Digital Elevation Model of Taholah, Washington: Procedures, Data Sources and Analysis

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1. Introduction

The National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), has developed an integrated bathymetric–topographic digital elevation model (DEM) of Taholah, Washington, (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 Taholah DEM.

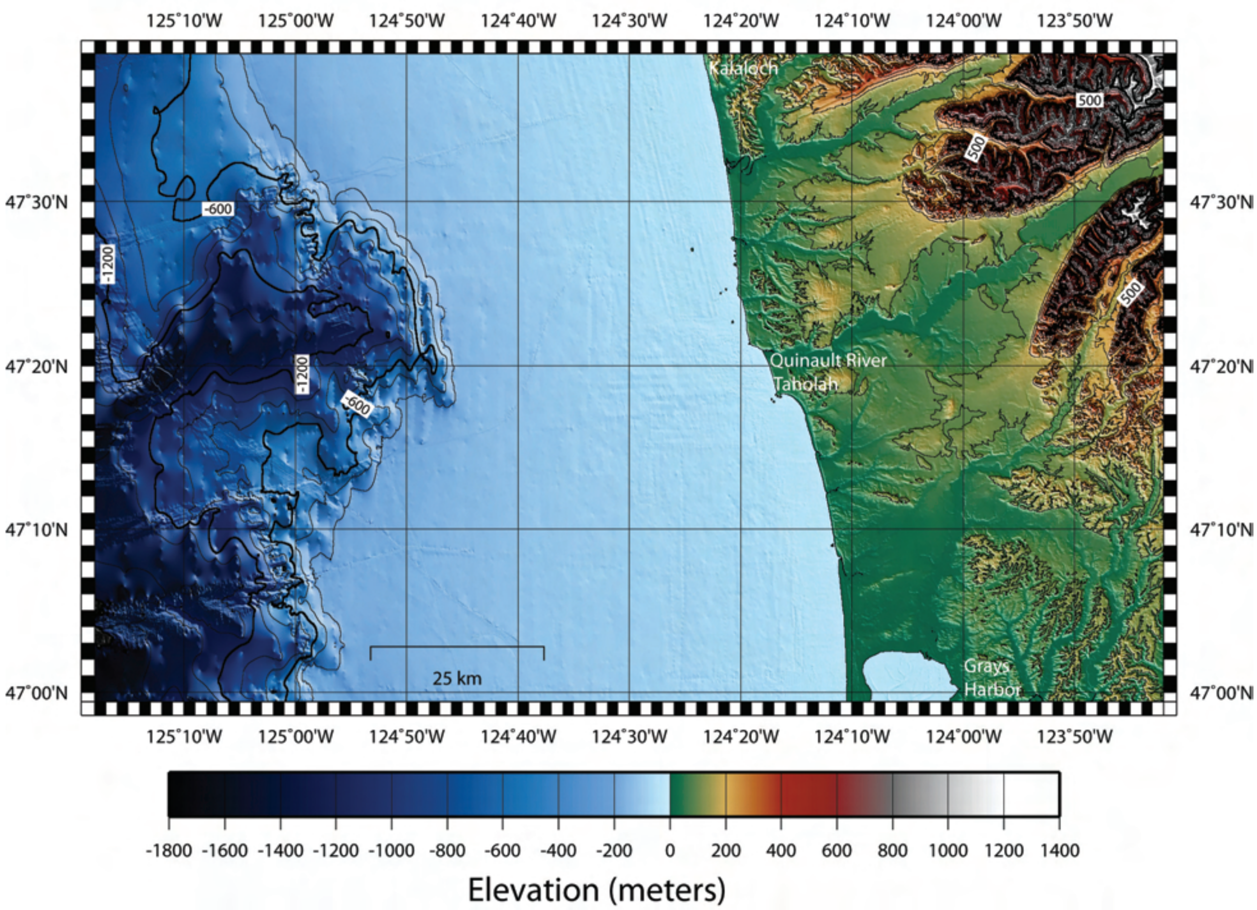

Figure 1. *Shaded-relief image of the Taholah, Washington DEM. Contour interval is 200 meters for bathymetry and 100 meters for topography.*

1. The Taholah 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 Taholah, Washington, (47°20.44′ N, 124°17.15′ W) 1/3 arc-second of latitude is equivalent to 11.12 meters; 1/3 arc-second of longitude equals 7.56 meters.

2. Study Area

The Taholah DEM covers the southern to central coastline of Washington from Grays Harbor to Kalaloch (Fig. 1). It overlaps the southern region of NGDC's La Push DEM (http://www.ngdc.noaa.gov/dem/showdem.jsp?dem=La%20Push&state=WA&cell=1/3%20arc-second) and the northern region of NGDC's Astoria DEM (http://www.ngdc.noaa.gov/dem/showdem.jsp?dem=Astoria&state=OR&cell=1/3%20arc-second) by approximately 11 km, providing complete coverage of the Pacific coastline of Washington. Taholah, population of approximately 900, is located at the mouth of the Quinault River (Fig. 1).

The Washington coastline is unstable and continually eroding from wave action because of exposed softer sedimentary rocks. There are three main rock formations in the Taholah region: the Hoh rock assemblage of more resistant sandstone and conglomerate, the Quinault Formation of softer sandstones rich in marine fossils and sedimentary structures, and the Late Cenozoic deposits of semi-consolidated silt, sand, and gravel. The soft rocks are easily eroded, creating landslide hazards. Evidence of this can be seen south of Taholah where extensive slumped cliffs exist (Fig 2A). North of Taholah, erosion-resistant rocks can be seen in the rocky headlands (Fig 2B). A unique feature in the Taholah region is a large gas mound, called the Garfield Gas Mound, found approximately a quarter mile inland from the mouth of the Quinault River. Natural gas seeps out of a mud-filled vent from the mound that is several hundred feet in diameter and about 50 feet above the surrounding terrain. The gas is derived from the Hoh rock formation, and has been tested for petroleum though none was found (http://www.nps.gov/history/history/online_books/geology/publications/state/wa/1980-72/preface.htm).

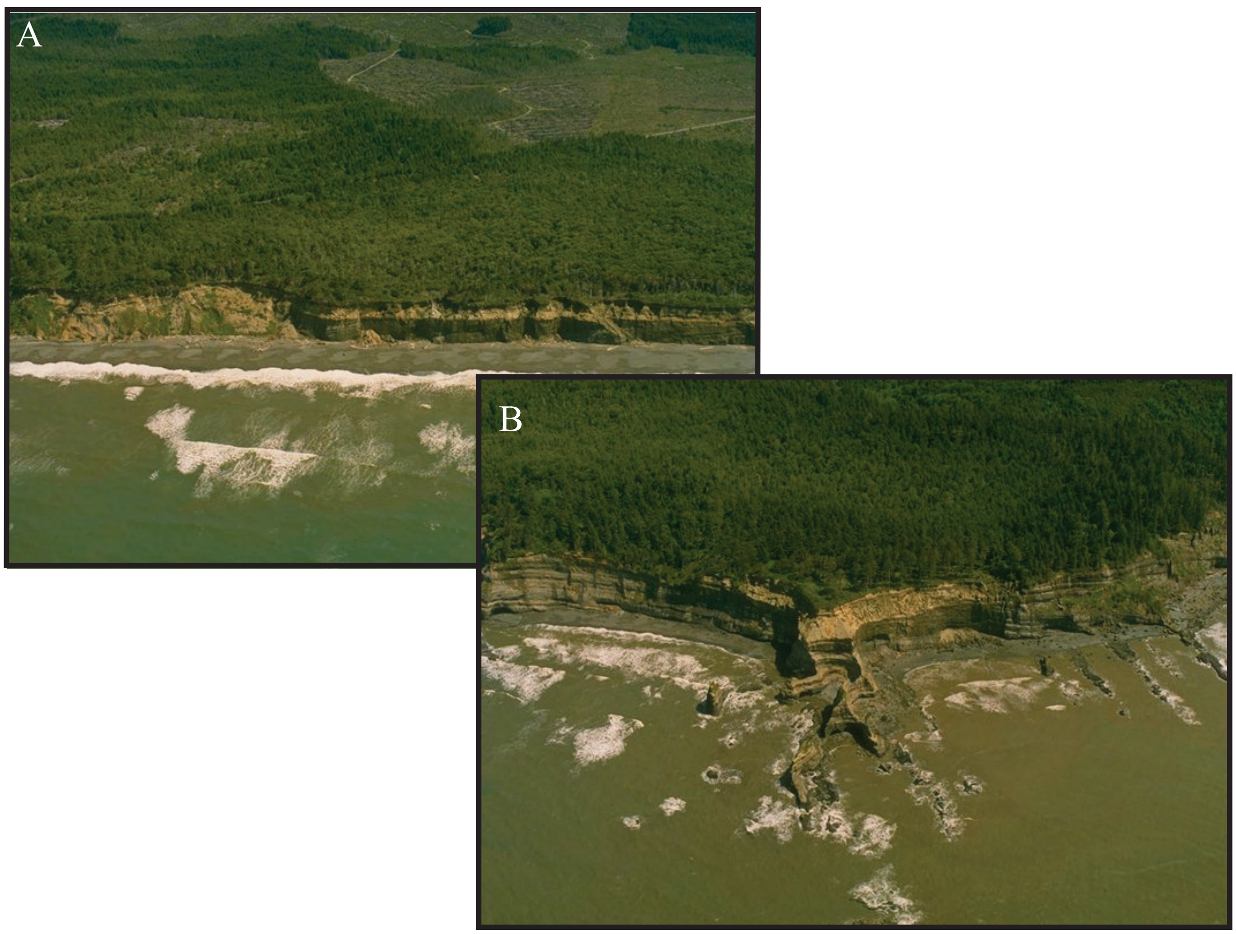

Figure 2. *Aerial photographs of the Washington coast; A) slump due to erosion just south of Taholah; B) rocky headland of erosion-resistant rock just north of Taholah. (http://apps.ecy.wa.gov/shorephotos/index.html)*

3. Methodology

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

Table 1: PMEL specifications for the Taholah, Washington DEM.

