NOAA Technical Memorandum NESDIS NGDC-25

DIGITAL ELEVATION MODEL OF CENTRAL OREGON COAST: PROCEDURES, DATA SOURCES AND ANALYSIS

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UNITED STATES DEPARTMENT OF COMMERCE

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1. Introduction

In September 2008, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed an integrated bathymetric–topographic digital elevation model (DEM) of Central Oregon Coast (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 will be used for tsunami inundation modeling, as part of the tsunami forecast system SIFT (Short-term Inundation Forecasting for Tsunamis) developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the Central Oregon Coast DEM.

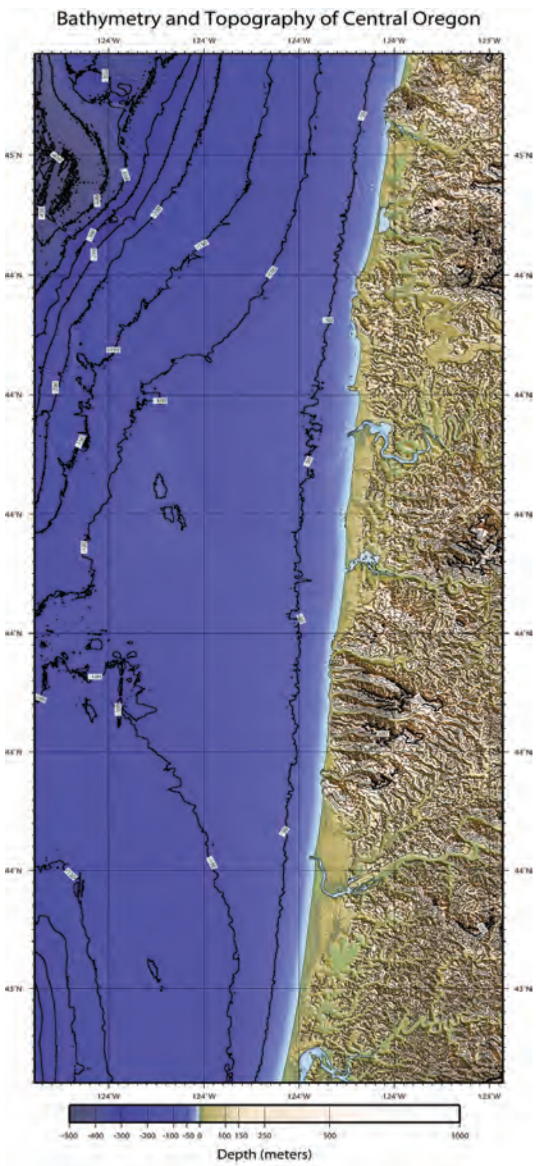

Figure 1. *Shaded-relief image of the Central Oregon Coast DEM. Contour interval is 50 meters in water and 100 meters on land. Image is in Mercator projection.*

1. The Central Oregon Coast 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 Waldport, Oregon (44°25.80′ N, 124°3.60′ W; Fig. 2) 1/3 arc-second of latitude is equivalent to 10.29 meters; 1/3 arc-second of longitude equals 7.37 meters.

2. Study Area

The Central Oregon Coast DEM covers the coastal area of Oregon from Cascade Head south to the Umpqua River (Fig. 2). As part of the Cascadia Subduction Zone, the Oregon coast is subject to a variety of geologic hazards including landslides, earthquakes, volcanoes, and tsunamis. The major coastal communities located within the Central Oregon Coast DEM boundary are Lincoln City located north of Siletz Bay, Newport on the north side of Yaquina Bay, Waldport on the south side of Alsea Bay, and Florence at the Siuslaw River.

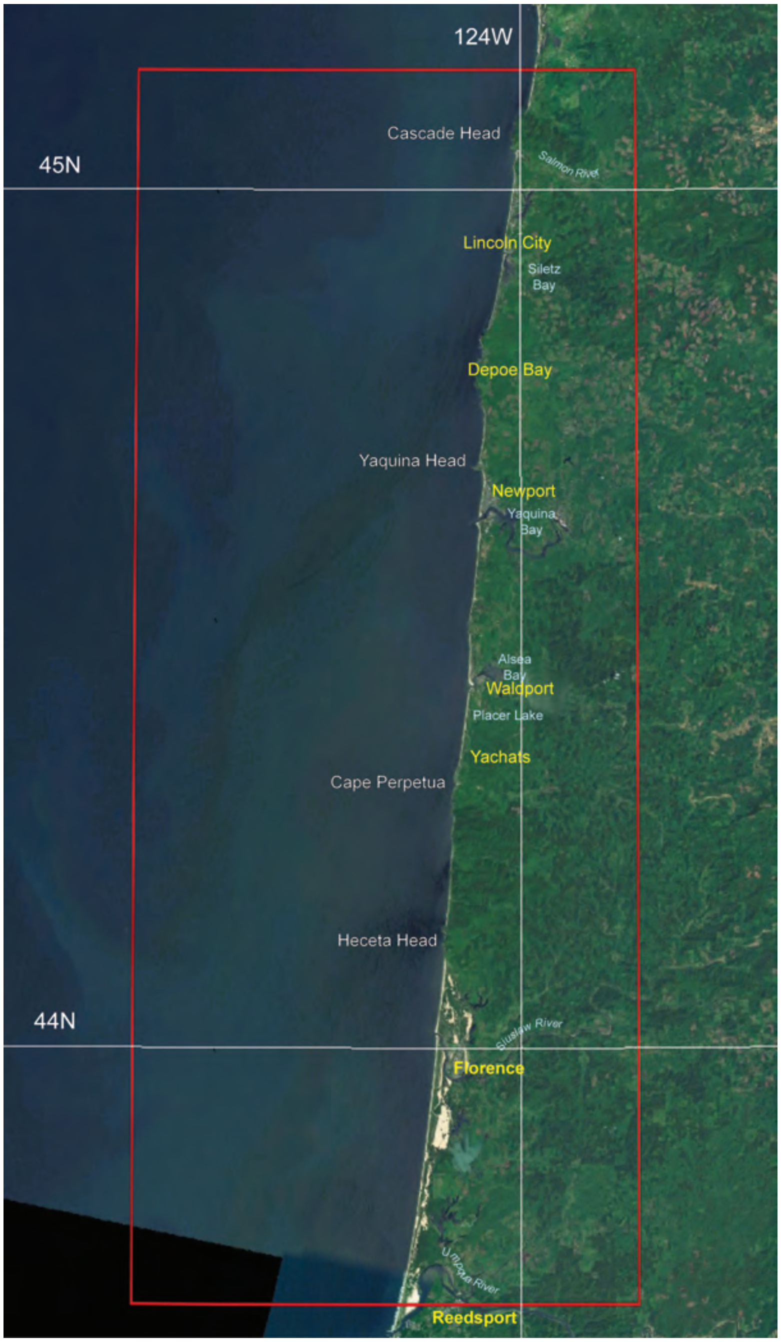

Figure 2. *NASA World Wind i-cubed Landsat 7 image of Central Oregon Coast; DEM boundary shown in red (http://worldwind.arc.nasa.gov/).*

3. Methodology

The Central Oregon Coast 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 1983 (NAD 83) and Mean High Water (MHW), respectively, for modeling of maximum flooding[2]. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1: PMEL specifications for the Central Oregon Coast DEM.

Grid Area	Central Oregon Coast
Coverage Area	123.81º to 124.63º W; 43.70º to 45.14º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System 1984 (WGS 84)
Vertical Datum	Mean High Water (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, and topographic digital datasets (Fig. 3) were obtained from several U.S. federal, state and local agencies including: NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS), Coastal Services Center (CSC), and Pacific Marine Environmental Laboratory (PMEL); the U.S. Geological Survey (USGS); the U.S. Army Corps of Engineers (USACE); and the Oregon Department of Fish and Wildlife (ORDFW). Safe Software's (http://www.safe.com/) FME data translation tool package was used to shift datasets to NAD 83 horizontal datum and to convert them into ESRI (http://www.esri.com/) ArcGIS shape files[3]. The shape files were then displayed with ArcGIS to assess data quality and manually edit datasets. Vertical datum transformations to MHW were accomplished using FME and ArcGIS, based upon data from the NOAA tide stations. Applied Imagery's Quick Terrain Modeler software (http://www.appliedimagery.com/) was used for editing data and to evaluate processing and gridding techniques.

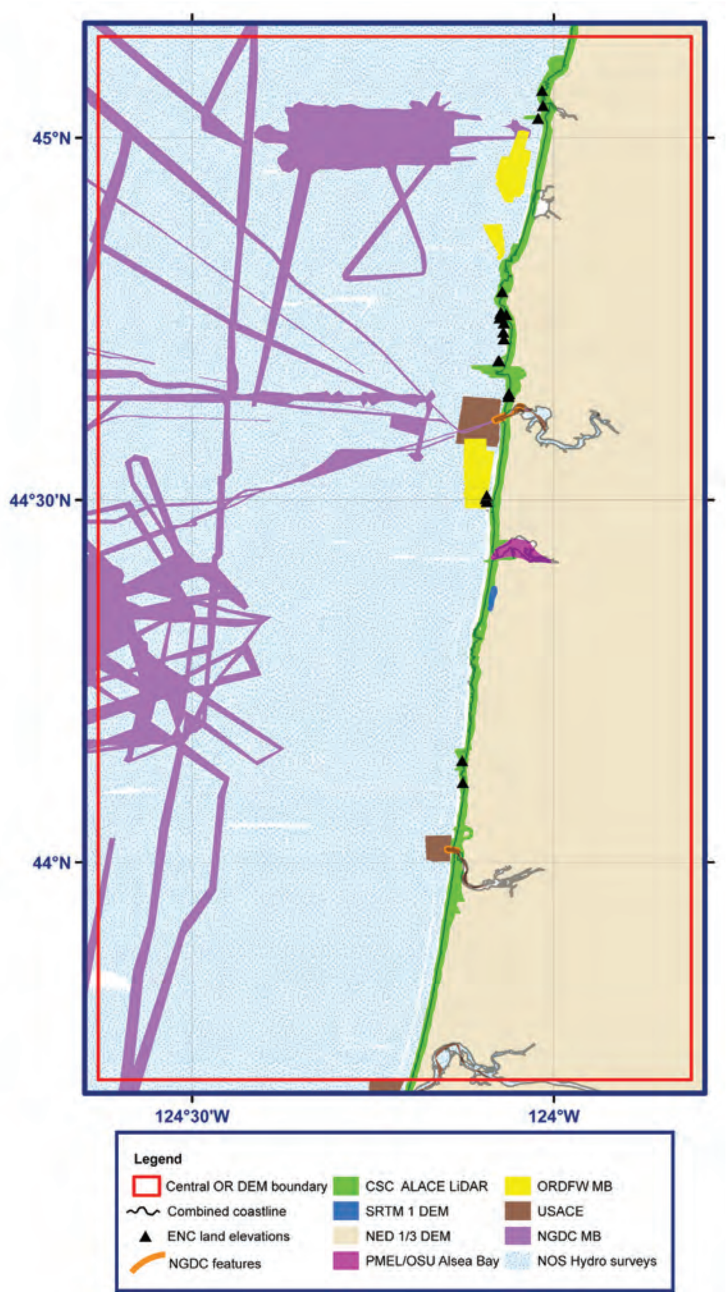

***Figure 3.** Source and coverage of datasets used to compile the Central Oregon Coast DEM.*

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 Central Oregon coastal region were obtained from NOAA's Office of Coast Survey as Electronic Navigational Charts and from the high resolution bathymetric–topographic DEMs of Port Orford and Garibaldi, Oregon created by NGDC (Table 2; Fig. 4). The NOAA National Shoreline from the National Geodetic Survey (NGS) was evaluated but not used in the Central Oregon Coast DEM.

Table 2: Shoreline dataset used in the Central Oregon Coast DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
OCS ENC extracted shoreline	2008	vector	1:185,238 to 1:191,730	WGS 84 geographic (meters)	Mean High Water	http://chartmaker.ncd.noaa.gov/MCD/enc/index.htm
NGDC Port Orford and Garibaldi DEM coastlines	2007	vector		WGS 84 geographic	Mean High Water	http://www.ngdc.noaa.gov/mgg/inundation/tsunami/

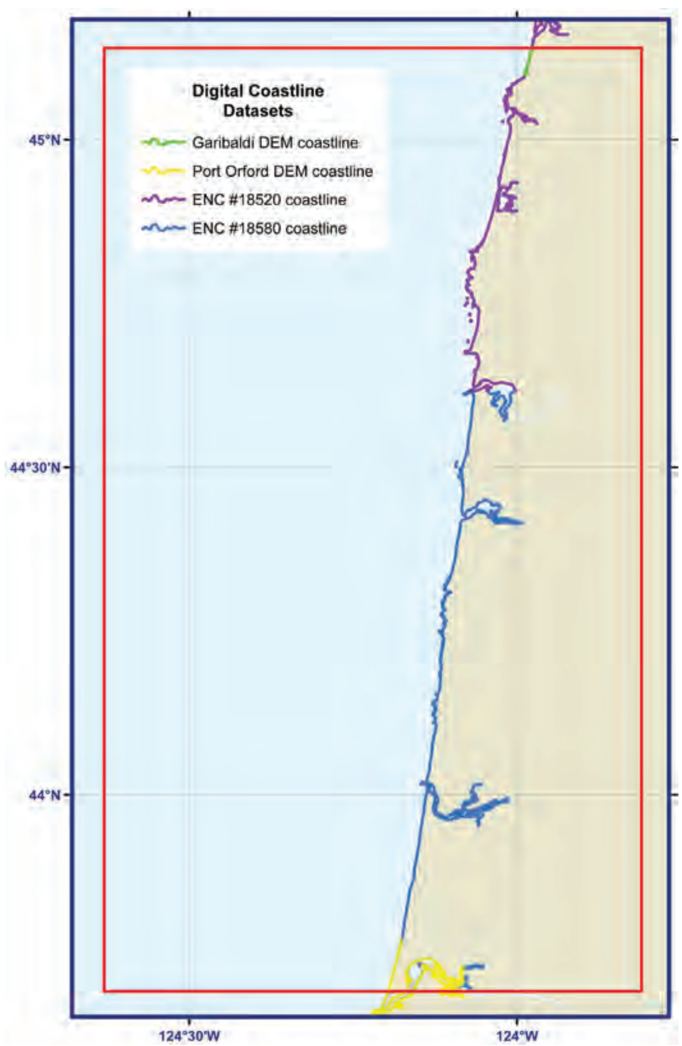

Figure 4. *Digital coastline datasets used for developing a coastline for the Central Oregon Coast DEM.*

1) OCS Electronic Navigational Charts

Two electronic navigational charts (ENCs) were available for the Central Oregon Coast area (Table 3) and downloaded from the NOAA's Office of Coast Survey website (http://chartmaker.ncd.noaa.gov/MCD/enc/index.htm). The coastline data were extracted from the ENC S-57 format to vector line shapefiles using FME and merged using the ArcCatalog merge tool. The ENC coastline dataset covers the entire DEM area.

