to units of feet for comparison), which is identified in the metadata as relative to NAVD88 vertical datum. Note the strong correlation between the "NAVD88" NED contours and NGVD29 USGS quadrangle contours.*

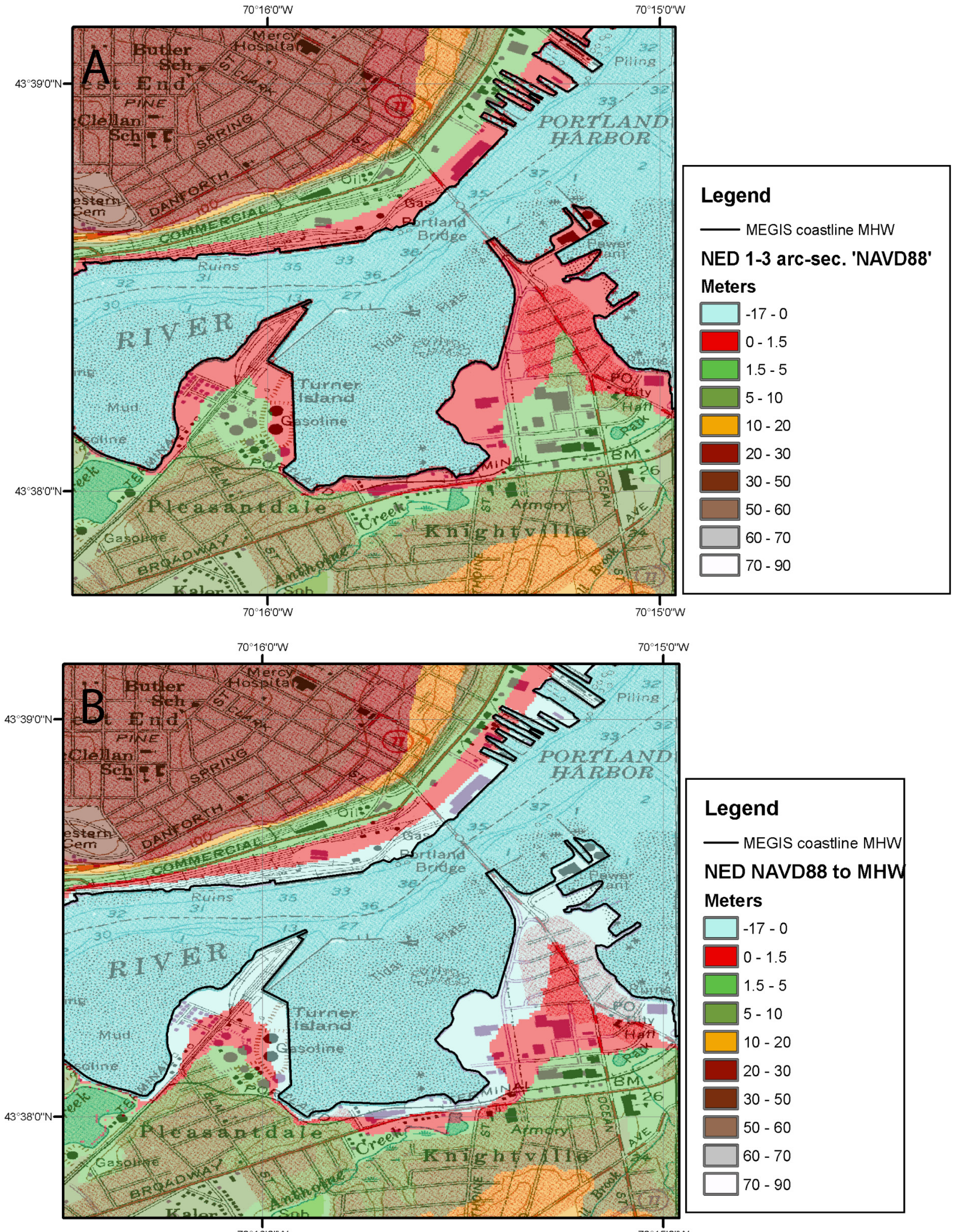

Figure 13. *Comparison of the NED DEM before and after its conversion from NAVD88 to MHW. A) Color image of "NAVD88" NED DEM, with georeferenced USGS topographic quadrangle in the background. Note that the "zero" contour is consistent with the MEGIS and USGS coastlines, which are relative to MHW. B) Color image of the NED DEM after conversion from NAVD88 to MHW, with USGS topographic quadrangle in the background. The "zero" contour for the NED data is now significantly inland relative to the MHW MEGIS and quadrangle coastlines, which would produce coastal flooding with each tidal cycle.*