Grid Area	Taholah, Washington
Coverage Area	123.70º to 125.30º W; 46.99º to 47.65º 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

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 3) were obtained from several U.S. federal and state agencies including: NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS) and Coastal Services Center (CSC); the U.S. Geological Survey (USGS); and the Washington State Department of Transportation (WASDOT). Safe Software's (http://www.safe.com/) *FME*[3] 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* shapefiles. The shapefiles 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 NOAA tide stations (see Section 3.2.1). Applied Imagery's *Quick Terrain Modeler* software (http://www.appliedimagery.com/) was used for evaluating some datasets before the final gridding process.

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. *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.

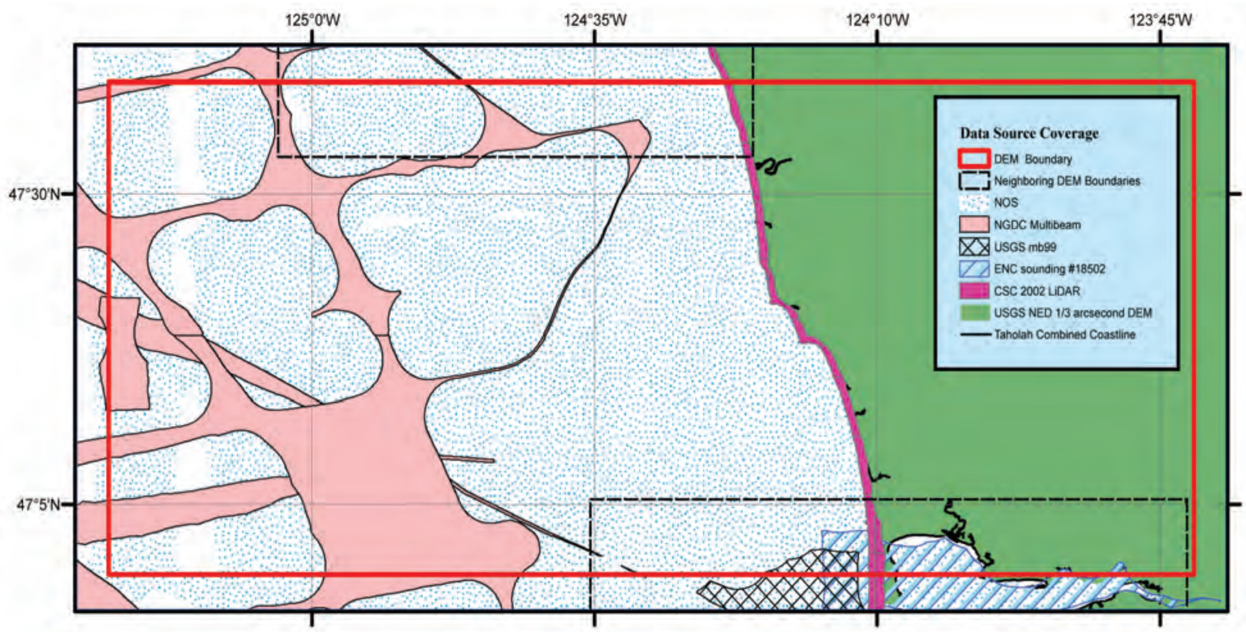

Figure 3. *Source and coverage of datasets used to compile the Taholah DEM.*

3.1.1 Shoreline

Coastline datasets of the Taholah region were obtained from NOAA's Office of Coast Survey as Electronic Navigational Charts (ENCs), and NGDC's La Push, Washington (Taylor et al., 2008) and Astoria, Oregon (Carignan et al., 2009) DEMs (Table 2; Fig. 4). NGDC evaluated but did not use the Washington Department of Transportation (WASDOT; http://www.wsdot.wa.gov/) coastline, as the NGDC and ENC coastlines matched the bathymetric datasets more closely.

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

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Coordinate System*	*URL*
OCS ENC extracted shoreline	2004	vector	1:180,789	WGS 84 geographic	Mean High Water	http://www.nauticalcharts.noaa.gov/
NGDC Astoria DEM coastline	2008	vector		WGS 84 geographic	Mean High Water	http://www.ngdc.noaa.gov/dem/selectdem.jsp
NGDC La Push DEM coastline	2007	vector		WGS 84 geographic	Mean High Water	http://www.ngdc.noaa.gov/dem/selectdem.jsp

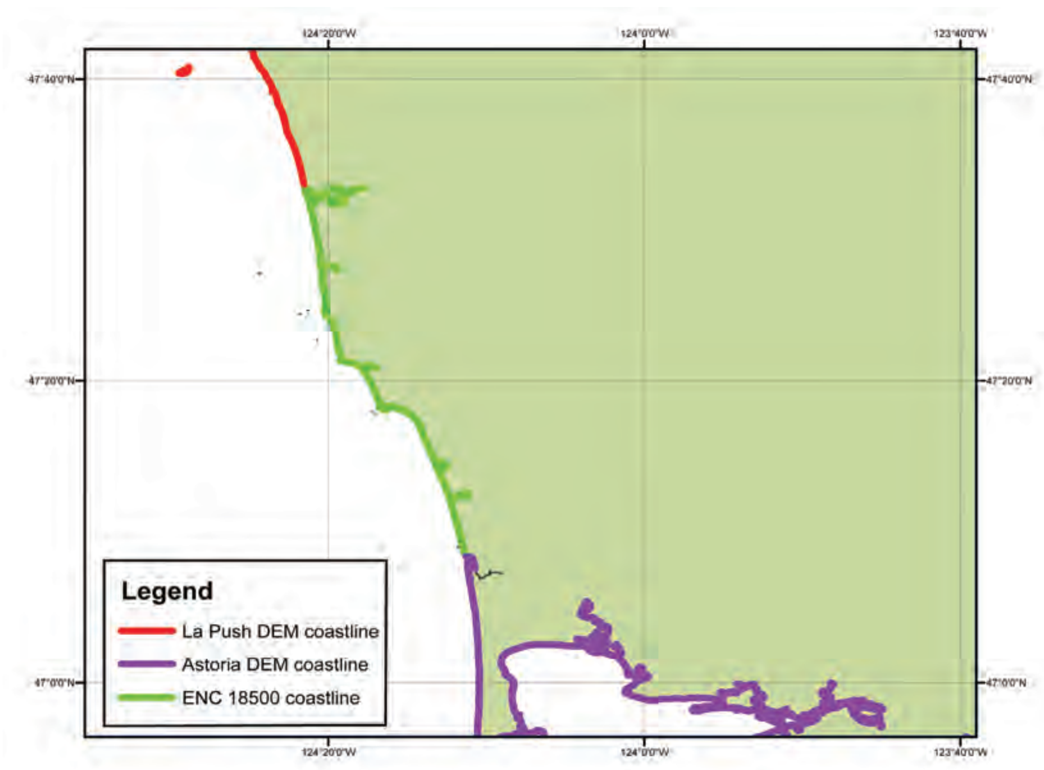

Figure 4. *Digital coastline datasets used in developing a combined coastline of the Taholah, Washington region.*

1) OCS Electronic Navigational Chart Coastline

Two electronic navigational charts (ENCs) were available for the Taholah area (Table 3) and downloaded from the NOAA's Office of Coast Survey web site (http://chartmaker.ncd.noaa.gov/MCD/enc/index.htm). The coastline data were extracted from the ENC S-57 format to vector line shapefiles. The ENC coastline dataset from chart #18500 was used to create a 'combined coastline'. Chart #18502 covers the southern region of the DEM and had been used in developing the Astoria DEM coastline.

Table 3: Electronic Navigation Charts available in the Taholah, Washington region.

Chart	*Title*	*Edition*	*Edition Date*	*Format*	*Scale*
18500	Columbia River to Destruction Island	29	2004	ENC and RNC	1:180,789
18502	Greys Harbor - Westhaven Cove	86	2007	ENC and RNC	1:40,000

2) NGDC Astoria DEM coastline

The southern Taholah DEM boundary overlaps the Astoria DEM (http://www.ngdc.noaa.gov/dem/selectdem.jsp) northern boundary by approximately 11 kilometers. The coastline used in developing the Astoria DEM (Carignan et al., 2009) was clipped to the Taholah DEM boundary and merged with the OCS chart coastline dataset using *ArcCatalog* tools.