Table 3: Digital nautical chart data available in the Central Oregon Coast region.

Chart	*Title*	*Edition*	*Edition Date*	*Format*	*Scale*
18520	Yaquina Head to Columbia River – Netarts Bay	10 (ENC)	2008	ENC and RNC	1:185,238
18561	Approaches to Yaquina Bay	12	2003	RNC	1:50,000
18580	Cape Blanco the Yaquina Head	6 (ENC)	2008	ENC and RNC	1:191,730
18581	Yaquina Bay and River	17	2002	RNC	1:10,000
18583	Siuslaw River	39	2005	RNC	1:20,000
18584	Umpqua River – Pacific Ocean to Reedsport	48	2007	RNC	1:20,000
18587	Coos Bay	70	2005	RNC	1:20,000

2) NGDC Port Orford and Garibaldi DEM coastlines

Both the northern and southern Central Oregon Coast DEM boundaries overlap DEMs previously developed by NGDC. Coastlines from these existing DEMs for Garibaldi and Port Orford were clipped to the Central Oregon Coast boundary and merged using the ArcCatalog 'merge' tool.

The coastline datasets were merged using ArcCatalog into a 'combined' coastline and visually compared to Google Earth satellite imagery (http://earth.google.com/userguide/v4/#imagery_dates), USGS topographic maps available on NASA World Wind (http://worldwind.arc.nasa.gov/index.html), and USACE aerial photos to ensure features such as jetties and breakwaters were present in the 'combined' coastline. Coastal features were added using ArcMap editing tools. To represent the most recent topographic data, the 'combined' coastline was adjusted to match the NOAA Coastal Services Center 2002 ALACE LiDAR dataset along the coast. In bays and along rivers where LiDAR was not available, the 'combined' coastline was adjusted to ensure recent USACE hydrographic surveys were located in channels. Further modifications were made using RNCs and NED topographic data to reflect shoreline locations accurately.

3.1.2 Bathymetry

Bathymetric datasets used in the compilation of the Central Oregon Coast DEM include 35 NOS hydrographic surveys; 24 USACE hydrographic channel line surveys; 12 multibeam swath sonar surveys downloaded from the NGDC multibeam sonar database; 2 multibeam sonar surveys from the Oregon Department of Fish and Wildlife, Marine Resources Program (ORDFW); and a hydrographic survey of Alsea Bay conducted by Oregon State University and provided by NOAA/PMEL (Table 4; Fig. 5).

Table 4: Bathymetric datasets used in compiling the Central Oregon Coast DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NOS	1927 to 1987	Hydrographic survey soundings	Ranges from 10 m to 1 km (varies with scale of survey, depth, traffic, and probability of obstructions)	NAD 27 or NAD 83 geographic	Mean Lower Low Water	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
USACE	2005 to 2008	Hydrographic surveys	various, from 3 to 40 meter point spacing	NAD 83 Oregon State Plane North (feet)	Mean Lower Low Water	https://www.nwp.usace.army.mil/op/nwh/xyzcoastal.asp
NGDC	1987 to 2003	Multibeam sonar swath files	raw MB files gridded to 1/3 arc-second	WGS 84 geographic	assumed Mean Sea Level	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
PMEL/OSU	2002	Extracted bathymetric points	10 meters	WGS 84 geographic	Mean Sea Level	
ORDFW	2003	Multibeam sonar swath surveys	1 meter point data and 2 meter DEM	WGS 84 UTM Zone 10 North	Mean Lower Low Water	

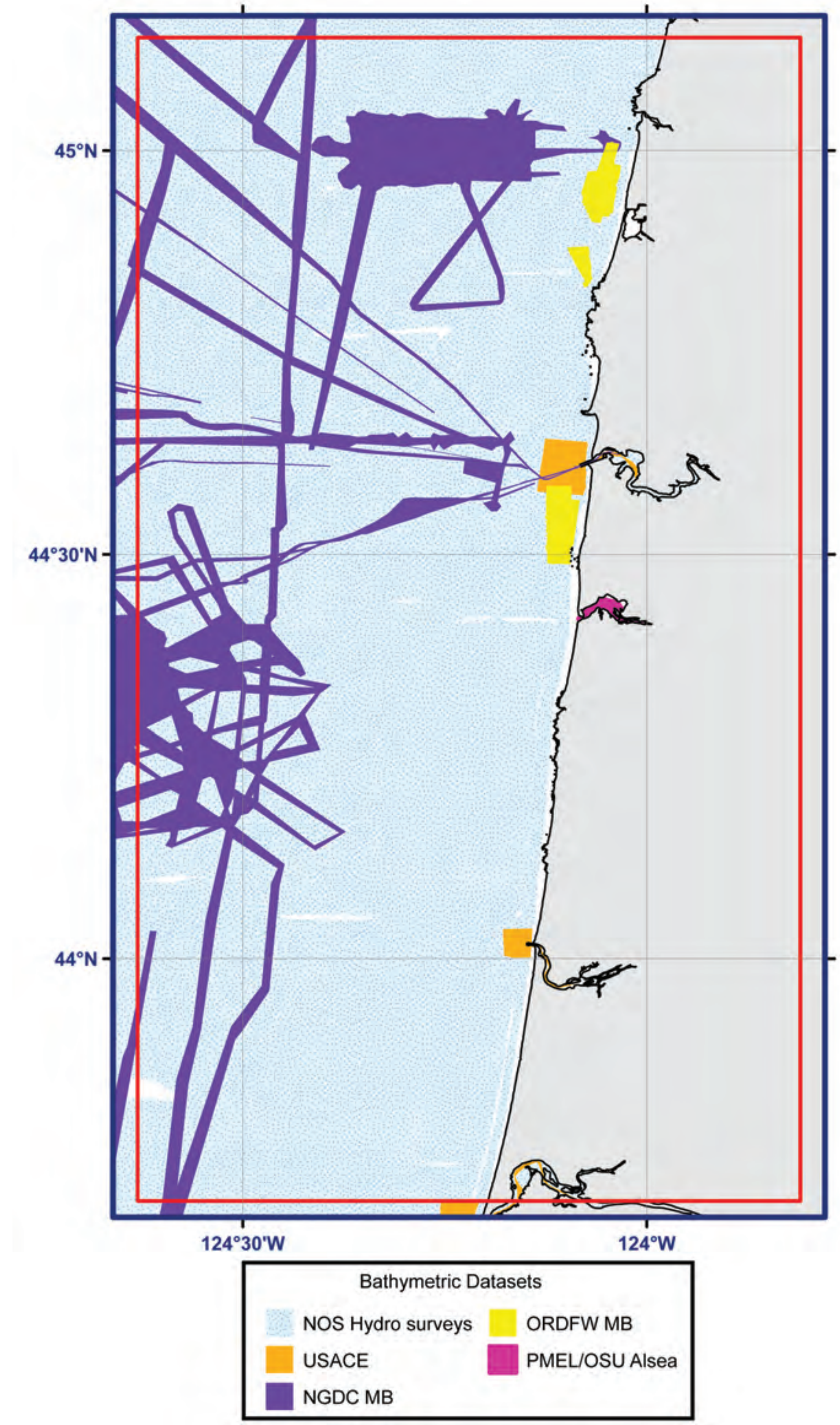

Figure 5. *Spatial coverage of bathymetric datasets used to compile the DEM.*

1) NOS hydrographic survey data

A total of 35 NOS hydrographic surveys conducted between 1927 and 1987 were available for use in developing the Central Oregon Coast DEM. The hydrographic survey data were originally vertically referenced to Mean Lower Low Water (MLLW) and horizontally referenced to either NAD 1913, NAD 27, or NAD 83 datums if the datum was known and recorded (Table 5; Fig. 6).

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) referenced to NAD 83. The surveys were subsequently clipped to a polygon 0.05 degree (~5%) larger than the Central Oregon Coast DEM area to support data interpolation along grid edges.

After converting all NOS survey data to MHW, 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 and other bathymetric datasets, the 'combined' coastline, and NOS raster nautical charts (RNCs). The surveys were clipped to remove soundings that overlap the more recent multibeam surveys, USACE surveys, and where soundings from older surveys have been superseded by more recent NOS surveys.

Table 5: Digital NOS hydrographic surveys used in compiling the Central Oregon Coast DEM.

Survey ID	*Scale*	*Date*	*Digital Data Horizontal Datum*	*Vertical Datum*	*Original Horizontal Datum*
H04746	20,000	1927	NAD 27	MLLW	NAD1913
H04747	20,000	1927	NAD 27	MLLW	NAD1913
H04748	20,000	1927	NAD 27	MLLW	NAD1913
H04749	20,000	1927	NAD 27	MLLW	NAD1913
H04753	120,000	1927	NAD 27	MLLW	NAD1913
H04754	80,000	1927	NAD 27	MLLW	NAD 27
H04756	40,000	1927	NAD 27	MLLW	NAD1913
H04757	120,000	1927	NAD 27	MLLW	NAD1913
H04758	80,000	1927	NAD 27	MLLW	NAD 27
H04878	20,000	1928	NAD 27	MLLW	NAD1913
H04879	20,000	1928	NAD 27	MLLW	NAD1913
H04880	20,000	1928	NAD 27	MLLW	NAD1913
H04881	20,000	1928	NAD 27	MLLW	NAD1913
H04882	40,000	1928	NAD 27	MLLW	NAD1913
H04883	40,000	1928	NAD 27	MLLW	NAD1913
H04884	20,000	1928	NAD 27	MLLW	NAD1913
H04885	20,000	1928	NAD 27	MLLW	NAD1913
H04888	120,000	1928	NAD 27	MLLW	NAD1913
H04889	120,000	1928	NAD 27	MLLW	NAD1913
H04890	40,000	1928	NAD 27	MLLW	NAD1913
H04894	40,000	1928	NAD 27	MLLW	NAD1913
H04895	80,000	1928	NAD 27	MLLW	NAD 27
H04896a	80,000	1928	NAD 27	MLLW	NAD 27
H07896	5,000	1952	NAD 27	MLLW	NAD 27
H08039	5,000	1953	NAD 27	MLLW	NAD 27
H08040	10,000	1953	NAD 27	MLLW	NAD 27
H08041	10,000	1953	NAD 27	MLLW	NAD 27
H09238	10,000	1971	NAD 27	MLLW	NAD 27
H09239	10,000	1971	NAD 27	MLLW	NAD 27
H09240	2,500	1971	NAD 27	MLLW	NAD 27

B00019	50,000	1985	NAD 83	MLLW	NAD 83
B00020	50,000	1985	NAD 83	MLLW	NAD 83
B00048	50,000	1986	NAD 83	MLLW	NAD 83
B00051	50,000	1986	NAD 83	MLLW	NAD 83
B00095	20,000	1987	NAD 83	MLLW	NAD 83