2) Coastal Services Center coastal lidar survey

NOAA CSC provides online access to coastal topographic lidar data from numerous federal agencies through its web site (http://www.csc.noaa.gov/ldart). A joint NOAA/NOS/CSC 2004 lidar survey from Portsmouth to Back Bay was available for use in the Portland DEM. Original data were in ASCII XYZ format, and NAD 83 geographic and NAVD88 datums. Due to the large size of the survey, NGDC tiled this survey into 26 tiles of 1 million points each for easier visualization and editing. The dataset was used to help define the position of the MHW combined coastline from Cape Elizabeth to Back Bay and areas of Old Orchard Beach (Fig. 14). The survey contained returns from the surface of water bodies, which were removed in *ArcMap* by clipping to the combined coastline.

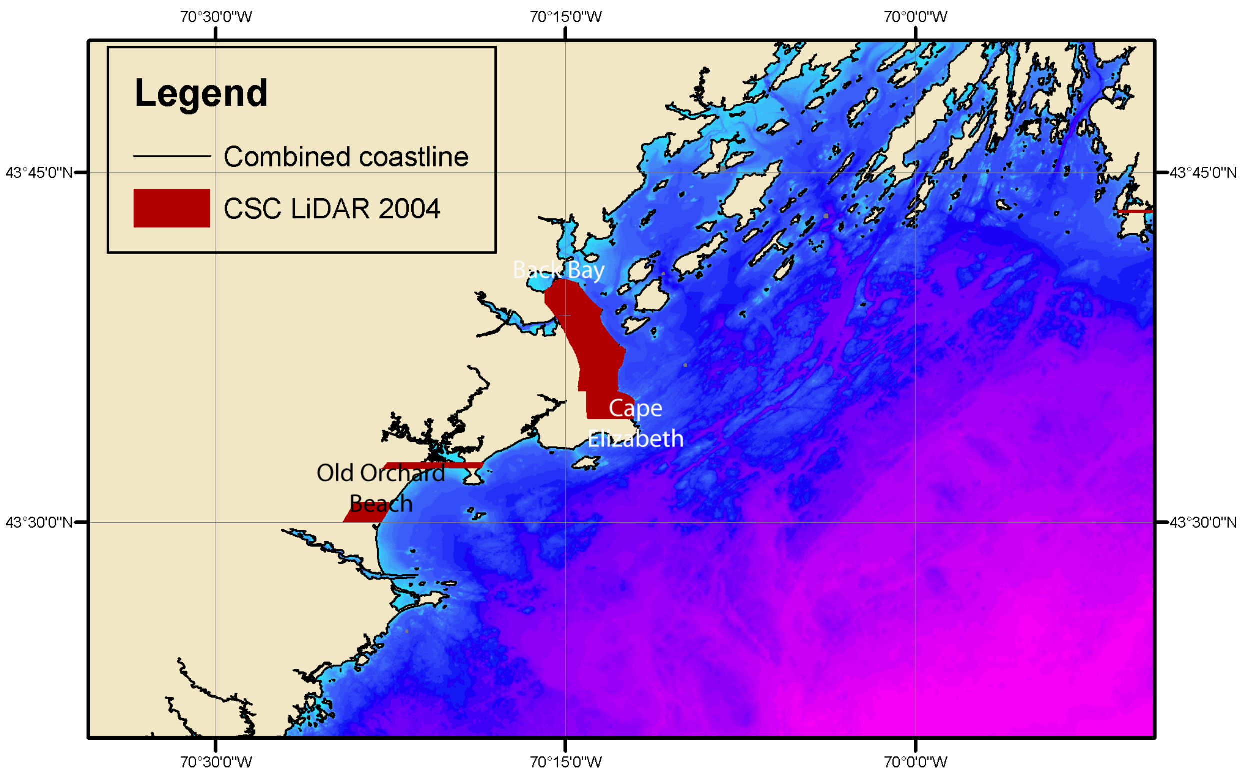

Figure 14. *CSC 2004 coastal lidar coverage in the Portland region. CSC lidar data were superseded by the more recent JALBTCX dataset and only used in areas where JALTCBX lidar was not present. Blue and purple represent pre-gridded 1 arc-second bathy surface. Combined coastline in black.*

3) NGDC digitized elevations

Several manmade features were either poorly represented or not represented at all in available digital elevation datasets: the Casco Bay Bridge columns (Fig. 15) and coastal jetties and breakwaters. The two main columns for the Casco Bay Bridge were digitized to a height of 15 meters while the cylindrical columns to the front and back of the main columns were digitized to a height of 5 meters. Point spacing for both features were approximately 1 to 3 meters.