3) NGDC La Push DEM coastline

The northern Taholah DEM boundary overlaps the La Push DEM (http://www.ngdc.noaa.gov/dem/selectdem.jsp) southern boundary by approximately 11 kilometers. The coastline used in developing the La Push DEM (Taylor et al., 2008) was clipped to the Taholah DEM boundary and merged with the OCS chart coastline dataset using *ArcCatalog* tools. The coastline was edited to align with datasets transformed to a common vertical datum using an improved methodology (Fig.5; see Section 3.2.1).

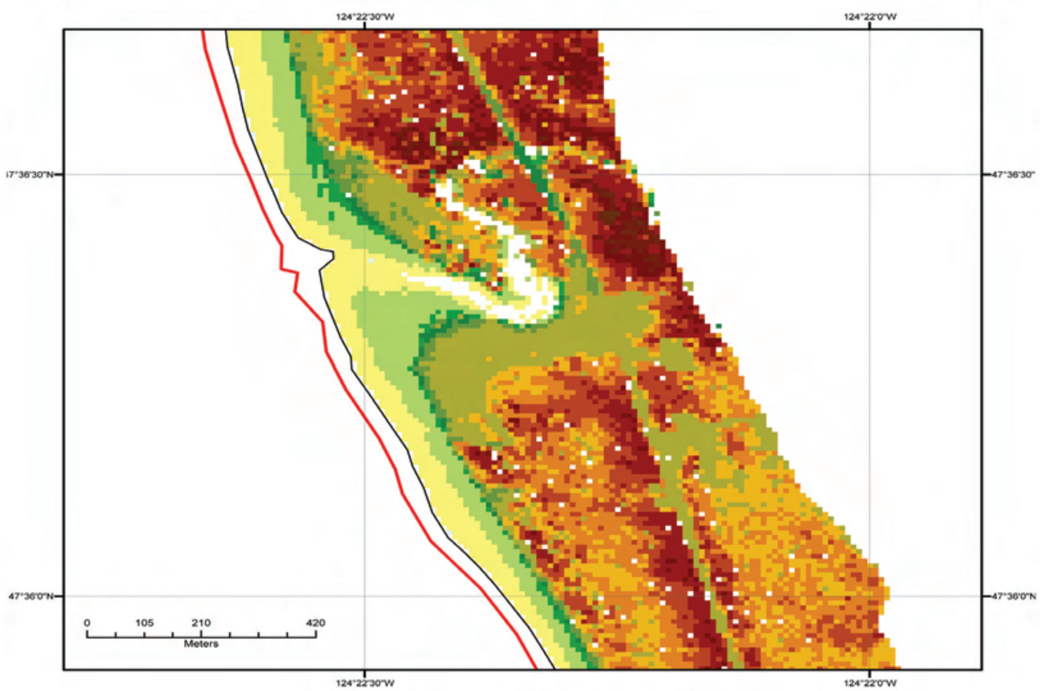

Figure 5. *Comparison between the La Push DEM coastline (red) and the Taholah DEM 'combined coastline' (black), aligned with the MHW 2002 ALACE LiDAR data. NGDC used an improved vertical datum transformation method in developing the Taholah DEM, resulting in an approximate 50 m horizontal difference in the position of the La Push and Taholah coastlines.*

The 'combined coastline' datasets were visually compared to *Google Earth* satellite imagery (http://earth.google.com/userguide/v4/#imagery_dates), the Washington State Department of Ecology aerial photo collection (http://apps.ecy.wa.gov/shorephotos/), and USGS topographic maps available on NASA World Wind (http://worldwind.arc.nasa.gov/index.html) to ensure features such as jetties, levees, and rocks were present in the coastline and to accurately reflect morphologic changes along the coastline (Fig. 6). The 'combined coastline' was adjusted to match the 2002 ALACE LiDAR data available from the Coastal Services Center (see Section 3.1.3). 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).

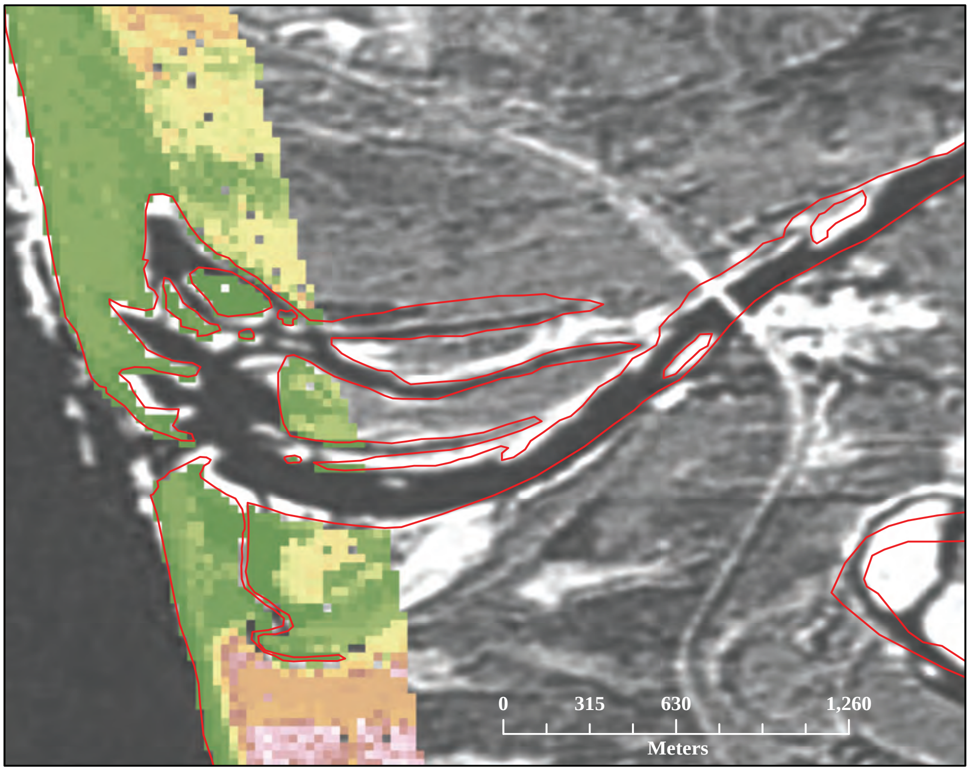

Figure 6. *The 2002 CSC ALACE LiDAR data overlying a Google Earth satellite image of the Quinault River. The image was georeferenced and used in combination with recent aerial photographs to manually adjust the 'combined coastline', shown in red.*

3.1.2 Bathymetry

Bathymetric datasets used in the compilation of the Taholah DEM include 25 NOS hydrographic surveys, five multibeam swath sonar surveys from NGDC and USGS, and extracted ENC sounding data (Table 4; Fig. 7). Two additional multibeam surveys provided to NGDC by the National Marine Sanctuary were evaluated but not used because of errors in the sound velocity measurements during collection of data, which created artificial "ridges" along the edges of each track.

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

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NOS	1862 to 2005	Hydrographic survey soundings	Ranges from 10 m to 1.2 km (varies with scale of survey, depth, traffic, and probability of obstructions)	NAD 13, NAD 27 or NAD 83 geographic, or undetermined	MLLW	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NGDC	1993 to 1999	Multibeam swath sonar files	raw MB files gridded to 1 arc-second	WGS 84 geographic	assumed MSL	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
USGS	1999	Multibeam swath sonar files	~ 10 meters	NAD 83 State Plane Washington South (meters)	MLLW	http://walrus.wr.usgs.gov/swces/data.html#era4
OCS ENC #18502	2005	extracted soundings from ENC	1: 191,730	WGS 84 geographic	MLLW	http://www.nauticalcharts.noaa.gov/