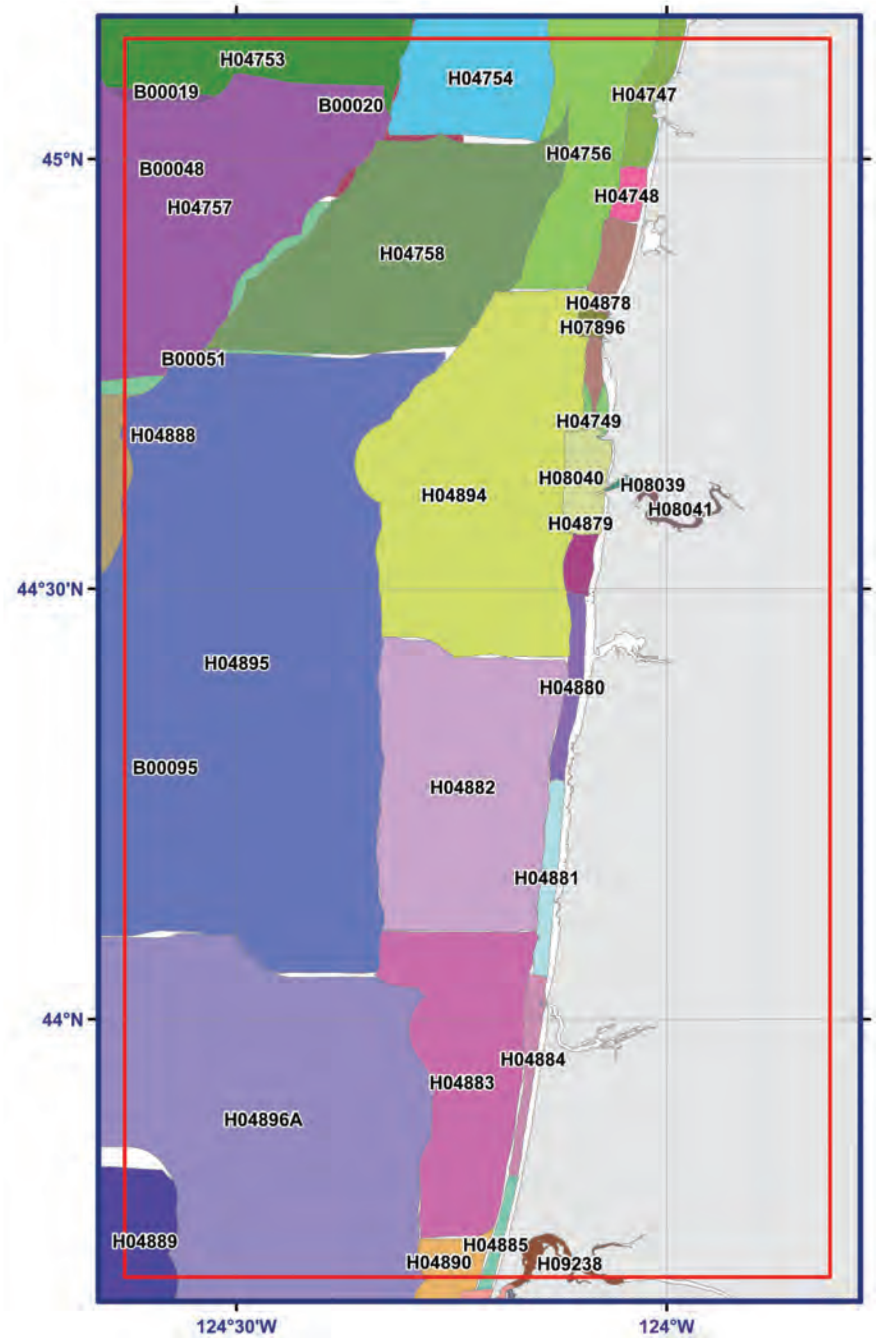

Figure 6. *Digital NOS hydrographic survey coverage in the Central Oregon Coast DEM region. Some older surveys were not used as they have been superseded by more recent surveys. DEM boundary in red.*

2) USACE hydrographic channel line surveys

Twenty-four hydrographic channel line surveys (survey lines that run parallel to the channel) and offshore or basin surveys were available for use in the Central Oregon Coast DEM (Table 6, Figs. 7, 8, and 9). The surveys were downloaded in xyz format from the USACE Portland District website (https://www.nwp.usace.army.mil/op/nwh/xyzcoastal.asp). The data were transformed from NAD 83 State Plane Oregon North to NAD 83 geographic and MLLW to MHW, converted to shape files using FME and quality checked in ArcMap against other bathymetric datasets.

Table 6: USACE hydrographic surveys used in compiling the Central Oregon Coast DEM.

Region	*Survey ID*	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Survey Format*
Depoe Bay - Boat basin	deb	2005	MLLW	NAD 83 State Plane Oregon North (feet)	Basin survey with <5 meter point spacing
Yaquina River - Depot Slough	dsl	2008	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~6 meters apart with <2 meter point spacing
- Bay & Harbor	yb2	2008	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~20 meters apart with ~10 meter point spacing
- South Beach Marina	yb3	2008	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~20 meters apart with ~10 meter point spacing
- Entrance	YB1110607	2008	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~15 meters apart with ~15 meter point spacing
- Section 103 interim	ybd	2006	MLLW	NAD 83 State Plane Oregon North (feet)	Offshore survey spacing ~80 meters apart with ~20 meter point spacing
- North site	YDN071707	2007	MLLW	NAD 83 State Plane Oregon North (feet)	Offshore survey spacing ~80 meters apart with ~20 meter point spacing
- South site	yds	2007	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~20 meters apart with ~10 meter point spacing
- Approaches	yqa	2006	MLLW	NAD 83 State Plane Oregon North (feet)	Offshore survey spacing ~300 meters apart with ~30 meter point spacing
Siuslaw River - Cannery Hill Reach	ss2	2008	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~20 meters apart with ~10 meter point spacing
- Spruce Point Bend	ss3	2008	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~20 meters apart with ~10 meter point spacing
- Florence	ss4	2008	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~20 meters apart with ~10 meter point spacing
- Entrance	SS1012308	2008	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~20 meters apart with ~10 meter point spacing
- Approaches	ssa	2006	MLLW	NAD 83 State Plane Oregon North (feet)	Offshore survey spacing ~300 meters apart with ~30 meter point spacing
- Site B	SSB071707	2007	MLLW	NAD 83 State Plane Oregon North (feet)	Offshore survey spacing ~80 meters apart with ~20 meter point spacing

Umpqua River - Entrance	UP1012308	2007	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~20 meters apart with ~10 meter point spacing
- Salmon Harbor Reach	UP2022508	2008	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~20 meters apart with ~10 meter point spacing
- Barretts Range	UP3031808	2008	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~20 meters apart with ~10 meter point spacing
- Mile 6 Bar	UP4031908	2008	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~20 meters apart with ~10 meter point spacing
- Cannery Sands	UP5032008	2007	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~20 meters apart with ~10 meter point spacing
- Reedsport Reach	UP6032408	2008	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~20 meters apart with ~10 meter point spacing
- Approaches	upa	2007	MLLW	NAD 83 State Plane Oregon North (feet)	Offshore survey spacing ~300 meters apart with ~30 meter point spacing
- Section 103 site	UPD050107	2008	MLLW	NAD 83 State Plane Oregon North (feet)	Offshore survey spacing ~60 meters apart with ~20 meter point spacing
- Winchester Bay	WIN042908	2008	MLLW	NAD 83 State Plane Oregon North (feet)	Channel line survey spacing ~7 meters apart with ~10 meter point spacing

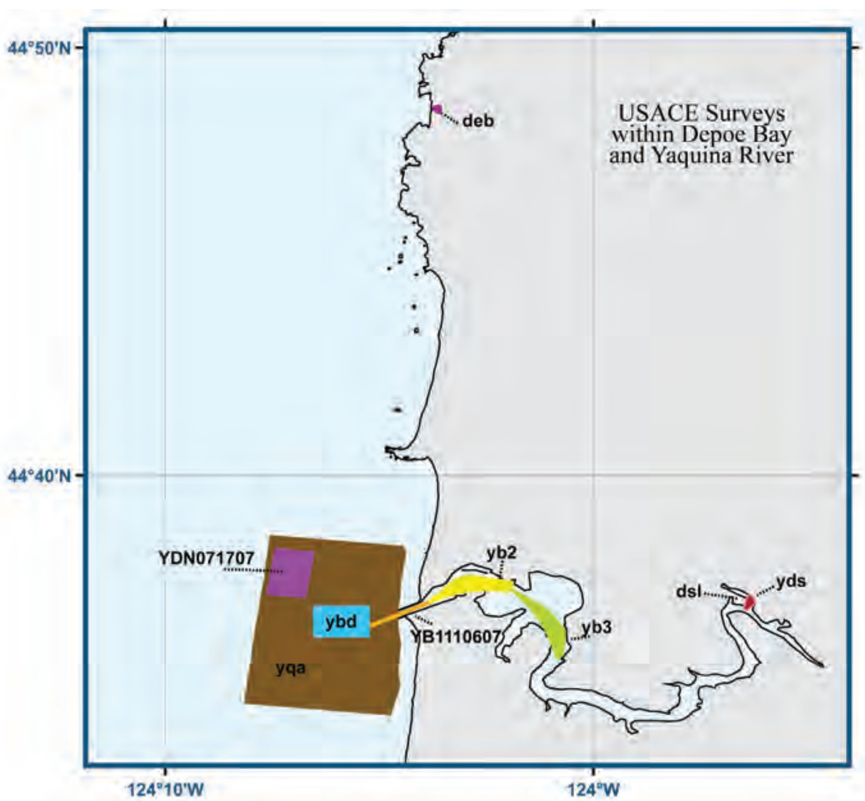

Figure 7. *Spatial coverage of USACE hydrographic channel line and offshore surveys for Depoe Bay and the Yaquina River.*

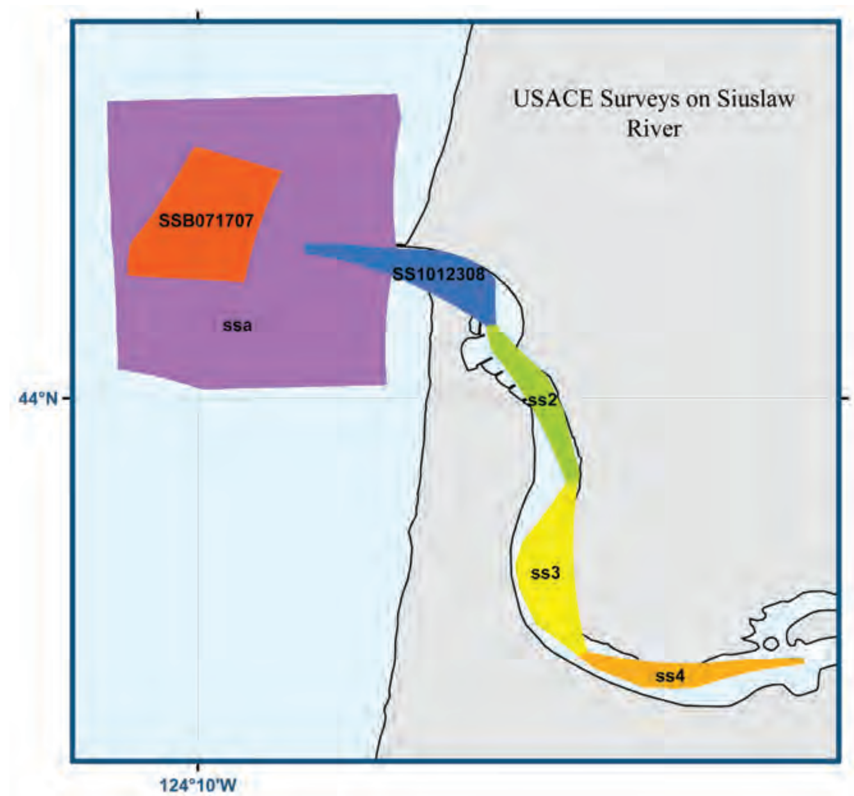

Figure 8. *Spatial coverage of USACE hydrographic channel line and offshore surveys for the Siuslaw River.*

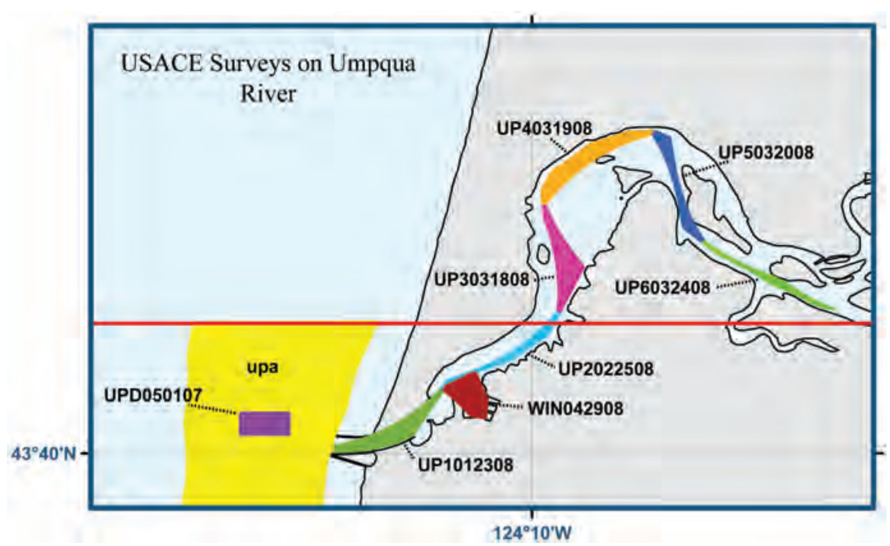

Figure 9. *Spatial coverage of USACE hydrographic channel line and offshore surveys for the Umpqua River.*

3) Multibeam swath sonar files

Eleven multibeam swath sonar surveys were available from the NGDC multibeam database (http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html) for use in the Central Oregon Coast DEM (Table 7, Fig. 10). This database is comprised of the original swath sonar files of surveys conducted mostly by the U.S. academic fleet. Most of the multibeam swath surveys offshore were transits rather than dedicated sea-floor surveys. All have a horizontal datum of WGS 84/NAD 83 geographic and undefined vertical datum, assumed to be equivalent to mean sea level (MSL).