NGDC digitized coastal jetties in Portland Harbor and the Scarborough River estuary. Jetties were assigned a value of either 0.5 or 1 meter above MHW, with points located every 5 meters along each jetty or breakwater.

Figure 15. *Photograph of Casco Bay Bridge. Digitized features include the two main columns supporting the drawbridge and the cylindrical columns to the front and back of the main columns.*

3.1.4 *Topography-Bathymetry*

One topographic-bathymetric dataset was available from JALBTCX, covering the southwestern and northeastern portion of the Portland DEM from Portsmouth to Cape Elizabeth (Fig. 16; Table 9).

Table 9: Topographic-bathymetric dataset used in compiling the Portland DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
JALBTCX	2007	Coastal lidar	< 5 meters	NAD 83 geographic, UTM zone 19N	NAVD88 (meters)	http://shoals.sam.usace.army.mil

1) **Joint Airborne Lidar Bathymetry Technical Center of Expertise topographic-bathymetric lidar**

The 2007 JALBTCX lidar dataset provided topographic-bathymetric coverage for the coastal and near shore regions south of Cape Elizabeth to Portsmouth. These data were obtained in NAD 83 UTM zone 19N horizontal datum and NAVD88 vertical datum. *FME* was used to re-project the grids to NAD 83 geographic and to MHW. Point spacing was less than 5 meters, with full coverage at the shoreline to more sparse coverage farther from shore, where "clumps" of data surround rocks and kelp.

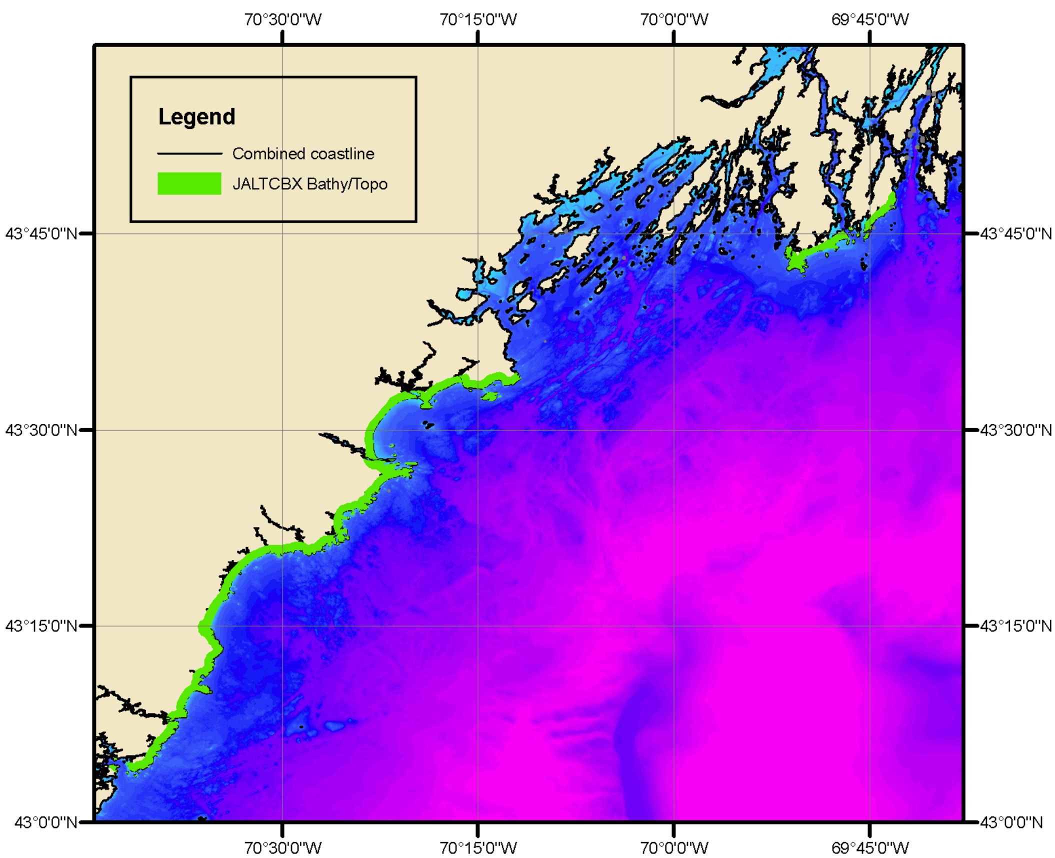

Figure 16. *Coverage of JALBTCX 2007 topographic-bathymetric lidar survey in the Portland region. Blue and purple represent pre-gridded 1 arc-second bathy surface. Combined coastline in black.*