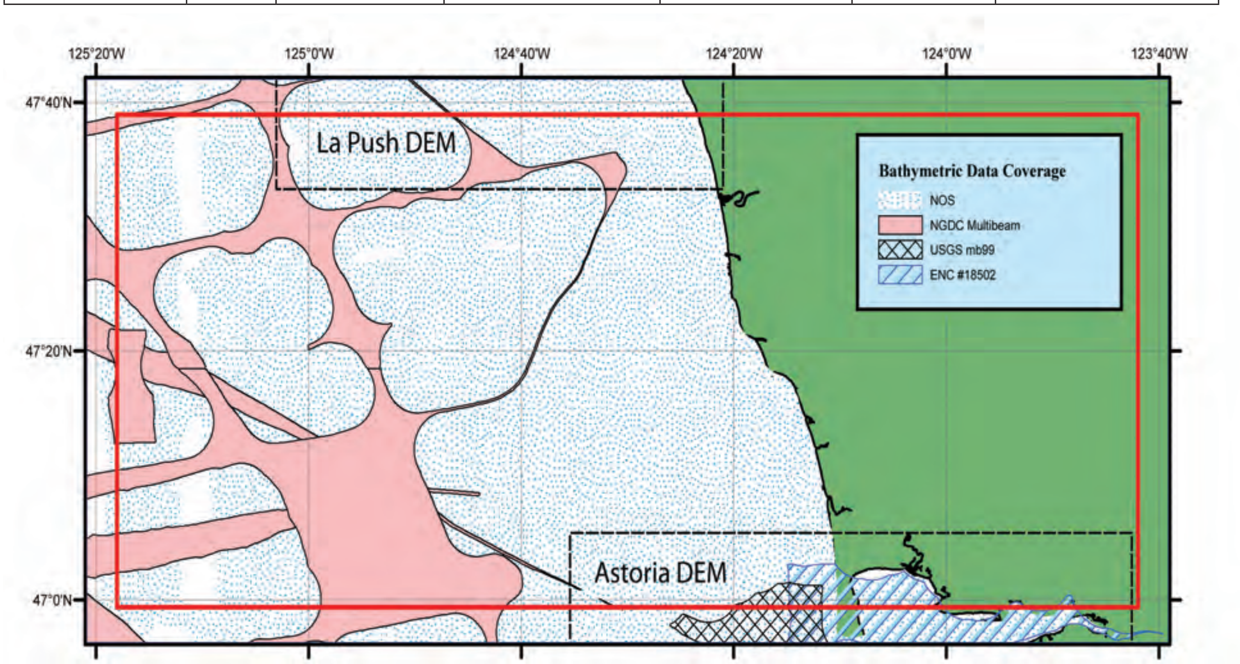

Figure 7. *Spatial coverage of bathymetric datasets used in compiling the Taholah DEM. The 'combined coastline' is in black, DEM boundary is in red, and neighboring DEM boundaries are dashed black.*

1) NOS hydrographic survey data

A total of 25 digital NOS hydrographic surveys conducted between 1862 and 2005 were available for use in developing the Taholah 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 geographic datums, if the datum was known and recorded (Table 5; Fig. 8).

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) and were referenced to NAD 83[4]. The surveys were subsequently clipped to a polygon 0.05 degrees (~5%) larger than the Taholah DEM area to support data interpolation along grid edges.

After converting all NOS survey data to MHW (see Section 3.2.1), the data were displayed in ESRI *ArcMap* and reviewed for digitizing errors against scanned original survey smooth sheets and edited as necessary. The surveys were also compared to 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, and where soundings from older surveys have been superseded by more recent NOS surveys.

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

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum of Digital Records*
H00809	1862	20,000	mean lower low water	undetermined
H01589A	1883	20,000	mean lower low water	undetermined
H04633A	1926	120,000	mean lower low water	NAD 1913
H04633B	1926	120,000	mean lower low water	NAD 27
H04710	1927	20,000	mean lower low water	NAD 13
H04715	1927	20,000	mean lower low water	NAD 13
H04716	1927	20,000	mean lower low water	NAD 13
H04728	1927	40,000	mean lower low water	NAD 13
H04729	1927	40,000	mean lower low water	NAD 13
H04735	1927	80,000	mean lower low water	NAD 27
H04775	1927	120,000	mean lower low water	NAD 13
H05068	1930	40,000	mean lower low water	NAD 27
H05107	1930	20,000	mean lower low water	NAD 27
H05108	1930	20,000	mean lower low water	NAD 27
H05110	1930	40,000	mean lower low water	NAD 27
H05114	1930	120,000	mean lower low water	NAD 27
H06647	1940	10,000	mean lower low water	NAD 27
H06665	1941	10,000	mean lower low water	NAD 27
H08250	1956	10,000	mean lower low water	NAD 27
H08251	1956	10,000	mean lower low water	NAD 27
H08252	1955	20,000	mean lower low water	NAD 27
H08293	1956	10,000	mean lower low water	NAD 27
H11282	2005	10,000	mean lower low water	NAD 83
H11299	2005	10,000	mean lower low water	NAD 83
H11300	2005	10,000	mean lower low water	NAD 83

4. NGDC's *GEODAS* 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.

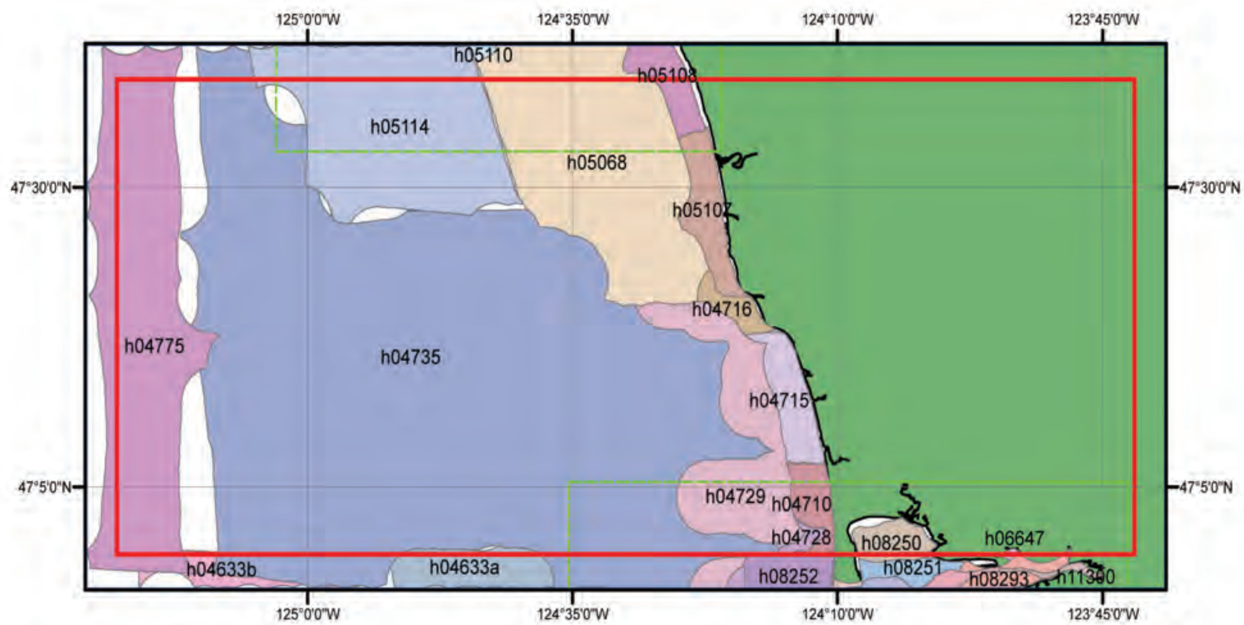

Figure 8. *Digital NOS hydrographic survey coverage in the Taholah region. DEM boundary in red.*

2) Multibeam swath sonar files

Four multibeam swath sonar surveys were downloaded from the NGDC multibeam database (http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html; Table 6, Fig. 9). The NGDC multibeam database is comprised of the original swath sonar files collected mostly by the U.S. academic fleet. The downloaded data were gridded to 1/3 arc-second resolution using *MB-System*, an NSF-funded free software application specifically designed to manipulate submarine multibeam sonar data (http://www.ldeo.columbia.edu/res/pi/MB-System/).

Most of the multibeam swath sonar surveys were transits rather than dedicated sea-floor surveys. All have a horizontal datum of WGS 84 geographic and undefined vertical datum, which was assumed to be mean sea level (MSL).

Table 6: Multibeam swath sonar surveys used in compiling the Taholah DEM.

Cruise ID	*Ship*	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Institution*
REM-01MV	Melville	1993	assumed MSL	WGS 84 geographic	University of California, Scripps Institution of Oceanography (UC/SIO)
REM-02MV	Melville	1993	assumed MSL	WGS 84 geographic	University of California, Scripps Institution of Oceanography (UC/SIO)
SO108	Sonne	1996	assumed MSL	WGS 84 geographic	University of Kiel, Germany, GEOMAR Forshungszentrum
AVON09MV	Melville	1999	assumed MSL	WGS 84 geographic	University of California, Scripps Institution of Oceanography (UC/SIO)

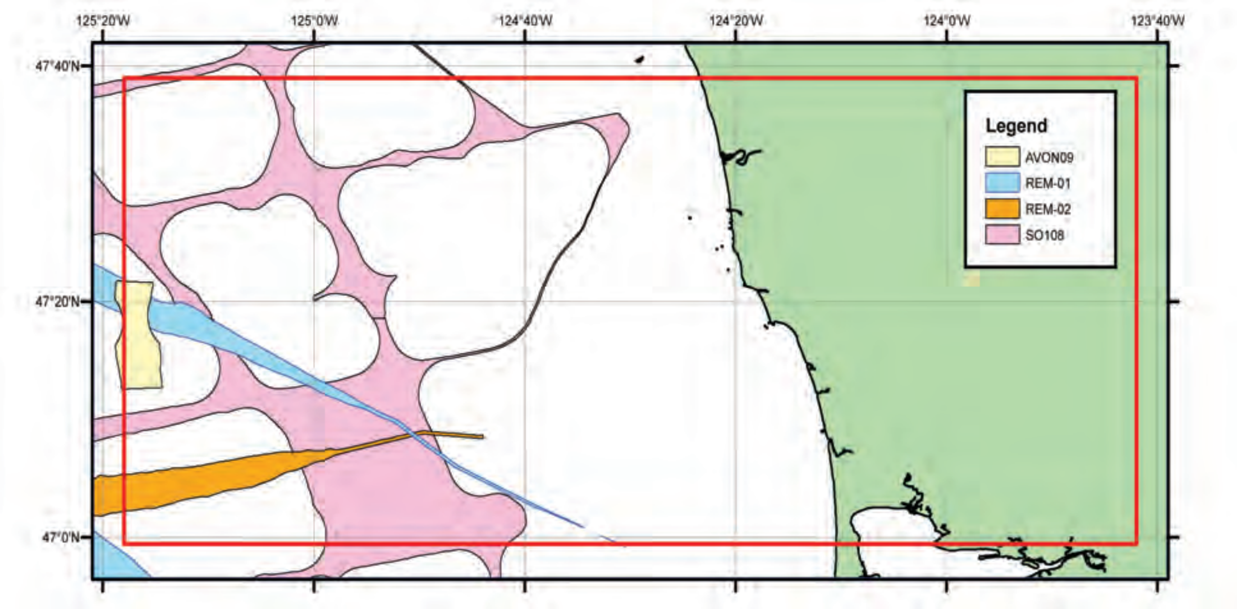

Figure 9. *Spatial coverage of multibeam swath sonar surveys from the NGDC multibeam bathymetry database.*