The downloaded data were gridded to 1/3 arc-second resolution using MB-System. MB-System is an NSF-funded free software application specifically designed to manipulate multibeam swath sonar data (http://www.ldeo.columbia.edu/res/pi/MB-System/). The gridded data were converted to shapefiles and transformed to MHW using FME. Individual surveys were evaluated for errors and compared to neighboring high resolution NOS survey data and the RNCs. Techniques used to remove errors included filtering data by elevation using FME, clipping large regions of points using QT Modeler, and editing single points using ArcMap editing tools. Figure 11 shows numerous anomalous elevation values deeper than -10,000 meters in the northern section of the CNTL04RR survey. These values were removed from the survey by filtering out elevations below -500 meters using FME and edited in ArcMap by comparing to neighboring surveys and nautical chart soundings.

Table 7: Multibeam swath sonar surveys used in compiling the Central Oregon Coast DEM.

Cruise ID	*Ship*	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Institution*
AII8L20	Atlantis II	1987	assumed Mean Sea Level	WGS 84 geographic	University of Rhode Island (URI)
AII8L21	Atlantis II	1987	assumed Mean Sea Level	WGS 84 geographic	University of Rhode Island (URI)
AII8L22	Atlantis II	1987	assumed Mean Sea Level	WGS 84 geographic	University of Rhode Island (URI)
RNDB05WT	Washington	1988	assumed Mean Sea Level	WGS 84 geographic	University of California, Scripps Institution of Oceanography (UC/SIO)
SO108	Sonne	1996	assumed Mean Sea Level	WGS 84 geographic	University of Kiel, Germany, GEOMAR Forshungszentrum
Tecfluc	Ocean Alert (1)	1998	assumed Mean Sea Level	WGS 84 geographic	Monterey Bay Aquarium Research Institute (MBARI)
Tran2new	Ocean Alert (2)	1999	assumed Mean Sea Level	WGS 84 geographic	Monterey Bay Aquarium Research Institute (MBARI)
Heceta	Ocean Alert	1998	assumed Mean Sea Level	WGS 84 geographic	Monterey Bay Aquarium Research Institute (MBARI)
LWAD99MV	Melville	1999	assumed Mean Sea Level	WGS 84 geographic	University of California, Scripps Institution of Oceanography (UC/SIO)
AT07L20	Atlantis I	2002	assumed Mean Sea Level	WGS 84 geographic	Woods Hole Oceanographic Institution (WHOI)
AT07L14	Atlantis I	2002	assumed Mean Sea Level	WGS 84 geographic	Woods Hole Oceanographic Institution (WHOI)
CNTL04RR	Revelle	2003	assumed Mean Sea Level	WGS 84 geographic	University of California, Scripps Institution of Oceanography (UC/SIO)

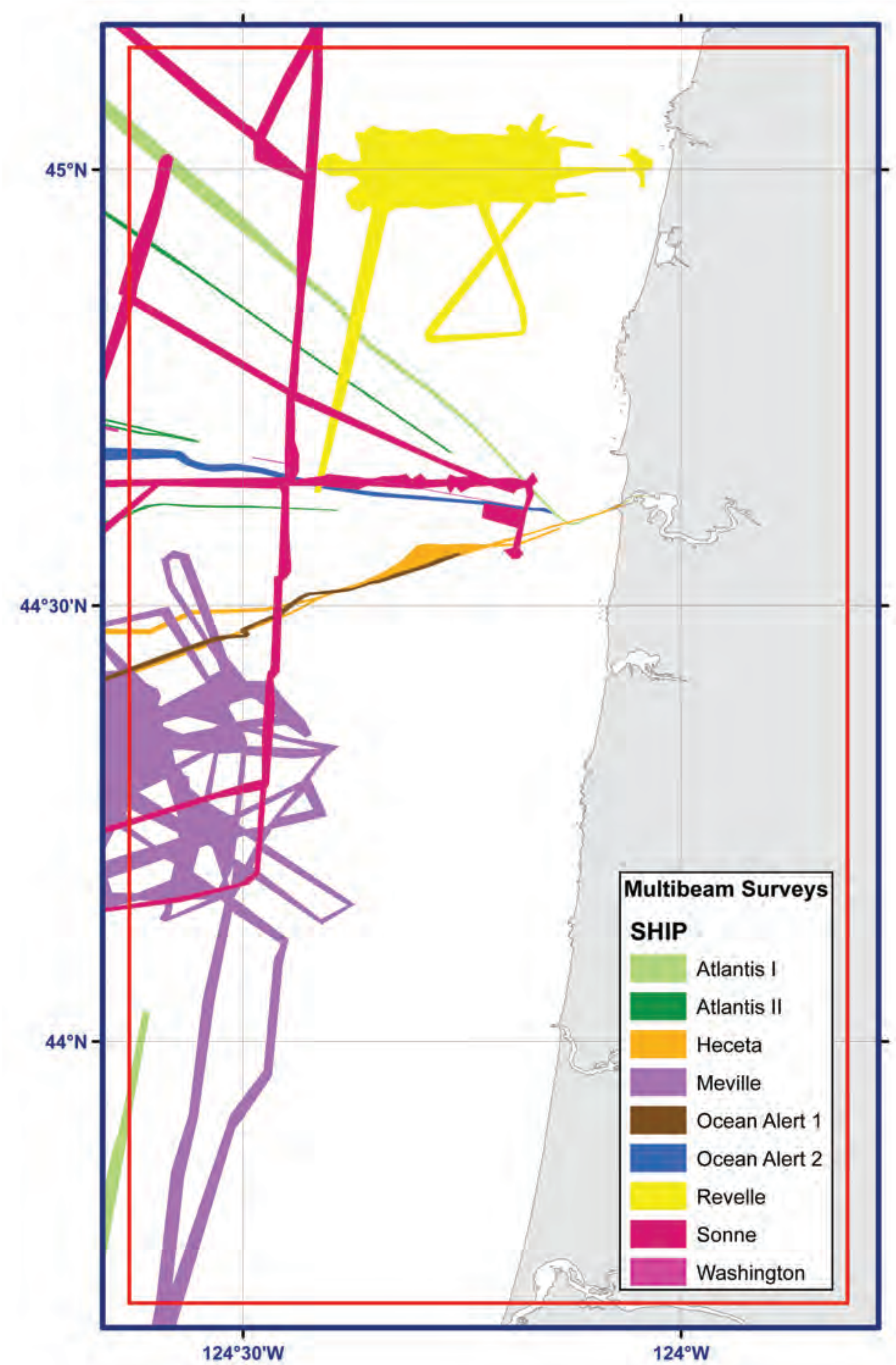

Figure 10. *Spatial coverage of multibeam swath sonar surveys in the NGDC multibeam database that were used in the Central Oregon Coast DEM.*

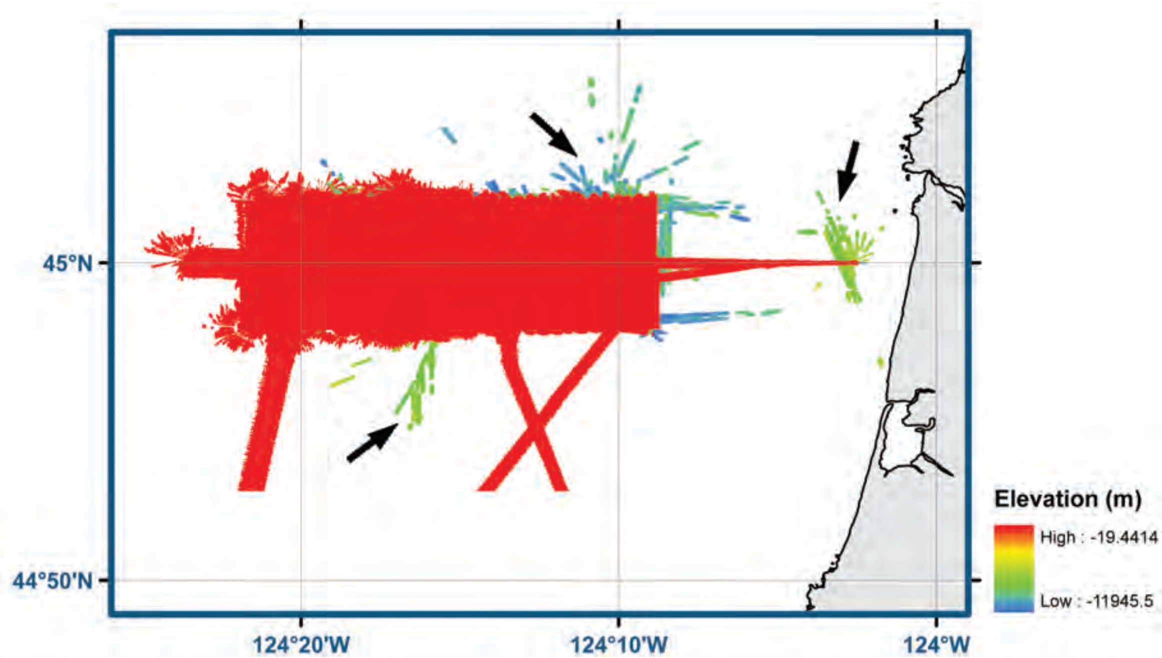

Figure 11. *The CNTL04RR multibeam survey located offshore of Cascade Head and Siletz Bay colored by elevation. The arrows point to areas where elevations were incorrect by hundreds of meters. These values were deleted.*

4) PMEL/OSU Alsea Bay extracted hydrographic survey

PMEL provided NGDC with bathymetric and topographic data of the Alsea Bay area, collected by Oregon State University. Only the bathymetry from this dataset was used for the DEM, as the topographic data were derived from USGS NED DEMs where higher resolution CSC LiDAR data are now available. The bathymetric elevations were extracted from the dataset in xyz format and converted to MHW using FME. Figure 12 shows the extracted points with RNC #18561 for Alsea Bay area in the background.

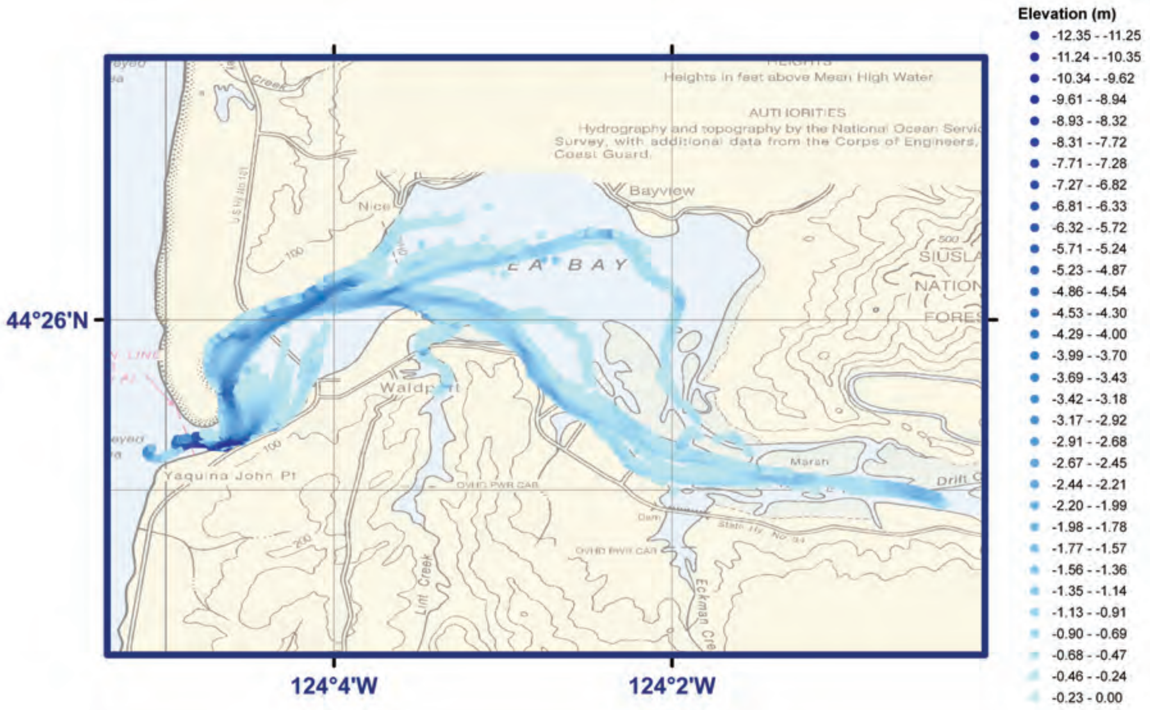

Figure 12. Spatial coverage of PMEL/OSU bathymetric data for Alsea Bay with RNC #18561 in the background.

5) Oregon Department of Fish and Wildlife multibeam survey of Siletz Reef and DEM of Seal Rock

The Oregon Department of Fish and Wildlife (ORDFW) provided NGDC with a 1 meter resolution multibeam survey of Siletz Reef and a 2 meter DEM of Seal Rock (Fig. 13). The multibeam survey data were converted from WGS 84 UTM Zone 10 North horizontal datum and MLLW to NAD 83 geographic and MHW using FME and reviewed in ArcMap. The Seal Rock DEM was converted to MHW using ArcCatalog, converted to points using FME, and reviewed in ArcMap.