3.2 Establishing Common Datums

3.2.1 *Vertical datum transformations*

Datasets used in the compilation and evaluation of the Portland DEM were originally referenced to a number of vertical datums including MLLW, MLW, MSL, NAVD88, and NGVD29. All data were transformed to MHW to provide the maximum flooding for inundation modeling. Units were converted from feet to meters when necessary.

1) **Bathymetric data**

The NOS hydrographic surveys, the ENC extracted soundings, USGS 15-meter-resolution grid, USACE harbor surveys, UNH multibeam swath sonar survey, and NOS shallow-water multibeam bathymetric data were transformed from NGVD29, MLLW, MLW, and MSL to MHW, using the differences between as measured at the Portland NOAA tide station, #8418150 (see Table 10; http://tidesandcurrents.noaa.gov/).

2) **Topographic and topographic-bathymetric data**

CSC coastal topographic lidar and JALBTCX topographic-bathymetric lidar datasets were originally referenced to NAVD88. The USGS NED 1/3 arc-second DEMs were originally referenced to NGVD29 or MSL (see Sec. 3.1.3). Conversion to MHW, using *FME* software, was accomplished by using the difference between MHW and the NGVD29 and NAVD88 vertical datums, as measured at the Portland tide station, #8418150 (Table 10).

Table 10. Relationship between MHW and other vertical datums in the Portland region.

Vertical datum	*Difference to MHW*
NAVD88	-1.285
MSL	-1.381
NGVD29 +	-1.507
MLW	-2.781
MLLW	-2.886

* Datum relationships determined by tidal station #8418150 at Portland, Maine.
+ Assumed to be equivalent to MSL.

3.2.2 *Horizontal datum transformations*

Datasets used in compiling the Portland DEM were originally referenced to WGS 84 and NAD 83 geographic, and NAD 27 Maine State Plane (feet), NAD 83 UTM zone 19N, and WGS 84 UTM zone 19 (meters) horizontal datums. The relationships and transformational equations between these horizontal datums are well established. Data were converted to a horizontal datum of NAD 83 geographic 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 shapefiles were analysed in *ArcMap* for consistency between datasets. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shapefiles were then converted to xyz files in preparation for gridding. Problems included:

- Erroneous values in NOS hydrographic surveys. These values were checked against survey smoothsheets and deleted in *ArcMap*.
- Data values over the ocean, bays and rivers in the NED topographic DEMs. The dataset required automated clipping to the combined coastline.
- Discrepancies discovered in NED vertical datum. NGDC shifted the NED data from NGVD29 to MHW and set all resulting values less than 0.5 m to 0.5 m.
- Coastal topographic lidar data contained returns from the ocean surface. These data were clipped to the combined coastline.
- Digital, measured bathymetric values from NOS surveys date back over 140 years. More recent data, such as the USACE hydrographic surveys differed from older NOS data by as much as 10 meters. The older NOS survey data were excised where more recent bathymetric data exists.
- CSC lidar included returns from piers and docks. These values were manually excised by clipping to the combined coastline.

3.3.2 Smoothing of bathymetric data

The NOS hydrographic surveys are generally sparse at the resolution of the 1/3 arc-second Portland DEM: in deep water the NOS survey data have point spacing up to 4 km 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" bathymetric grid was generated using *GMT*, an NSF-funded shareware software application designed to manipulate data for mapping purposes.

The NOS hydrographic point data, in xyz format, were clipped to remove overlap with the USGS and USACE survey data, NGDC-digitized soundings, and where NOS soundings crossed the modern combined coastline. The NOS data were then combined with these bathymetric data and the ENC sounding data into a single file, along with points extracted from the combined coastline (to provide a buffer along the entire coastline). The coastline elevation value was set to -1.0 m to ensure that the bathymetric surface was below zero in areas where coastal bathymetry data are sparse or nonexistent (e.g., bays).