After assessing individual survey quality, the gridded data were transformed to MHW (see section 3.2.1) and xyz format using *FME*, displayed in *QT Modeler* and edited using *ArcMap* and *QT Modeler*. Figure 10 shows data errors along the edge of the swath in survey SO108 due to noise. These deep valleys along the edges were seen in all four surveys, mostly in the shallower water, and were manually deleted in *ArcMap* before creating the gridded bathymetric surface (see Section 3.3.2).

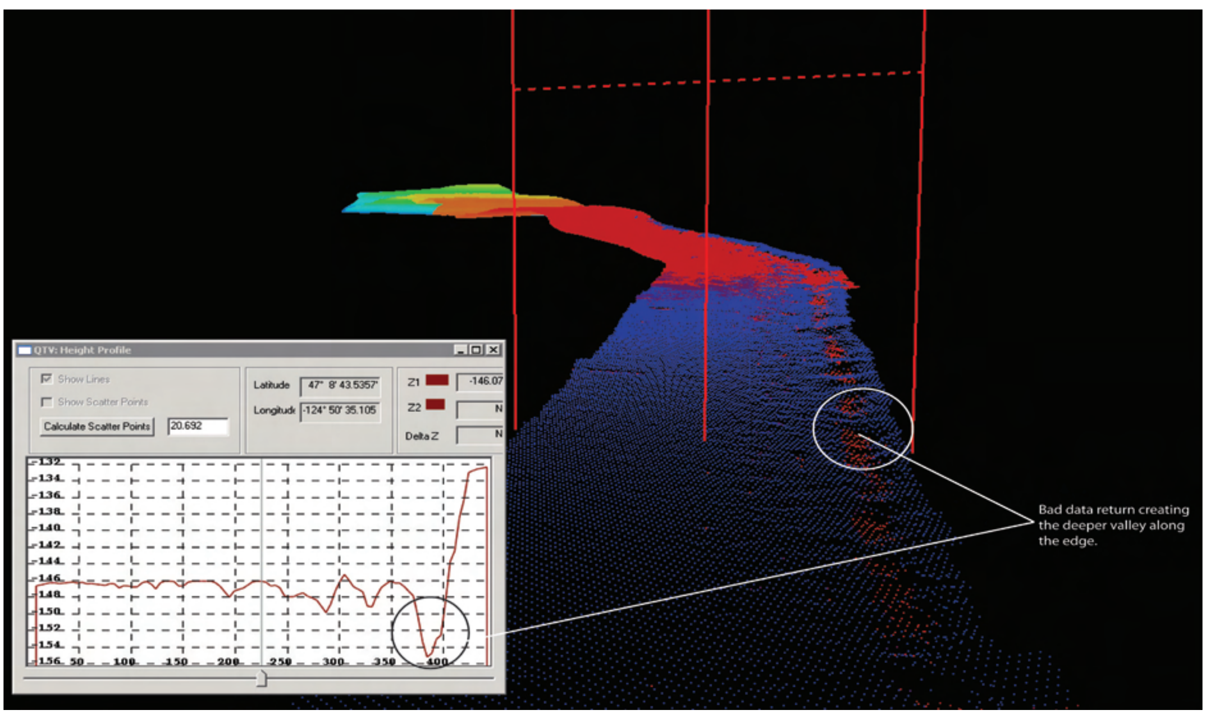

Figure 10. *Errors along the edge of a multibeam swath sonar survey. The anomalous valley and ridge were removed using ArcGIS. Color image created with QT Modeler.*

3) USGS multibeam swath sonar survey

The USGS multibeam swath sonar survey mb99 covered the southeastern region of the DEM offshore of Grays Harbor and was downloaded from the USGS Southwest Washington Coastal Erosion Study website (http://walrus.wr.usgs.gov/swces/data.html#era4). The survey was converted to a shapefile using *ArcCatalog*; vertical and horizontal datums were transformed using *FME*. When displayed for analysis, the data revealed horizontal lines across the entire dataset and anomalous depths inconsistent with adjacent bathymetric data, and were removed using *ArcMap* editing tools and *QT Modeler* (Fig. 11).

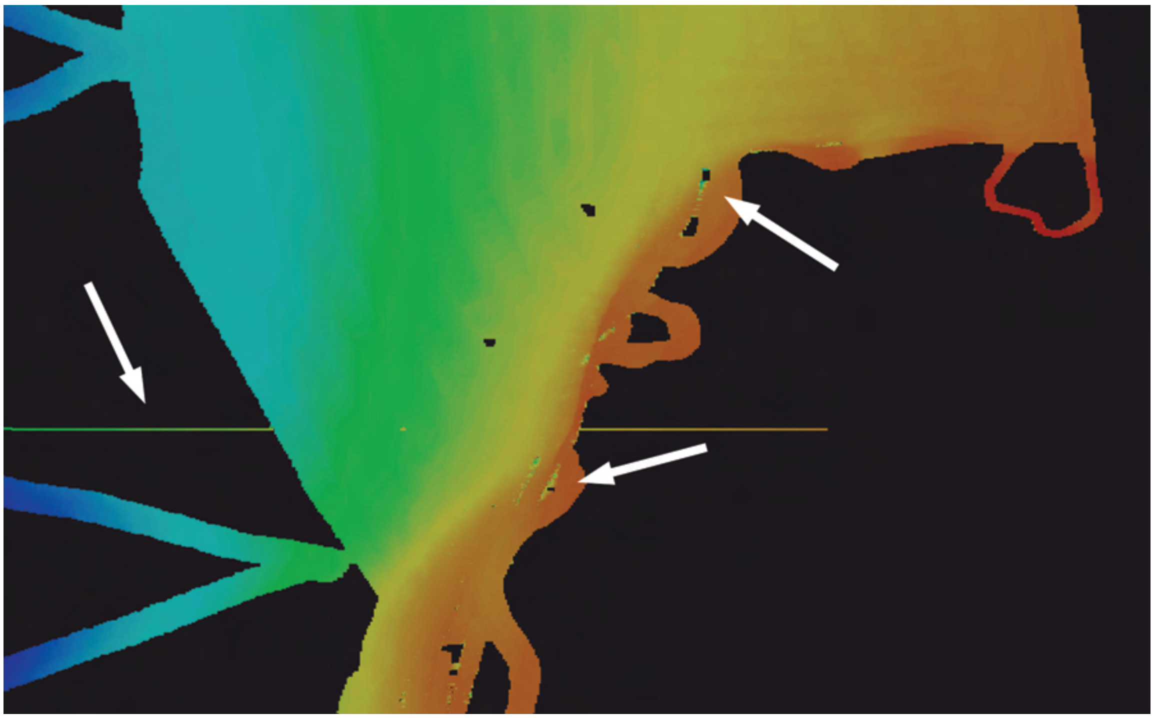

Figure 11. *Color image of USGS multibeam swath sonar survey mb99. White arrows point to errors in data, which were removed before use in developing the Taholah DEM. Image created with QT Modeler.*

3.1.3 Topography

Two topographic datasets were used to build the Taholah DEM (Table 7; Fig. 12). The USGS NED 1/3 arc-second DEM provided full coverage for the Taholah region and the 2002 CSC ALACE LiDAR dataset provided coverage along the entire Pacific coastline. NGDC evaluated but did not use the lower resolution Shuttle Radar Topography Mission (SRTM) Elevation 1 arc-second DEM available from USGS. NGDC also digitized some elevations to ensure that features were accurately represented in the Taholah DEM.