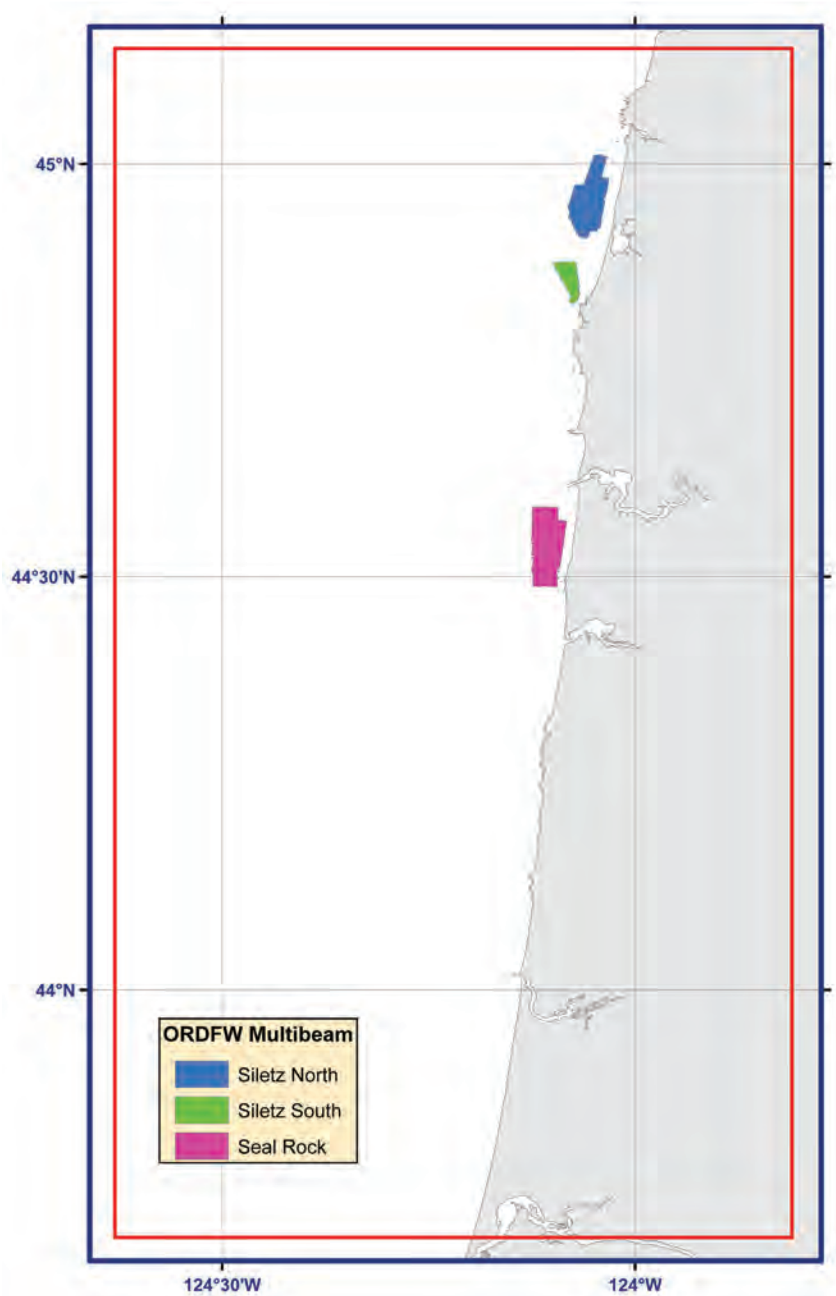

Figure 13. *Spatial coverage of ORDFW multibeam dataset.*

3.1.3 Topography

Five topographic datasets in the Central Oregon coastal region were obtained and used to build the Central Oregon Coast DEM (Table 8; Fig. 14). The USGS NED 1/3 arc-second data provided full coverage for the DEM area and the CSC LiDAR Assessment of Coastal Erosion (ALACE) Project high-resolution data covered the entire coastline. An approximate 1 km^2 section of the Shuttle Radar Topography Mission (SRTM) Elevation 1 arc-second DEM was used, as was a selection of land elevation points extracted from the two ENCs available within the DEM area. NGDC also digitized some coastal features not fully resolved in the NED, CSC, and SRTM datasets.

Table 8: Topographic datasets used in compiling the Central Oregon Coast DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
USGS NED	1999	topographic DEM	1/3 arc-second	NAD 83 geographic	NAVD88 (meters)	http://ned.usgs.gov/
CSC ALACE	1997 - 2002	LiDAR points	~2 meters	NAD 83 geographic	NAVD88 (meters)	http://maps.csc.noaa.gov/TCM/
NASA SRTM	2000	topographic DEM	1 arc-second	WGS 84 geographic	NAVD88 (meters)	http://seamless.usgs.gov/
ENC land elevations	2008	S-57 extracted points		WGS 84 geographic	MHW	http://chartmaker.ncd.noaa.gov/MCD/enc/index.htm
NGDC digitized jetties		digitized points		WGS 84 geographic	MHW	

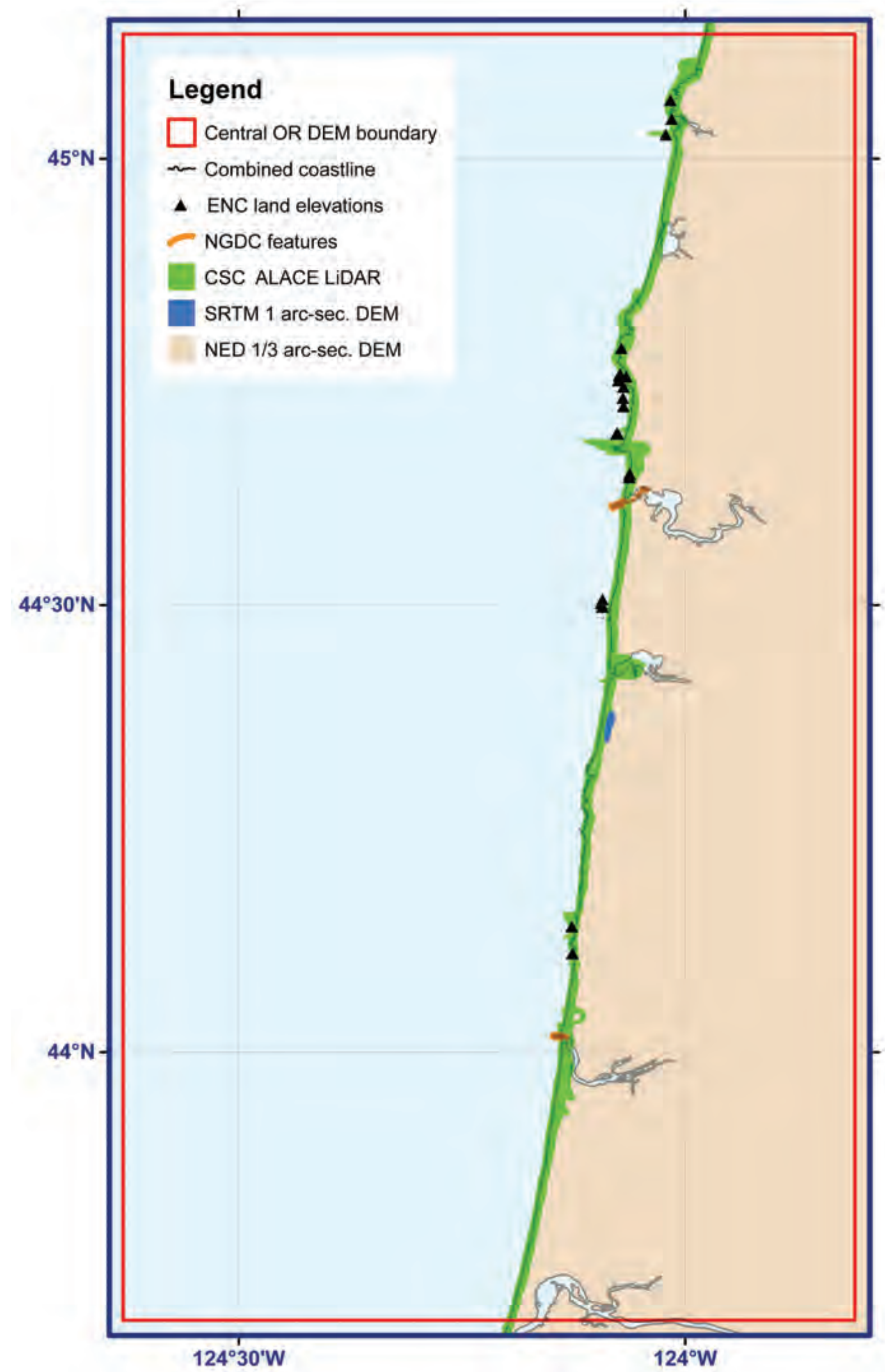

Figure 14. *Spatial coverage of topographic datasets used in compiling the Central Oregon Coast DEM.*

1) USGS NED topographic 1/3 arc-second DEMs

The U.S. Geological Survey (USGS) National Elevation Dataset (NED; http://ned.usgs.gov/) provides complete 1/3 arc-second coverage of the Central Oregon Coast coastal region[4]. Data are in NAD 83 geographic coordinates and NAVD88 vertical datum (meters), and are available for download as raster DEMs. 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; it has been revised using data collected in 1999. The NED DEMs were transformed to NAD 83 and MHW using Arc Catalog tools. The gridded data were evaluated in ArcMap and positive elevations over open water were removed by clipping data to the 'combined' coastline using Arc Catalog tools. The resulting data were converted to points with FME. Some land features were not resolved in the NED data. Figure 15A shows the NED data at Yaquina Harbor without the jetties and smaller harbor features visible in Figure 15B.

***Figure 15.** Comparison of the NED 1/3 arc-second DEM shown in QT Modeler (A) and USACE aerial photograph (B) of Yaquina Harbor. Note absence of jetties in the NED DEM at mouth of river. Photo from U.S. Army Corps of Engineers Digital Visual Library (https://eportal.usace.army.mil/sites/DVL/default.aspx).*

4. 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 NAD 83, except for AK, which is NAD 27. 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]

2) CSC ALACE LiDAR Project topography

The NASA/USGS Airborne LiDAR Assessment of Coastal Erosion (ALACE) Project topographic LiDAR data from 1997, 1998, and 2002 were downloaded from the NOAA CSC website (http://maps.csc.noaa.gov/TCM/) and transformed to NAD 83 and MHW using FME. As these data were not processed to bare earth and contained elevation values over open water as well as vegetation and buildings, NGDC processed the data using FME to simulate bare earth. The data were compared to the USGS NED topographic DEM and points were retained where the difference in elevation between the NED and the LiDAR data points was less than 12 meters. Most tall buildings and vegetation were eliminated while the high sand dunes and berms along the beaches remain. Figure 16 shows a comparison of a section of the LiDAR data before processing (image A) and after processing (image B). This technique also created a smoother seam between the topographic datasets in most areas. The data were clipped to the Central Oregon Coastline and filtered to remove elevation points located over ocean.

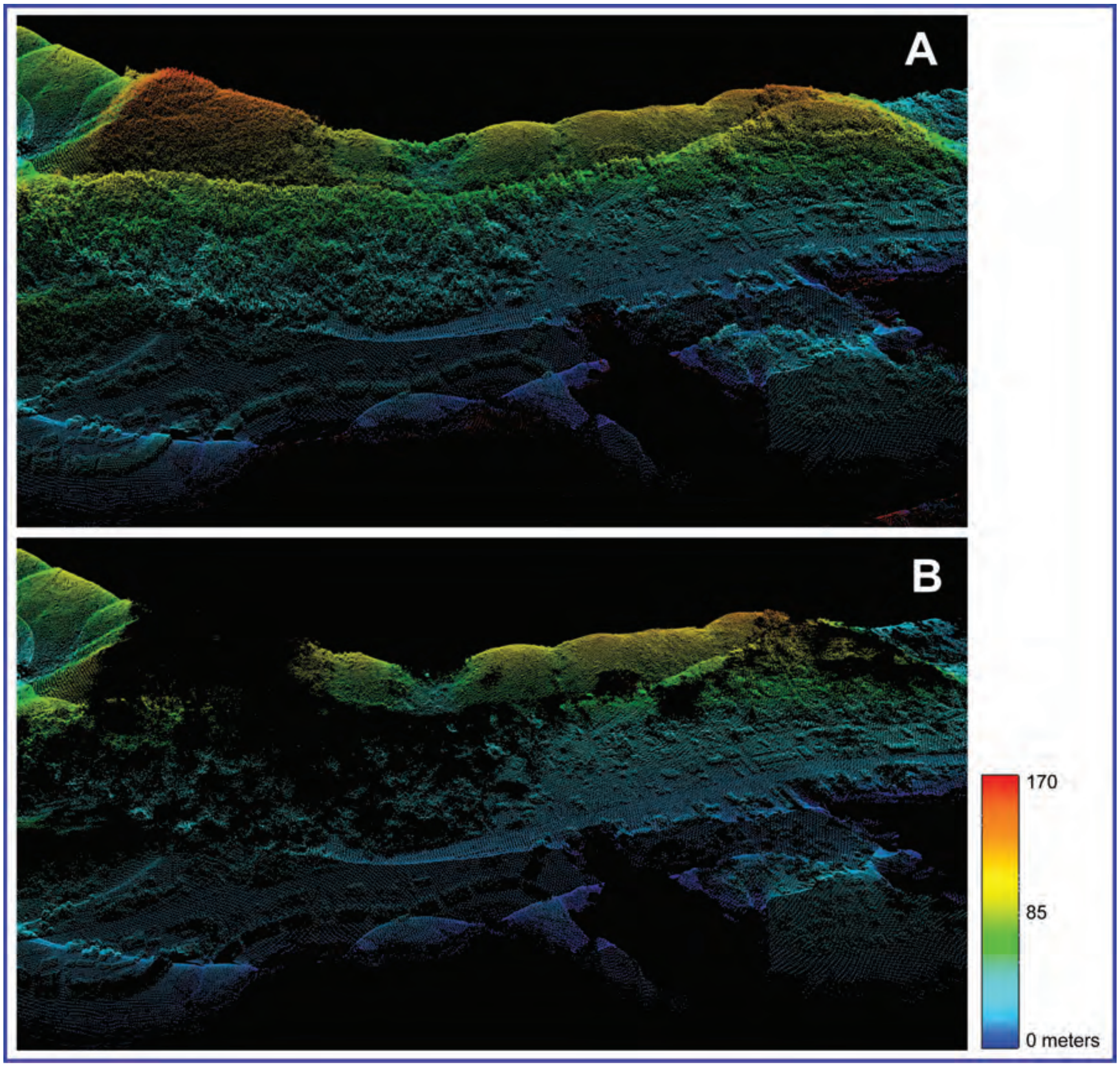

Figure 16. *Comparison of CSC 2002 ALACE LiDAR data before NGDC processing (image A) and post-processing (image B).*

3) NASA SRTM 1 arc-second DEM

The SRTM 1 arc-second DEM data[5] was used in lieu of the NED data near Placer Lake ~7 km south of Waldport where the transition from LiDAR to NED created a step of up to 8 meters in a preliminary DEM (Fig. 17). The SRTM DEM more accurately captured the topography of the area when compared to the CSC LiDAR data. The SRTM DEM was downloaded from the USGS seamless website and transformed from NAVD88 to MHW using ArcCatalog tools. A mask was created by converting a polygon of the area to a raster using ArcCatalog tools and clipping out the selection from the SRTM DEM. The selection was converted to points and transformed to MHW using FME for use in the final gridding process.