The point data were median-averaged using the *GMT* tool "blockmedian" to create a 1 arc-second grid 0.05 degrees (~5%) larger than the Portland DEM gridding region. The *GMT* tool "surface" was then used to apply a tight spline tension to interpolate elevations for cells without data values. The *GMT* grid created by "surface" was converted into an ESRI Arc ASCII grid file, and clipped to the combined coastline (to eliminate data interpolation into land areas). The resulting surface was compared with original soundings to ensure grid accuracy (e.g., Fig. 17), converted to a shapefile, and then exported as an xyz file for use in the final gridding process (see Table 11).

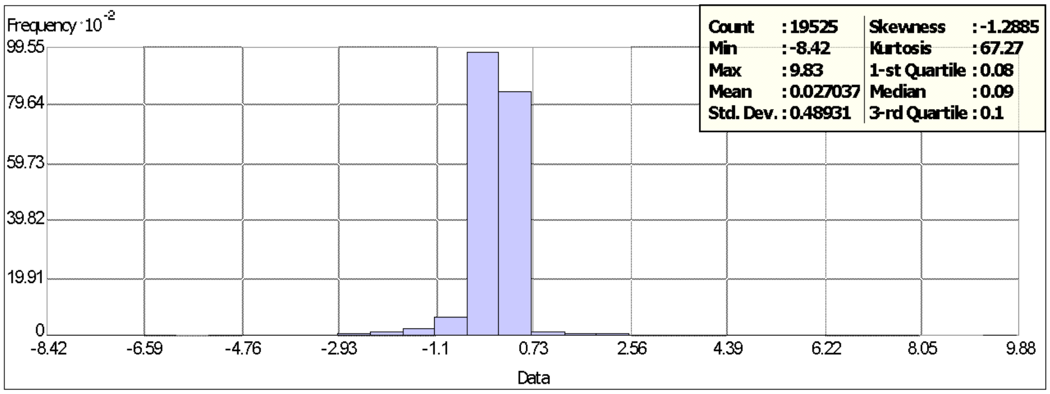

Figure 17. *Histogram of the differences between NOS hydrographic survey H10986 and the 1 arc-second pre-surfaced bathymetric grid.*

3.3.3 Gridding the data with MB-System

MB-System was used to create the 1/3 arc-second Portland DEM. *MB-System* is an NSF-funded shareware 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" was used to apply a tight spline tension to the xyz data, and interpolate values for cells without data. The data hierarchy used in the "mbgrid" gridding algorithm, as relative gridding weights, is listed in Table 11. Greatest weight was given to the USACE hydrographic harbor surveys and coastal topographic lidar data. Least weight was given to the pre-surfaced 1 arc-second bathymetric grid. Gridding was performed in quadrants with the resulting Arc ASCII grids seamlessly merged in *ArcCatalog* to create the final 1/3 arc-second Portland DEM.

Table 11. Data hierarchy used to assign gridding weight in *MB-System*.

Dataset	*Relative Gridding Weight*
JALBTCX	1000
NGDC digitized features	1000
Coastal topographic lidar	100
USACE hydrographic surveys	100
University of New Hampshire Multibeam	100
NOS shallow-water multibeam	100
USGS NED topographic DEM	10
USGS 15m. Grid	10
NOS hydrographic survey soundings	10
ENC soundings	10
Pre-surfaced bathymetric grid	1

3.4 Quality Assessment of the DEM

3.4.1. Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Portland DEM is dependent upon DEM cell size and the datasets used to determine corresponding DEM cell values. Topographic features have an estimated accuracy of about 10 meters: coastal topographic lidar data have an accuracy of approximately 6 meters, NED topography is accurate to within about 10 meters, and JALTCBX topographic-bathymetric lidar is accurate to within 6 meters. Bathymetric features are resolved only to within a few hundred meters in deep-water areas. Shallow, near-coastal regions, rivers, and harbor surveys 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 Portland DEM is also highly dependent upon the source datasets contributing to DEM cell values. Topographic areas have an estimated vertical accuracy between 0.1 to 0.3 meters for coastal topographic 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. Those values were derived from the wide range of input data sounding measurements from the early 20th 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 Portland DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (e.g., Fig. 21). The DEM was transformed to UTM zone 19 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 was accomplished using ESRI *ArcScene* (e.g., Fig. 22). Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 1 shows a color image of the 1/3 arc-second Portland DEM in its final version.