Table 7: Topographic datasets used in compiling the Taholah DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
USGS	1999-2000	NED DEM	1/3 arc-second	NAD 83 geographic	NAVD88 (meters)	http://ned.usgs.gov/
CSC ALACE	2002	LiDAR	~2 meters	NAD 83 geographic	NAVD88 (meters)	http://maps.csc.noaa.gov/TCM/
NGDC	2009	digitized points		WGS 84 geographic	MHW	

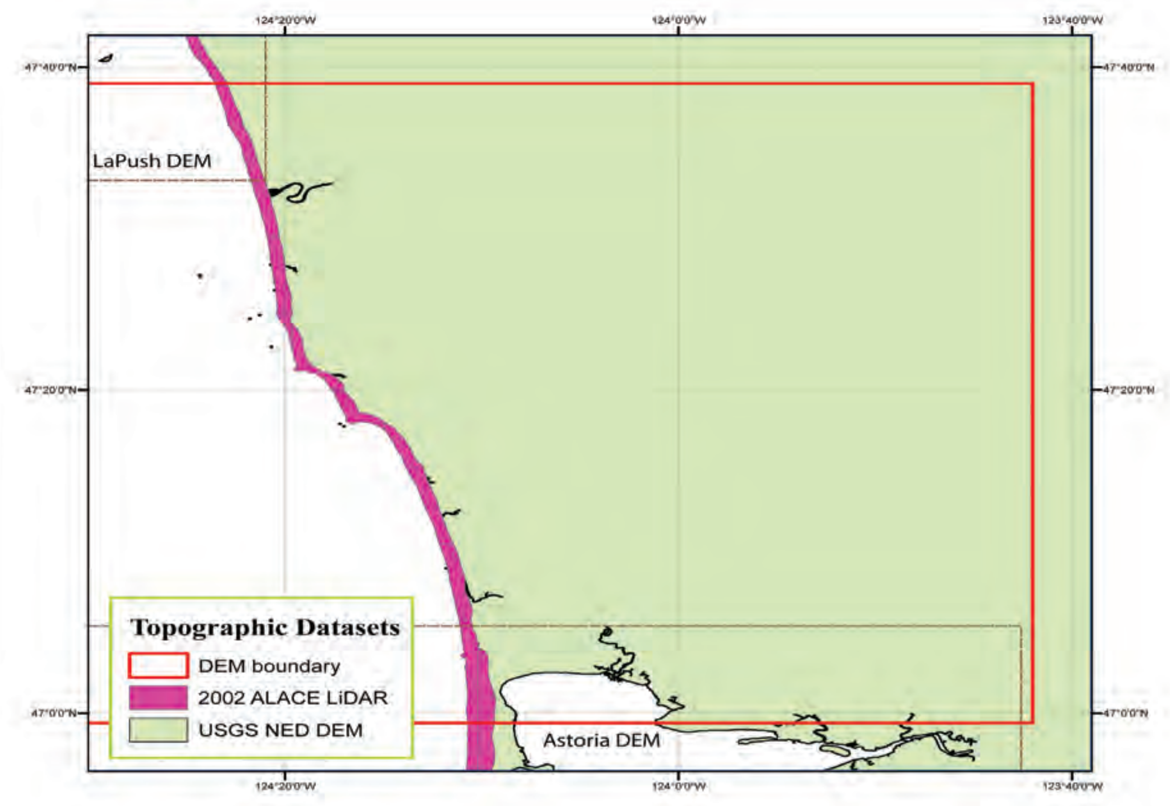

***Figure 12.** Spatial coverage of topographic datasets used in building the Taholah DEM. The 1/3 arc-second NED DEM shown in green covers the entire Taholah DEM area. The 2002 ALACE LiDAR shown in pink covers the entire Pacific coastline. Neighboring NGDC DEM boundaries are shown as dashed brown lines.*

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 Taholah region[5]. 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 and 2000. The NED DEM included "zero" elevation values over the open ocean, which were removed from the dataset by clipping to the 'combined coastline'.

2) CSC LiDAR ALACE topography

The 2002 NASA/USGS Airborne LiDAR Assessment of Coastal Erosion (ALACE) Project topographic LiDAR dataset was downloaded from the NOAA CSC website (http://maps.csc.noaa.gov/TCM/) and transformed to NAD 83 and MHW using *FME*. This dataset was not processed to bare earth and contained elevation values over open water as well as vegetation and buildings (Fig. 13). NGDC processed the data using *ArcMap* to simulate bare earth. Because the morphology of the coastline differs though out the DEM, NGDC processed the LiDAR data with varying techniques to bare earth in different regions along the coastline. For the region overlapping the Astoria DEM, 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 were less than 12 meters. Most tall buildings and vegetation were eliminated, while the high sand dunes and berms along the beaches remain. For the region overlapping the La Push DEM, the LiDAR data were filtered using *FME* to remove points with elevations greater than 10 meters. This process removed suspect returns from heavily forested near-shore areas while retaining high-resolution beach elevations. For the remainder of the coastline, depending on the elevation of the coastal bluffs and comparison with the NED data, LiDAR data were removed with elevations values greater than 20 to 40 meters, to retain coastal features but to remove forested regions. In low lying coastal towns, such as Taholah, LiDAR data were manually edited in *ArcMap* by NGDC to remove most buildings and trees. The data were then clipped to the 'combined coastline' and filtered to remove elevation points below zero.

3) NGDC digitized points

NGDC digitized elevation points in the Taholah, Washington DEM of rocks off the coast, based on RNC #18500, and of low lying streams where returns from treetops from the non-bare earth 2002 ALACE LiDAR were manually deleted.

5. 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]

__Figure 13.__ Color image of a preliminary Taholah DEM and the surrounding coastline before processing the LiDAR to bare earth. The trees and buildings were manually removed by NGDC.

After processing, the topographic data were viewed in *ArcMap* to make sure that the transitions along dataset edges were smooth. In some areas, the transition between the NED data and the LiDAR data formed a step of up to 30 meters. A 50 meter data buffer was generated in the NED data to reduce the sharpness of the border between the two datasets. Figure 14 shows a buffered cross section of the interpolated area between the NED and LiDAR datasets. Data were then converted to xyz format using *FME* for the final gridding process.

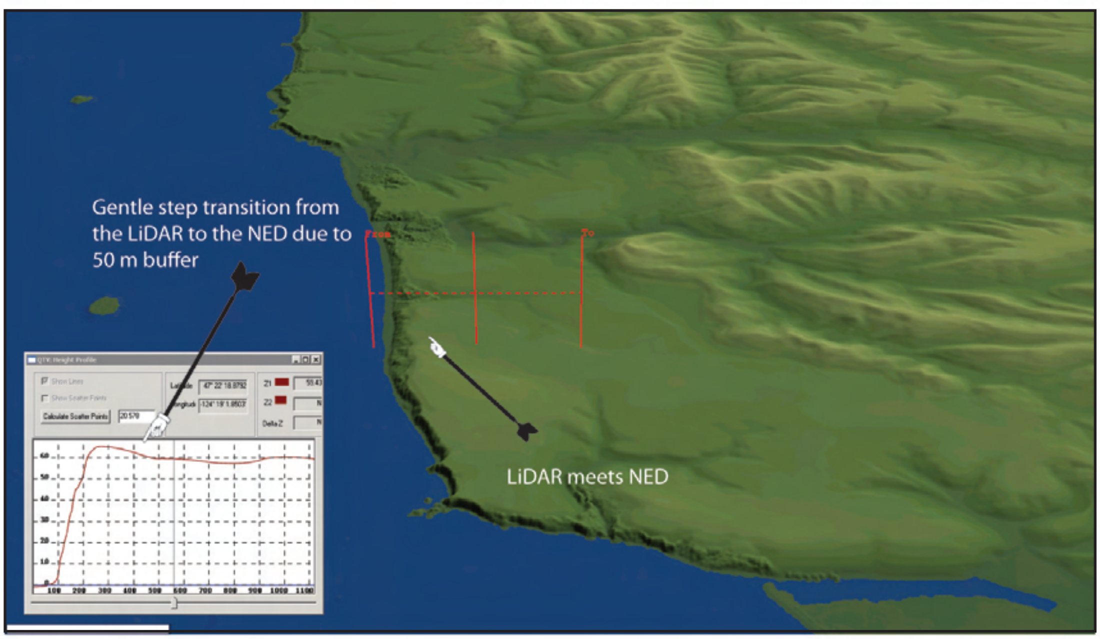

__Figure 14.__ Color image of the transition from the LiDAR to the NED data in the Taholah DEM. A 50 meter buffer was created between the LiDAR and the NED data to prevent a steep step from one data source to the other. With the buffer, a gentle slope can be seen between the LiDAR and the NED.

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Taholah 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 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, and the USGS and NGDC multibeam 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 degree. The USGS NED 1/3 arc-second DEMs and the CSC topographic LiDAR surveys were originally referenced to NAVD88. Conversion to MHW, using *FME* software, was accomplished by adding the offset grid to the survey data.

The offset grids are an improved method for vertical datum transformation of bathymetric and topographic datasets. This method was also used in developing the Astoria Oregon DEM (Carignan et al., 2009), creating a seamless overlap between the two DEMs. For the La Push, Washington DEM (Taylor et al., 2008), NGDC used a constant offset derived from the La Push Pier tide station #9442396 to perform vertical datum transformations. Because of the different vertical transformation methods, there is not a seamless overlap between NGDC's Taholah DEM and the neighboring La Push DEM.