Figure 18 shows Google Earth imagery (perspective view from the west) of the same area near Placer Lake as depicted in Figure 17. The area circled in yellow shows where SRTM data points were substituted for the NED data. Figure 19 shows the final Central Oregon Coast DEM at approximately the same location and perspective.

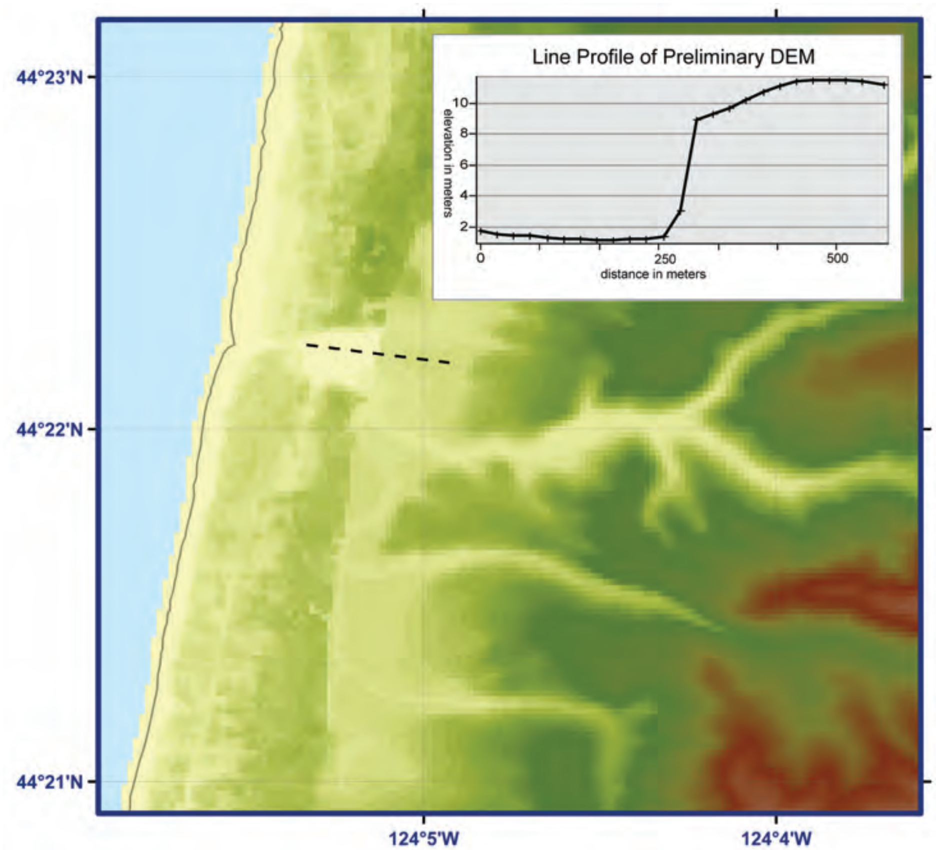

Figure 17. *Detail image of a preliminary DEM showing 'step' in elevation in the Placer Lake area. SRTM data were substituted for NED data to minimize dataset transition errors.*

5. 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]

Figure 18. *Aerial photo of Placer Lake from Google Earth imagery. Yellow line indicates where SRTM data replaced NED data in building the Central Oregon Coast DEM.*

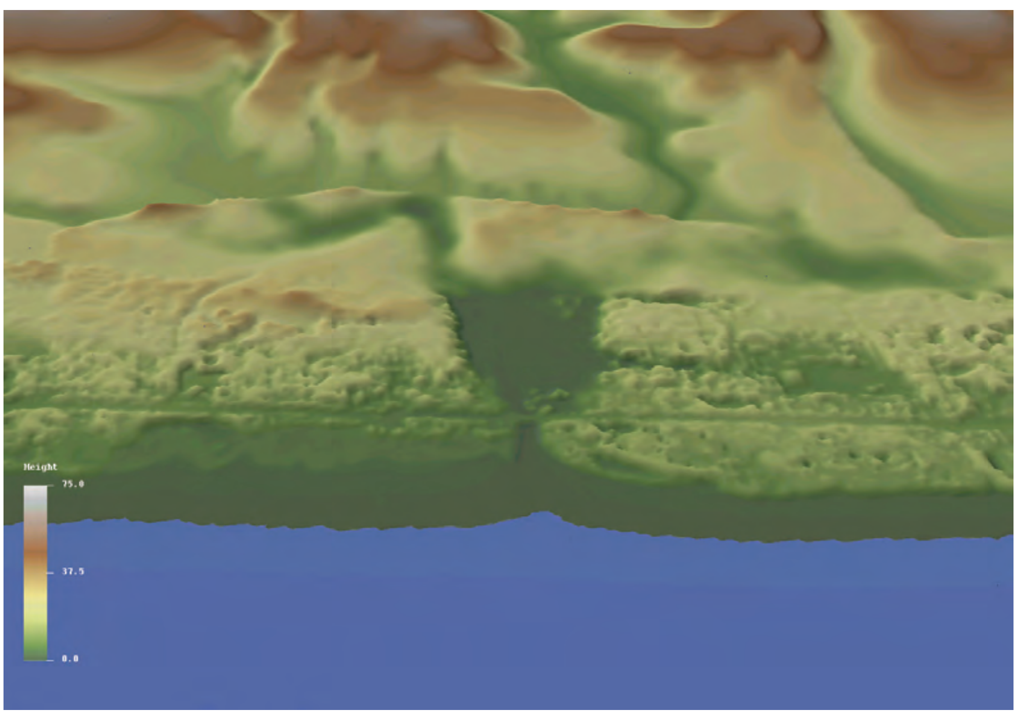

Figure 19. *Quick Terrain Modeler image of final Central Oregon Coast DEM at Placer Lake with similar perspective as Figure 18. Edge effects remain at this location but are significantly reduced.*

4) Extracted ENC S-57 land elevations

Land elevation points located on offshore rocks and islets were extracted from ENCs #18520 and #18580 (Fig. 20) as no elevation data were available in the other topographic datasets for these features. For rocks present in the 'combined' coastline with no associated digital elevations, NGDC digitized elevation values based on USGS topographic quads and NOAA RNCs.

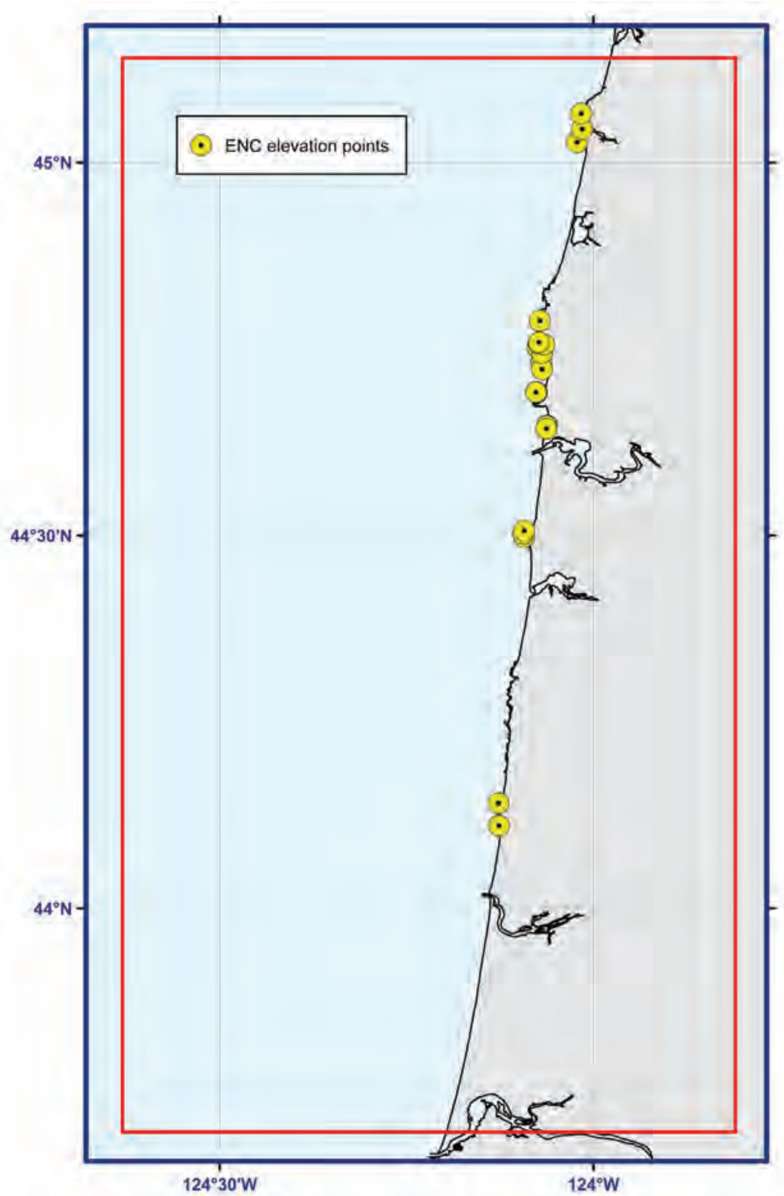

Figure 20. *The spatial coverage of the extracted ENC land elevation data.*

5) NGDC digitized jetties

The jetties at Yaquina River and Siuslaw River were not fully resolved in either the NED DEM or the CSC coastal LiDAR datasets. To ensure these features were represented in the final Central Oregon Coast DEM, NGDC digitized the jetties and assigned them elevations listed on the USACE Coastal Inlets Research Program website (http://cirp.wes.army.mil/cirp/). The features are shown in USACE aerial photos in figures 21 and 22 (https://eportal.usace.army.mil/sites/DVL/default.aspx).

Figure 21. *Aerial photo of Yaquina River jetties. Photo from U.S. Army Corps of Engineers Digital Visual Library (https://eportal.usace.army.mil/sites/DVL/default.aspx).*

Figure 22. *Aerial photo of Siuslaw River Jetties. Photo from U.S. Army Corps of Engineers Digital Visual Library (https://eportal.usace.army.mil/sites/DVL/default.aspx).*

ESRI shapefiles were created in ArcCatalog with point spacing of 5 meters and elevation values at MHW of 3.53 and 3.84 meters for Siuslaw jetty and 3.77 meters for Yaquina jetty. The breakwater in Yaquina Bay was added to the coastline and assigned a MHW elevation of 1 meter. Submerged groins located at the Yaquina inlet on the south side and at the end of the north jetty were not added to the coastline but were digitized and set to zero meters (Fig. 23). The north and south jetties of Siuslaw River were set to MHW elevations of 3.84 and 3.53 meters respectively (Fig. 24). After the topographic data were viewed in ArcMap to ensure the transitions between datasets were smooth, the data were converted to xyz format using FME for the final gridding process.