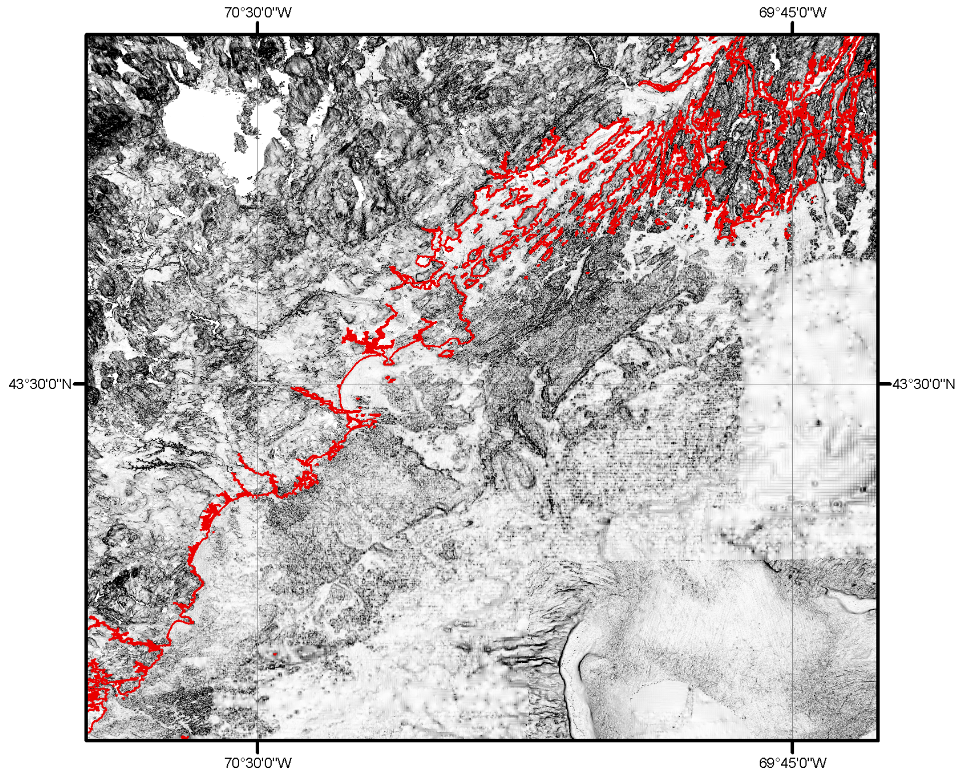

Figure 18. *Slope map of the Portland DEM. Flat-lying slopes are white; dark shading denotes steep slopes; combined coastline in red.*

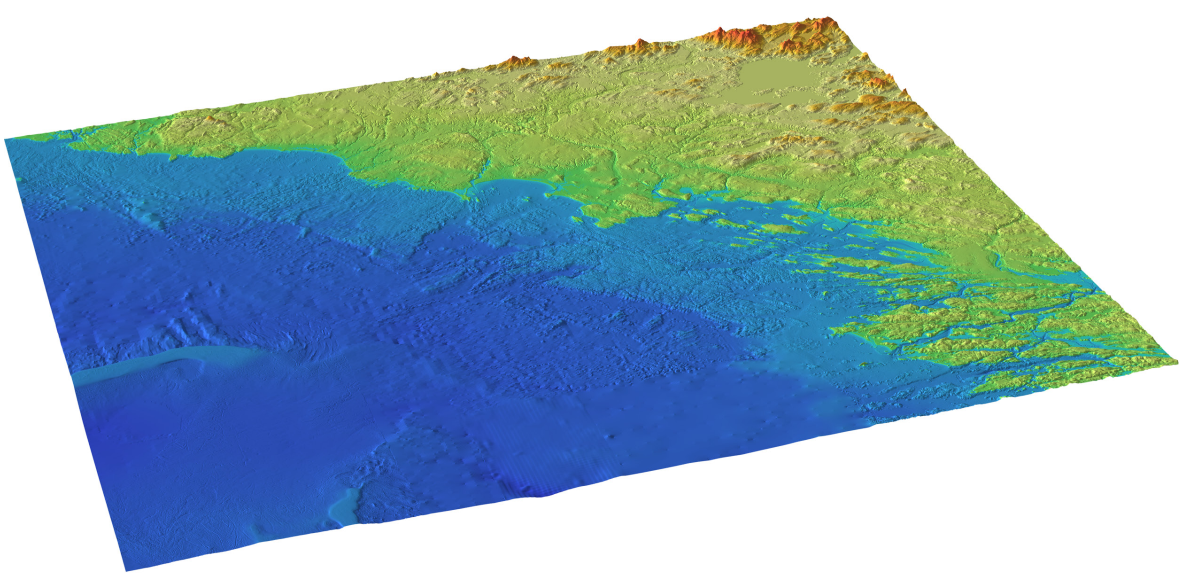

Figure 19. *Perspective view from the southeast of the Portland DEM. Vertical exaggeration–times 5.*

3.4.4 Comparison with source data files

To ensure grid accuracy, the Portland 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 differences between a coastal topographic lidar survey file and the Portland DEM is shown in Figure 20. Differences cluster around zero, with only a handful of points, in regions of steep topography, exceeding 1-meter discrepancy from the DEM.