3.2.2 Horizontal datum transformations

Datasets used to compile the Taholah DEM were originally referenced to WGS 84 geographic, NAD 83 geographic, NAD 27 geographic, NAD 1913, and NAD 83 State Plane Washington South. The relationships and transformational equations between these horizontal datums are well established. All data were converted to a horizontal datum of NAD 83/WGS 84 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 shapefiles were then converted to xyz files in preparation for gridding. Problems included:

- Elevations located over the open-ocean in the NED and LiDAR datasets.
- Inconsistent elevation values between the NED and LiDAR topographic data along the coast.
- Data errors in multibeam swath sonar surveys. Manual editing of the multibeam sonar data was necessary to remove these artifacts.
- Topographic CSC LiDAR dataset not processed to bare earth.
- Digital, measured bathymetric values from NOS surveys date back over 100 years. More recent data differed from older NOS data by as much as 10 meters nearshore and up to 75 meters in deeper water. The older NOS survey data were excised where more recent bathymetric data exists.

3.3.2 Smoothing of bathymetric data

The NOS hydrographic surveys are generally sparse at the resolution of the 1/3 arc-second Taholah 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 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/).

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 Taholah 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. 15) and exported as an xyz file for use in the final gridding process (see Table 8).

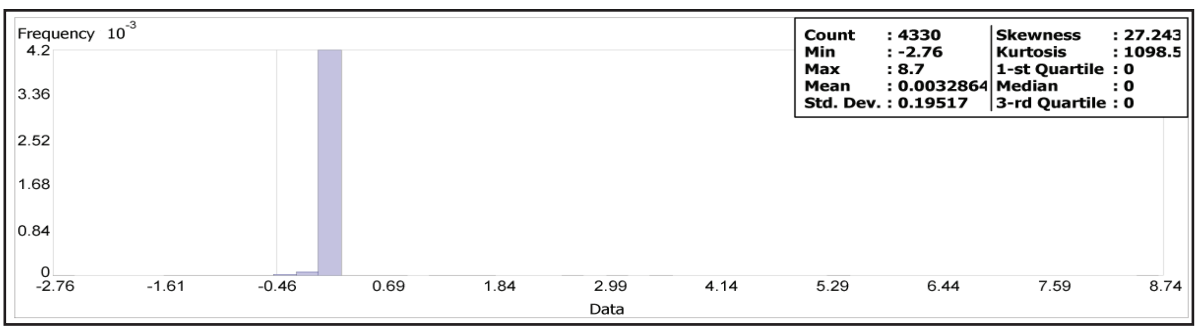

Figure 15. *Histogram of the differences between NOS hydrographic survey H08416 and the 1 arc-second pre-surfaced bathymetric grid.*

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 Taholah DEM. *MB-System* is an NSF-funded free 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 8. Greatest weight was given to the digitized features, such as the near shore rocks. Least weight was given to the coastline and 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 Taholah DEM.

Table 8. Data hierarchy used to assign gridding weight in MB-System.

Dataset	*Relative Gridding Weight*
NGDC digitized features	1,000
CSC topographic LiDAR	100
USGS NED topographic LiDAR	100
NOS hydrographic surveys	100
USGS Multibeam survey	100
NGDC Multibeam surveys	100
Extracted ENC soundings	100
Combined coastline	1
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 Taholah DEM is dependent upon the datasets used to determine corresponding DEM cell values. Topographic features have an estimated accuracy of 10 meters: CSC topographic LiDAR data have an accuracy between 1 and 3 meters; NED topography is accurate within 10 meters. Bathymetric features are resolved only to within a few hundreds of meters in deep-water areas. Shallow, near-coastal regions, rivers, and harbor surveys have an accuracy approaching that of sub-aerial 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 man-made morphologic change (i.e., channel dredging and building of jetties).

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the Taholah 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 LiDAR data, and up to 7 meters for NED topography. Bathymetric source data have an estimated accuracy between 0.1 meters and 5% of water depth. Values were derived from a 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 Taholah DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (e.g., Fig. 16). 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 17 shows a perspective view from the southwest of the 1/3 arc-second Taholah DEM in its final version.

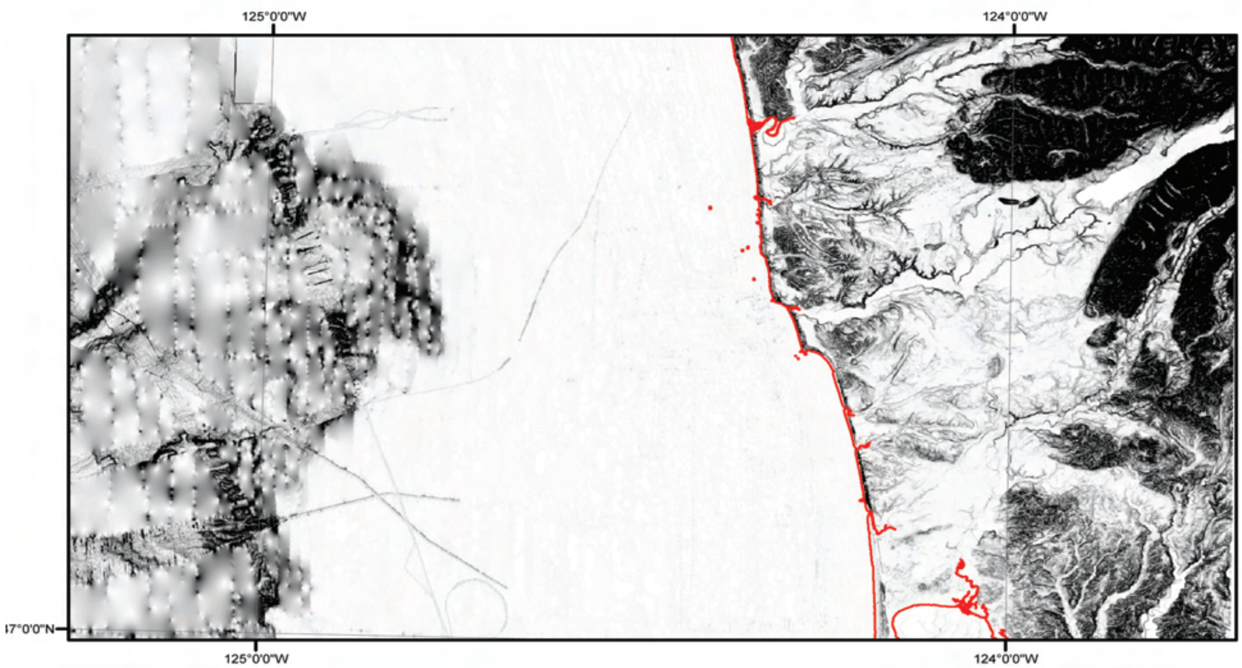

Figure 16. *Slope map of the Taholah DEM. Flat-lying slopes are white; dark shading denotes steep slopes; Taholah coastline in red.*

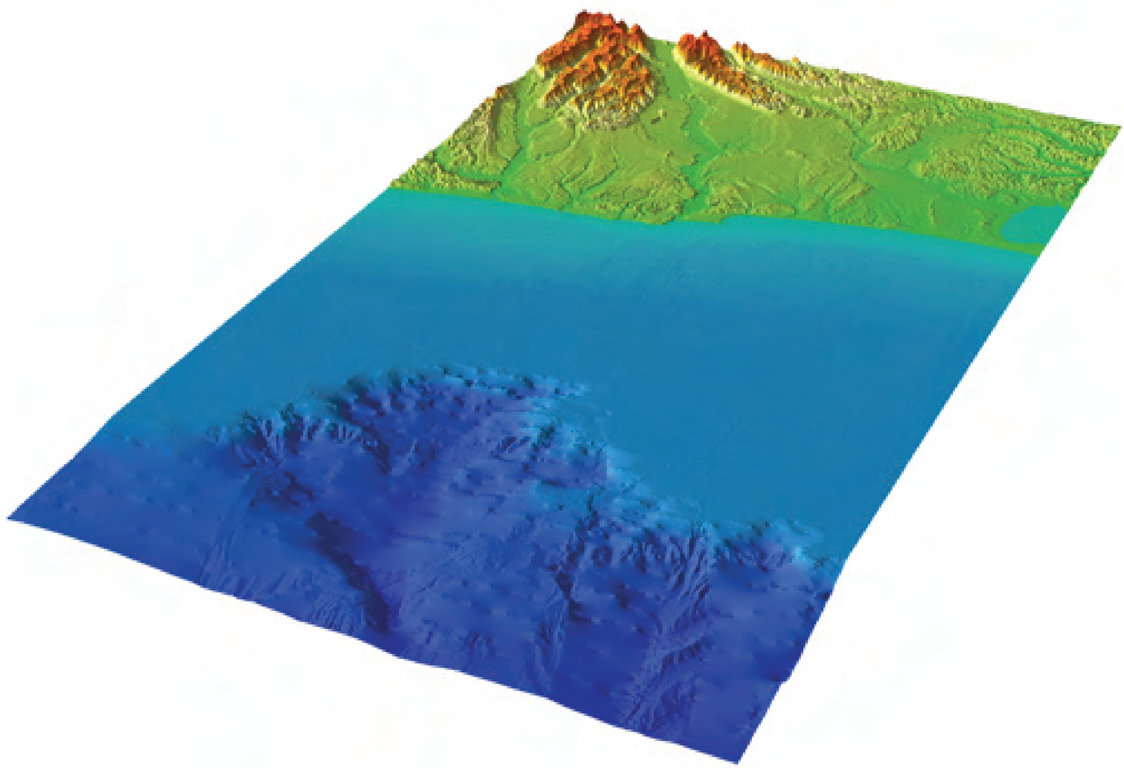

__Figure 17.__ Perspective view from the southwest of the Taholah DEM. 2x vertical exaggeration.

3.4.4 Comparison with source data files

To ensure grid accuracy, the Taholah 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 section of the non-bare earth CSC ALACE LiDAR survey file, located at the town of Taholah, and the Taholah DEM is shown in Figure 18. Differences range from 2.7 to -31 meters, where negative values indicate that elevations of the LiDAR data are higher than the DEM elevations. The area where the greatest difference occurred is in the low lying coastal streams where some LiDAR tree top elevations were supplanted by NGDC digitized points of ground surface elevations in the DEM (see Table 8).