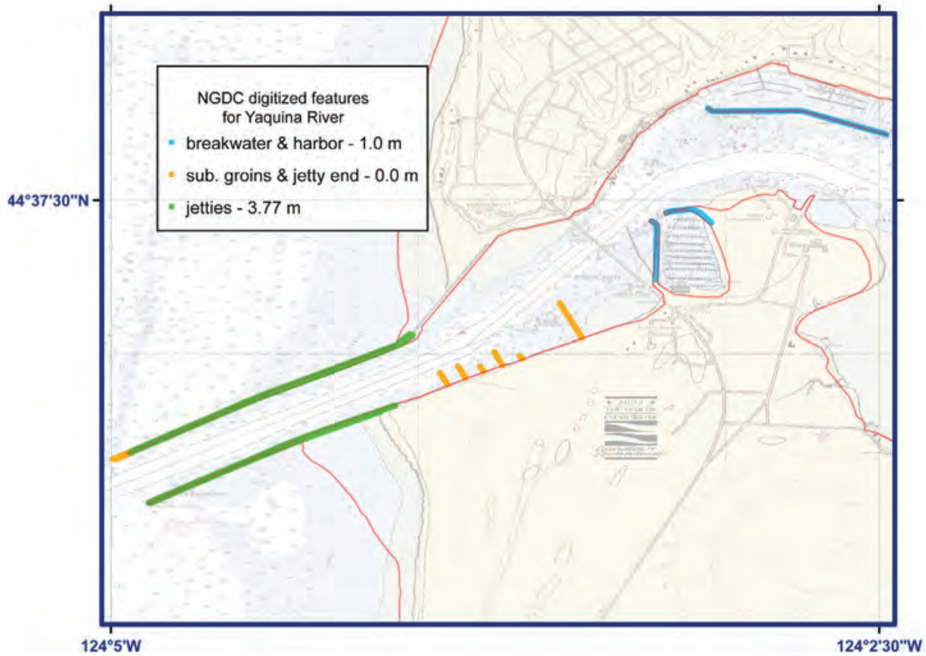

Figure 23. *NGDC digitized features at Yaquina River.*

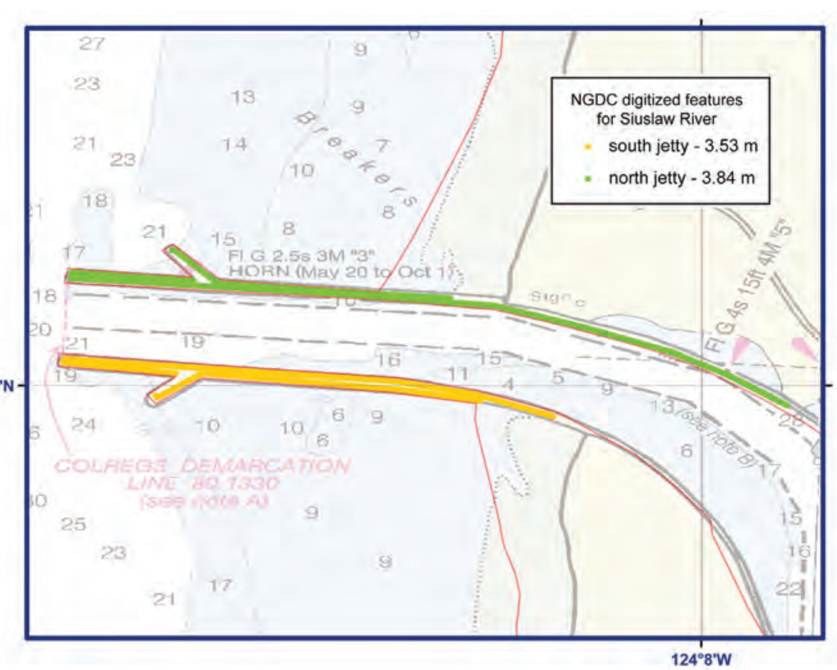

Figure 24. *NGDC digitized features at Siuslaw River.*

3.2 Establishing Common Datums

3.2.1 *Vertical datum transformations*

Datasets used in the compilation and evaluation of the Central Oregon Coast DEM were originally referenced to a number of vertical datums including Mean Lower Low Water (MLLW), Mean Sea Level (MSL), and NAVD88. All datasets were transformed to MHW to provide the maximum flooding for inundation modeling. Units were converted from feet to meters as appropriate.

1) **Bathymetric data**

NGDC created two offset grids approximating the relationship between MLLW and MHW, and MSL and MHW for the west coast of Oregon and Washington. The grids were built in ArcGIS using the Inverse Distance Weighting (IDW) tool and the differences between the vertical datums as measured at 25 NOAA tide stations in the area (http://tidesandcurrents.noaa.gov/). The grids spanned from 40.7167° to 48.4167° N, and 124.6867° to 122.8868° W with a grid cell size of 0.1 degrees. The NOS hydrographic surveys, USGS and NGDC multibeam surveys, and USACE surveys were transformed from MLLW and MSL to MHW, using FME software, by adding the appropriate offset grid.

2) **Topographic data**

NGDC created an offset grid approximating the relationship between NAVD88 and MHW along the Pacific Northwest coast. The grid was built in ArcGIS using the Inverse Distance Weighting (IDW) tool and the difference between the vertical datums as measured at 16 NOAA tide stations in the region (http://tidesandcurrents.noaa.gov/). The grids spanned from 40.7167° to 48.4167° N, and 124.6867° to 122.8868° W with a grid cell size of 0.1 degrees. The USGS NED 1/3 arc-second DEMs and the CSC topographic LiDAR data were originally referenced to NAVD88. The datasets were converted to MHW by adding the offset grid using FME.

Table 9. Relationship between Mean High Water and other vertical datums at the South Beach tide station #9435380 (Fig. 32).

Vertical datum	*Difference to MHW in meters*
MSL	-0.972
NAVD88	-2.105
MLLW	-2.330

3.2.2 *Horizontal datum transformations*

Datasets used to compile the Central Oregon Coast DEM were originally referenced to WGS 84 geographic, NAD 83 geographic, NAD 27 geographic, NAD 83 Oregon State Plane North, and NAD 83 UTM Zone 10 North datums. The relationships and transformational equations between these horizontal datums are well established. All data were converted to a horizontal datum of NAD 83 geographic using FME software or ArcGIS.

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 checked in ArcMap for consistency between datasets. 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:

- Suspect topographic elevations located on open-ocean in both NED and LiDAR datasets.
- Inconsistencies between the NED and LiDAR topographic data.
- Data errors in multibeam swath sonar surveys, which were expressed as anomalous spikes and groups of excessively deep elevations. Manual editing of the gridded multibeam sonar data were necessary to minimize these artifacts.
- Topographic CSC LiDAR dataset not processed to bare earth. The dataset required filtering of elevation values on land and removal of returns from the water surface.
- Digital bathymetric values from NOS surveys date back over 100 years. More recent data, such as the USACE hydrographic survey depths, differed from older NOS data by as much as 10 meters nearshore and up to 75 meters in deeper water compared to multibeam data. The older NOS survey data were excised where more recent bathymetric data exists.
- Topographic features not represented in any digital dataset. NGDC digitized these features for representation in the Central Oregon Coast DEM.

3.3.2 Smoothing of bathymetric data

The NOS hydrographic surveys are generally sparse at the resolution of the 1/3 arc-second Central Oregon Coast DEM: in both deep water and in some areas close to shore, the NOS survey data have point spacing up to 1900 m apart. In order to reduce the effect of artifacts in the form of lines of "pimples" in the DEM due to these low-resolution datasets, 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 share-ware software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/). Figure 24 shows a preliminary gridded bathymetric surface, with low-resolution NOS hydrographic survey H04753 points and the corresponding smooth sheet overlay. Anomalous features in preliminary surfaces were examined for digitizing errors against the smooth sheets and RNCs.

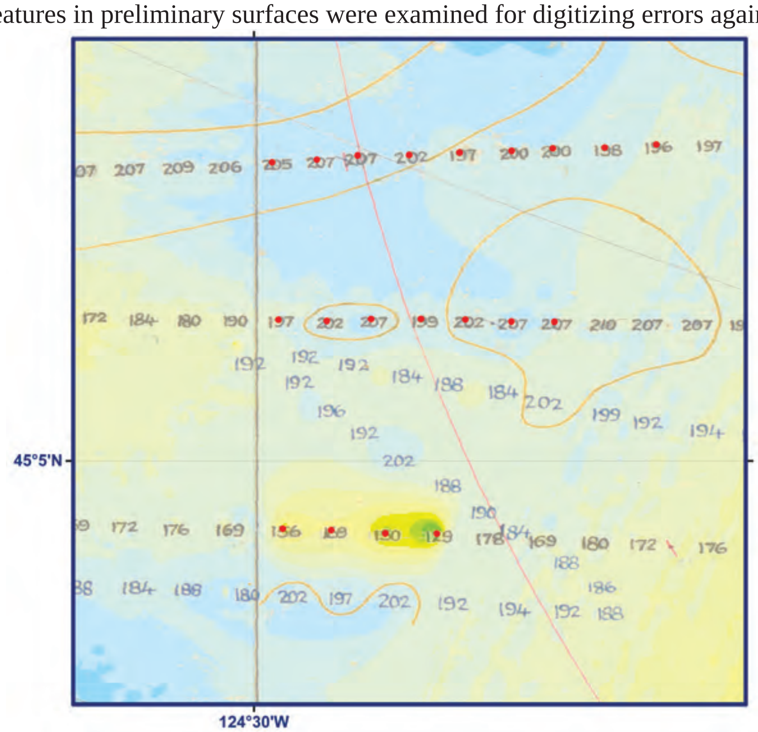

Figure 25. *A preliminary bathymetric surface showing local highs derived from low resolution older NOS hydrographic surveys. These points were not removed from the survey data as they reflect local relief and not digitizing errors.*

The NOS hydrographic point data, in xyz format, were clipped to remove overlap with the USACE soundings, NGDC multibeam data, ORDFW multibeam survey data, and nautical chart sounding data. The data were then combined 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 a bathymetric surface below zero in areas where data are sparse or non-existent.

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 Central Oregon Coast 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. 25) and exported as an xyz file for use in the final gridding process (see Table 10).

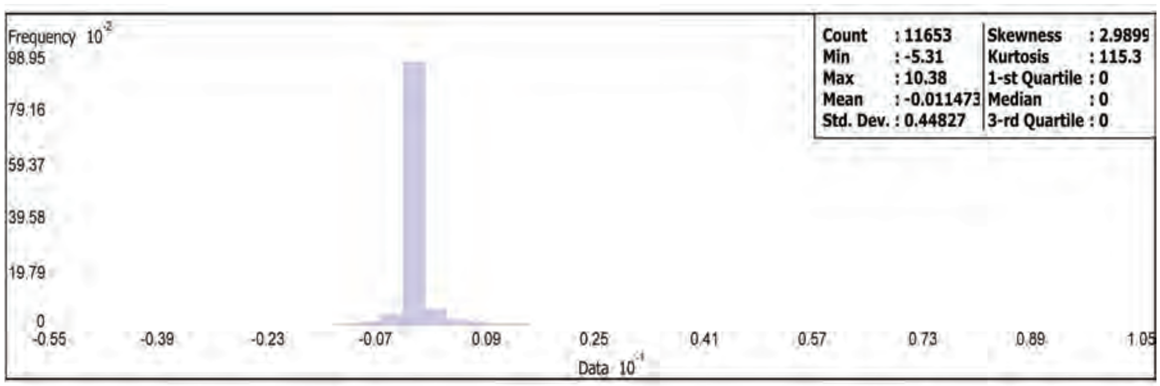

Figure 26. *Histogram of the differences between NOS hydrographic survey H08040 and the 1 arc-second pre-surfaced bathymetric grid.*

3.3.3 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 Central Oregon Coast DEM. MB-System is an NSF-funded free software application specifically designed to manipulate multibeam swath 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 10. Greatest weights were given to the USACE surveys, PMEL/OSU bathymetry, ORDFW Multibeam surveys, 2002 CSC LiDAR data, NGDC digitized jetty and ENC extracted land elevations. 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 Central Oregon Coast DEM.

Table 10. Data hierarchy used to assign gridding weight in MB-System.

Dataset	*Relative Gridding Weight*
NOS hydrographic surveys	10
NGDC Multibeam surveys	10
USACE surveys	1,000
PMEL/OSU bathymetry	1,000
ORDFW Multibeam surveys	1,000
Pre-surfaced bathymetric grid	1
Central Oregon Coast coastline	1
CSC 2002 ALACE topographic LiDAR	1,000
CSC 1998 ALACE topographic LiDAR	10
CSC 1997 ALACE topographic LiDAR	10
USGS NED topographic DEM	10
NGDC digitized jetty	1,000
ENC extracted land elevations	1,000
NASA SRTM topographic DEM	100

3.4 Quality Assessment of the DEM

3.4.1. Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Central Oregon Coast DEM is dependent upon the datasets used to determine corresponding DEM cell values. Topographic features have an estimated accuracy of 10 meters along the coast and greater inland: CSC topographic LiDAR data have accuracy between 1 and 3 meters; NED topography is documented to be accurate to within about 10 meters and the SRTM topography between 10 and 20 meters. Figure 27 illustrates the significant difference between the NED and SRTM data. Contour lines were generated for both of the topographic DEM datasets using ArcCatalog tools. The figure shows the 25 and 75 meter contours depicting geologic features that are similar in shape but offset by as much as 500 meters in low lying areas. At higher elevations, the offset decreases. Bathymetric features are resolved only to within a few tens of meters in deep-water areas. Shallow, near-coastal regions, rivers, and harbor surveys have an accuracy approaching that of sub-aerial coastal topographic features. Positional accuracy is limited by: the sparseness of deep-water soundings, potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys, and by manmade morphologic change (e.g., channel dredging and building of jetties).