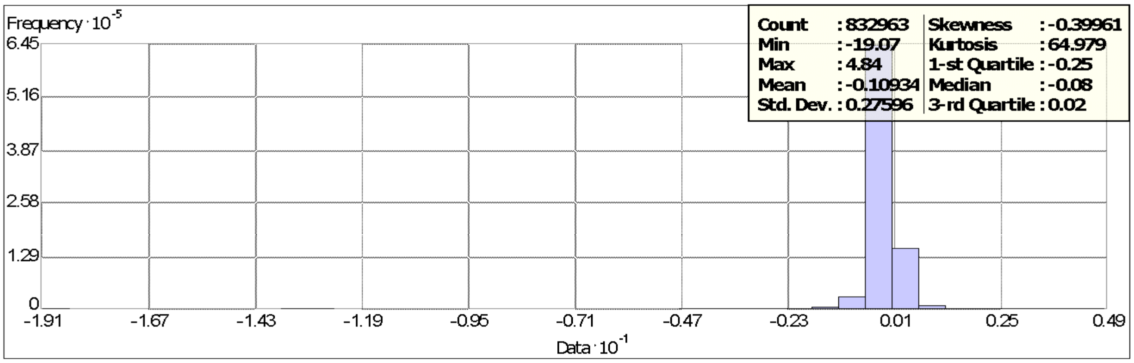

Figure 20. *Histogram of the differences between the 2004 CSC topographic lidar survey of southeast Portland Harbor and the Portland DEM.*

3.4.5 Comparison with National Geodetic Survey geodetic monuments

The elevations of 1122 NOAA NGS geodetic monuments were extracted from online shapefiles of monument datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), which give monument positions in NAD 83 geographic (typically sub-mm accuracy) and elevations in NAVD88 (in meters). Elevations were shifted to MHW vertical datum (see Table 10) for comparison with the Portland DEM (see Fig. 28 for monument locations). Differences between the Portland DEM and the NGS geodetic monument elevations range from -63.78 to 48.95 meters, with the majority of them being within a few meters; negative values indicate that the DEM is less than the monument elevation (Fig. 21). Inspection of datasheets for those monuments with significant discrepancy from the DEM show that they are caused by poor accuracy in monument location (+/- 6 arc-seconds; ~180 m), monuments located on manmade structures such as bridges, piers or lighthouses (not the ground surface), or by monuments that are lost.

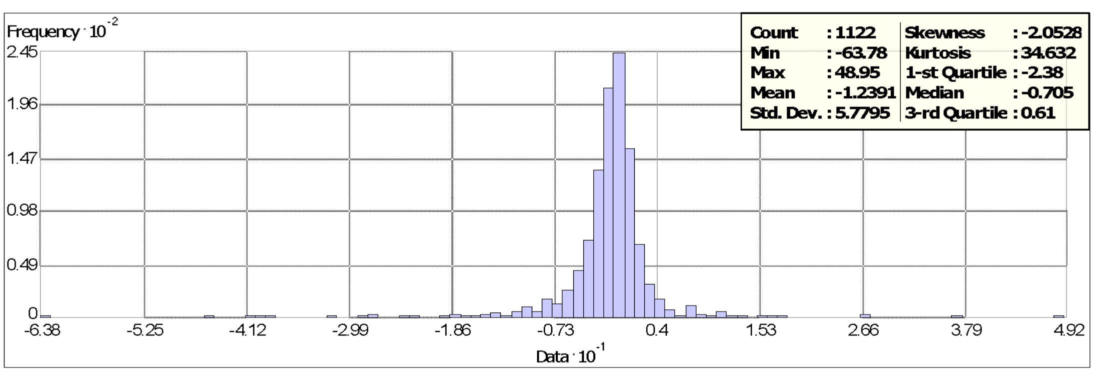

Figure 21. *Histogram of the differences between NGS geodetic monument elevations and the Portland DEM.*