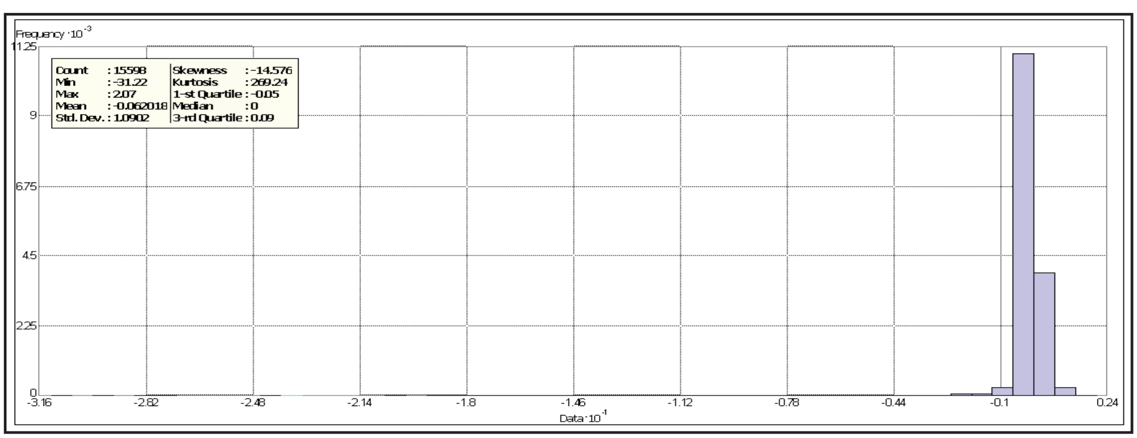

Figure 18. *Histogram of the differences between a section of the CSC ALACE LiDAR survey and the Taholah DEM.*

3.4.5 Comparison with NGS geodetic monuments

The elevations of 332 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 (typically sub-mm accuracy) and elevations in NAVD88 (in meters).

Elevations were shifted to MHW vertical datum using *FME* for comparison with the Taholah DEM (see Fig. 20 for monument locations). Differences between the Taholah DEM and the NGS geodetic monument elevations range from -51.78 to 24.08 meters, with the majority of them within ± 5 meters (Fig. 19). Negative values indicate that the DEM elevation is less than the monument elevation. The marker with a difference of -51.78 meters is located on the beach and NGS metadata states that it is not a suitable place for a permanent marker and have had to recover this lost marker several times. Monuments on unstable bluffs and rapidly changing shorelines, and lost monuments had the greatest negative and positive values. The horizontal accuracy of the monuments can be off as much as 50 meters due to lost monuments, and locations on bridges and unstable terrain, such as beaches and high bluffs.

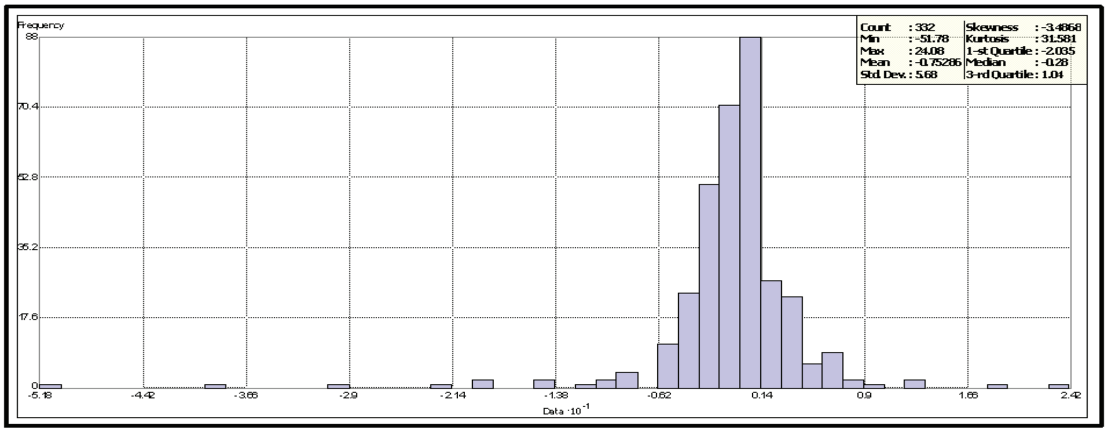

Figure 19. *Histogram of the differences between NGS geodetic monument elevations and the Taholah DEM.*

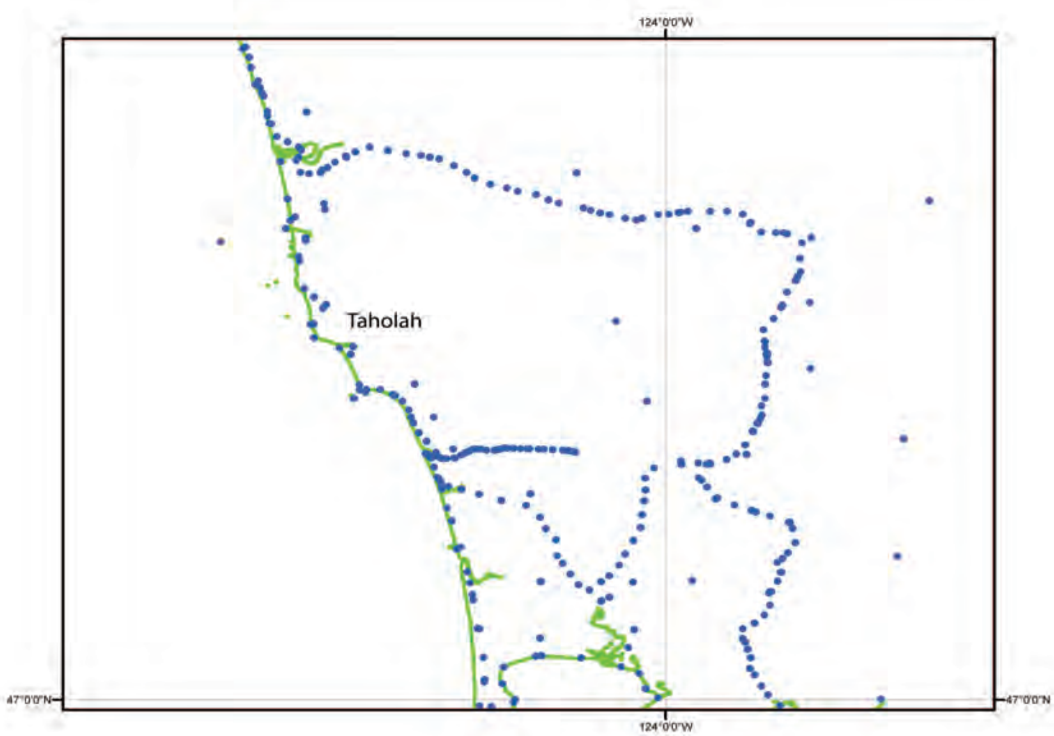

Figure 20. *Location of the NGS monuments used to assess the Taholah DEM.*

4. Summary and Conclusions

An integrated bathymetric–topographic digital elevation model of the Taholah, Washington region, with cell size 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 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 ESRI *ArcGIS, FME, GMT, MB-System*, and *Quick Terrain Modeler* software.

Recommendations to improve the Taholah 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 water.

5. Acknowledgments

The creation of the Taholah DEM was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Chris Chamberlin and Vasily Titov (PMEL); Ann Gibbs (USGS Pacific Science Center); Brooke McMahon and Crescent Moegling (NOAA/NOS Pacific Hydro Office) for processing raw multibeam data; and Nancy Wright (National Marine Sanctuary) for sending multibeam data not available on the their website.

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Nautical Chart #18500 (RNC and ENC), 29nd Edition, 2004. Columbia River to Destruction Island. Scale 1: 180,789. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18502 (ENC and RNC), 86th Edition, 2007. Greys Harbor – Westhaven Cove. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Taylor, L. A., Eakins, B. W., Carignan, K. S., Warnken, R. R., Sazonova, T., and Schoolcraft, D. C. 2009. Digital Elevation Models of La Push, Washington: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-14.

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/

Persistance of Vision Pty. Ltd,. (2004), Persistence of Vision™ Raytracer. Persistance of Vision Pty., Williamstown, Victoria, Australia, http://www.povray.org.

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/