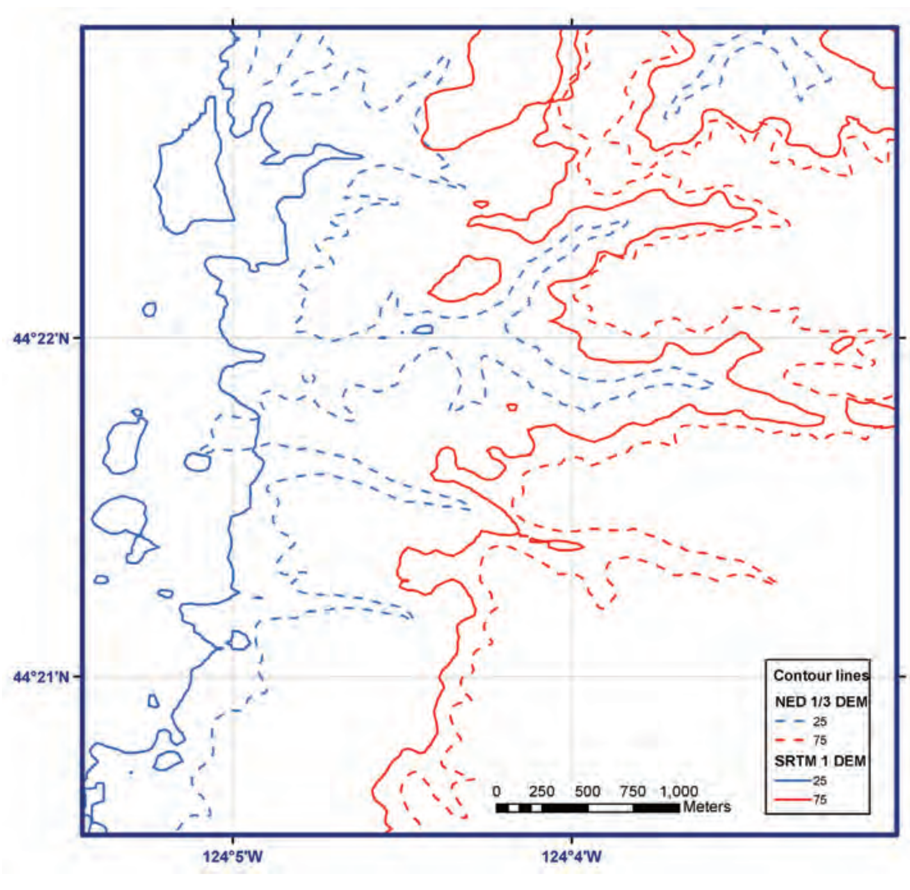

Figure 27. *Comparison of NED and SRTM contour lines.*

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the Central Oregon Coast 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 CSC 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. Those values were derived from the wide range of input sounding data 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 Central Oregon Coast DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (e.g., Fig. 28). The DEM was transformed to UTM Zone 10 coordinates (horizontal units in meters) in ArcCatalog for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Three-dimensional viewing of the UTM-transformed DEM was accomplished using ESRI ArcScene. Figure 29 shows a color perspective view of the 1/3 arc-second Central Oregon Coast DEM in its final version.

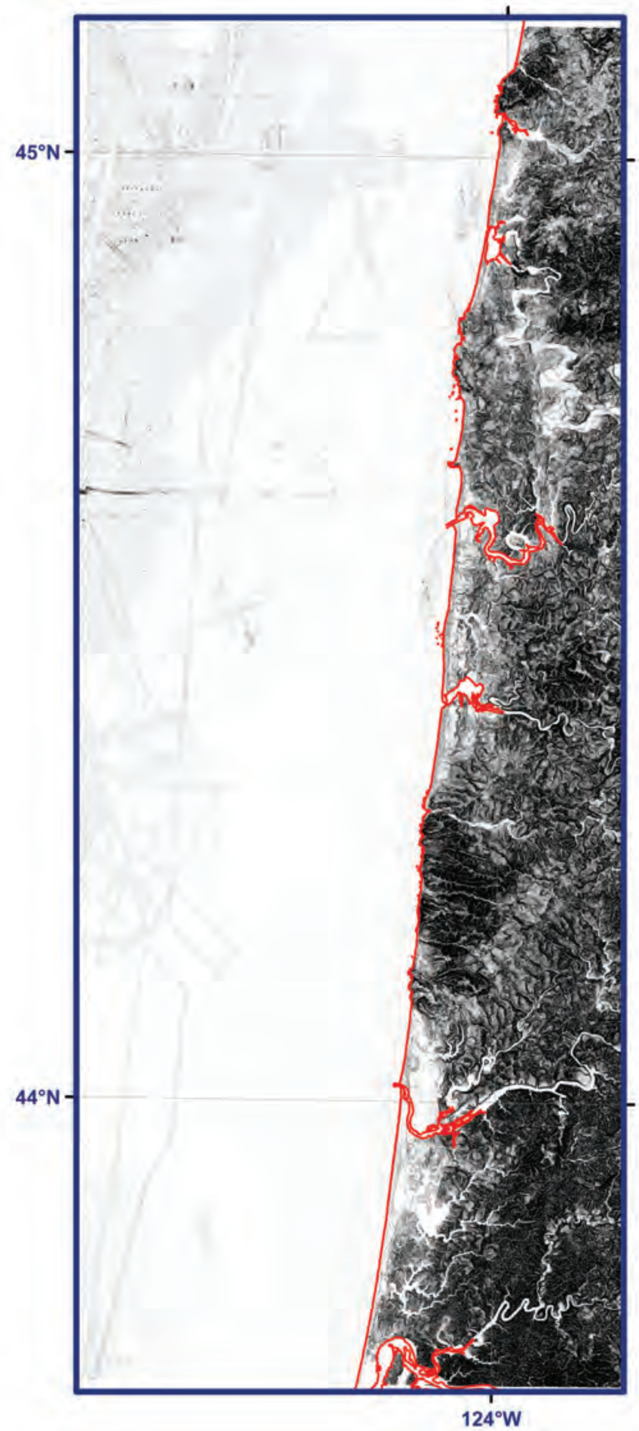

Figure 28. *Slope map of the Central Oregon Coast DEM. Flat-lying slopes are white; dark shading denotes steep slopes; Central Oregon Coast coastline in red.*

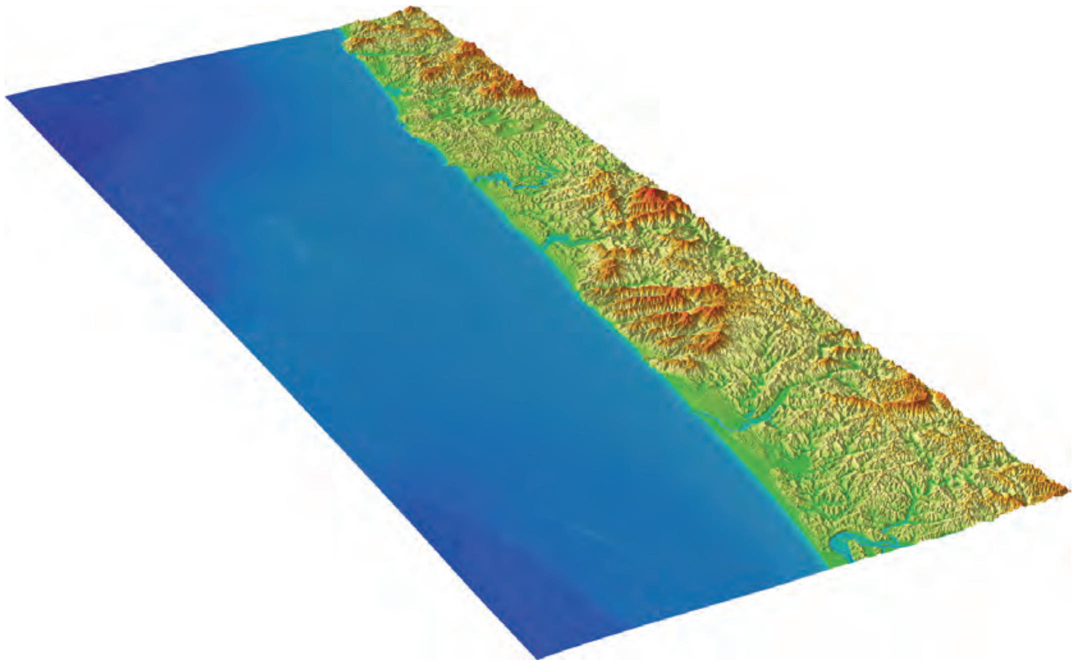

Figure 29. *Perspective view from the southwest of the Central Oregon Coast DEM. 2x vertical exaggeration.*

3.4.4 Comparison with source data files

To ensure grid accuracy, the Central Oregon Coast 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 the DEM and a section of CSC ALACE LiDAR survey file, located at Siletz and Depoe Bay, is shown in Figure 30. Differences range from -88.62 to 79.93 meters. Negative values result from the elevation of the LiDAR data being higher than the DEM elevation. The areas with the greatest differences are on heavily vegetated, steep hillsides.

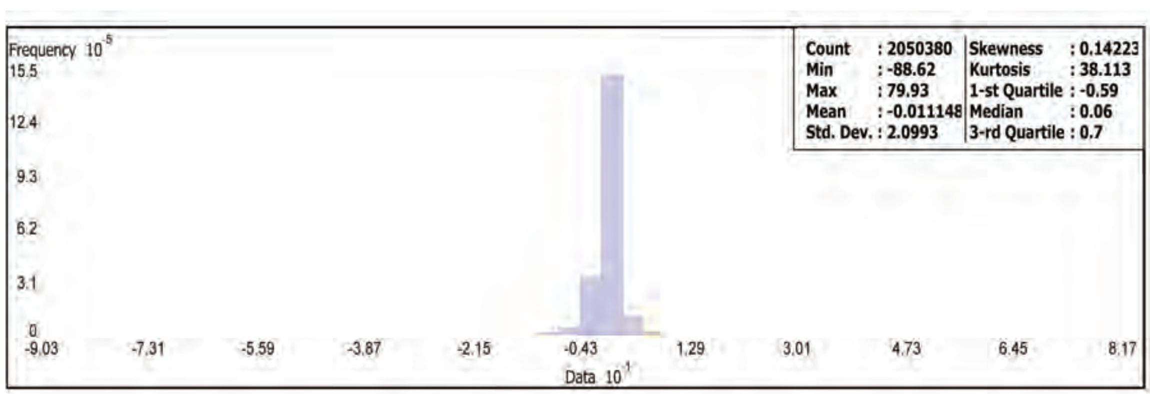

Figure 30. *Histogram of the differences between a section of the CSC ALACE LiDAR survey and the Central Oregon Coast DEM.*

3.4.5 Comparison with NGS geodetic monuments

The elevations of 814 NOAA NGS geodetic monuments were extracted from online shape files of monument datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), which give monument positions in NAD 83 (typically sub-mm accuracy) and elevations in NAVD88 (in meters). Monuments installed on lighthouses or buildings were not included in the assessment of the DEM.

Elevations were shifted to MHW vertical datum (see Table 10) for comparison with the Central Oregon Coast DEM (see Fig. 30 for monument locations). Differences between the Central Oregon Coast DEM and the NGS geodetic monument elevations range from -72.94 to 95.24 meters, with the majority of them within ± 12 meters (Fig. 32). Negative values indicate that the DEM is less than the monument elevation. Monuments located on steep embankments, installed on trees, and lost monuments had the greatest negative values. The monuments with the greatest positive values were either lost or located on ridgelines or in areas with steep terrain. NGS lists the horizontal accuracy of some of these monuments as ± 6 arc-seconds (~180 meters).

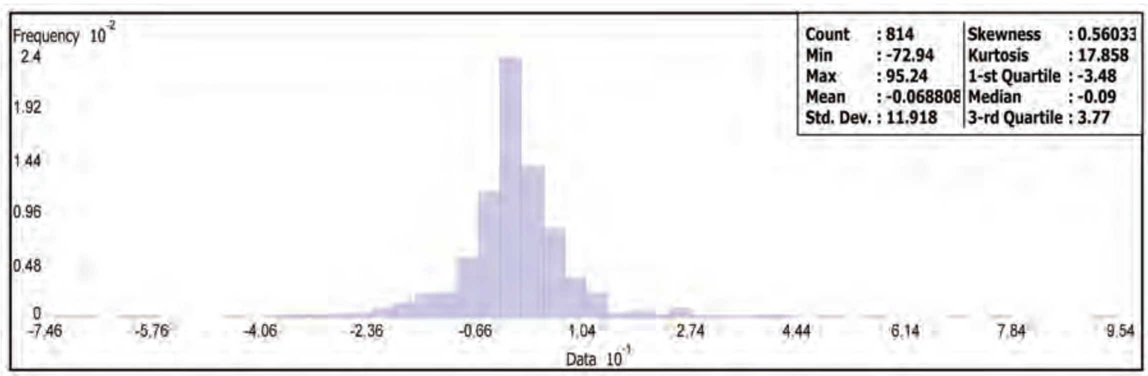

Figure 31. *Histogram of the differences between NGS geodetic monument elevations and the Central Oregon Coast DEM.*

Figure 32. *Location of NGS geodetic monuments, shown as green triangles, and the NOAA South Beach tide station, yellow circle. NGS monument elevations were used to evaluate the DEM.*

4. Summary and Conclusions

An integrated bathymetric–topographic digital elevation model of the Central Oregon coastal region, with cell spacing of 1/3 arc-second, 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 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, MB-System, and Quick Terrain Modeler software.

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

- Conduct hydrographic surveys for near-shore areas, especially in bays and river inlets.
- Complete bathymetric–topographic LiDAR surveying of entire region, especially within coastal zones.
- Process CSC topographic LiDAR data to bare earth.
- Re-survey older, low-resolution NOS hydrographic surveys in deeper waters.

5. Acknowledgments

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7. Data Processing Software

ArcGIS v. 9.2, developed and licensed by ESRI, Redlands, Oregon, 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, free software developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas/

GMT v. 4.1.4 – Generic Mapping Tools, free software 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, free software 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 (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/