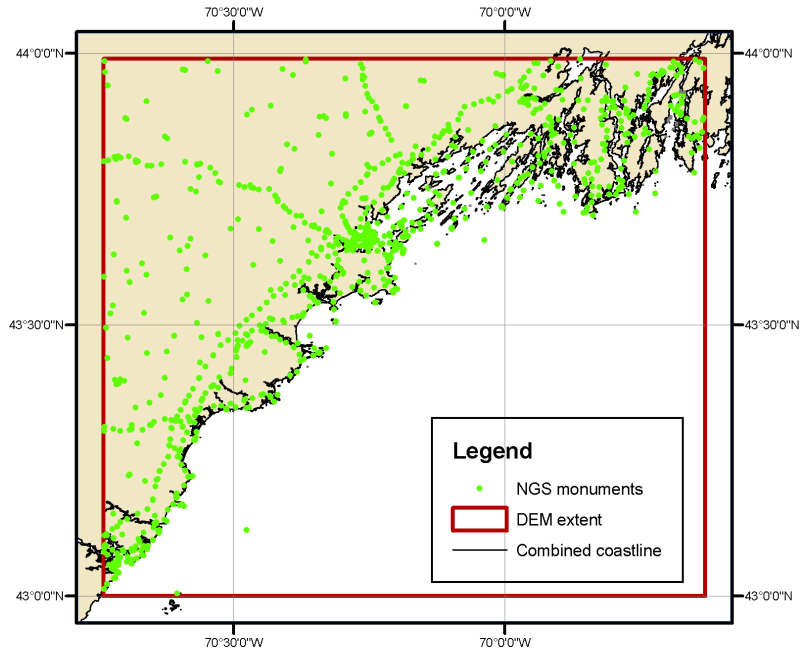

Figure 22. *Location of NGS geodetic monuments and NOAA tide stations in the Portland region. NGS monument elevations were used to evaluate the DEM.*

4. Summary and Conclusions

An integrated topographic-bathymetric DEM of the Portland, Maine region, with cell size of 1/3 arc-second, was developed for the PMEL NOAA Center for Tsunami Research. The best available digital data from U.S. federal and state agencies 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 *ArcGIS*, *FME*, *GMT*, *MB-System* and *Quick Terrain Modeler* software.

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

- Complete topographic lidar surveying of coastal areas in the region.
- Conduct high-resolution hydrographic surveys, concentrating in estuaries and harbors.
- Adjust the NED dataset to a single vertical datum in the Portland region (see Sec. 3.1.3).
- Conduct hydrographic surveys in areas of deeper water approximately 25 km to the south of Boothbay Harbor.

5. Acknowledgments

The creation of the Portland DEM was funded by the NOAA Center for Tsunami Research at PMEL. The authors thank Nazila Merati and Vasily Titov (PMEL), William Walker (USACE, New England district), Larry Mayer and Mashkoor Ahmad Malik (CCOM/JHC/UNH), and Christopher L. Macon (JALBTCX).

6. References

Electronic Navigational Chart #13278 (RNC), 8th Edition, 2008, Portsmouth to Cape Ann. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #13283 (RNC), 7th Edition, 2008, Cape Neddick Harbor to Isles of Shoals. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #13285 (RNC), 9th Edition, 2008, Portsmouth to Dover and Exeter. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #13286 (RNC), 6th Edition, 2008, Cape Elizabeth to Portsmouth. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #13288 (RNC), 6th Edition, 2008, Monhegan Island to Cape Elizabeth. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #13290 (RNC), 6th Edition, 2008, Casco Bay B. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #13292 (RNC), 15th Edition, 2008, Portland Harbor and Vicinity A. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #13295 (RNC), 6th Edition, 2008, Kennebec and Sheepscot River Entrances. Scale 1:15,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #13296 (RNC), 6th Edition, 2008, Boothbay Harbor to Bath Including Kennebec River. Scale 1:15,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #13298 (RNC), 4th Edition, 2008, Kennebec River-Bath to Courthouse Point. Scale 1:15,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Roworth, E. and Signell, R. P., Construction of Digital Bathymetry for the Gulf of Maine, longitude: 71.5 - 63 W, latitude : 39.5 - 46 N, U.S. Geological Survey Open-file Report 98-801, http://pubs.usgs.gov/of/1998/of98-801/

7. Data Processing Software

ArcGIS v. 9.2, developed and licensed by ESRI, Redlands, Maine, http://www.esri.com/

FME 2008 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. 4.3.0 – 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. 5.1.0, 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/

Quick Terrain Modeler v. 6.0.1, lidar processing software developed by John Hopkins University's Applied Physics Laboratory and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/