NOAA Technical Memorandum NESDIS NGDC-14

DIGITAL ELEVATION MODEL OF LA PUSH, WASHINGTON: PROCEDURES, DATA SOURCES AND ANALYSIS

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

1. Introduction

In July 2007, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed a topographic–bathymetric digital elevation model (DEM) of La Push, 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) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the La Push DEM.

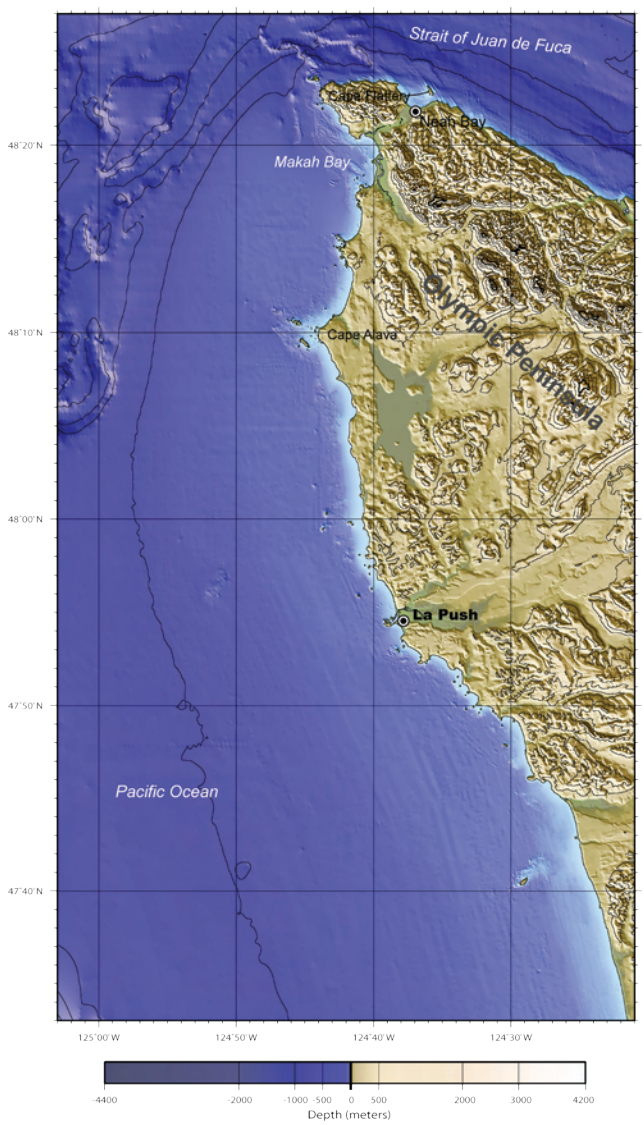

Figure 1. *Shaded-relief image of the La Push, Washington DEM. Contour interval is 100 meters.*

1. The La Push 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 La Push, Washington (47°54.48′ N, 124°38.1′ W) 1/3 arc-second of latitude is equivalent to 10.295 meters; 1/3 arc-second of longitude equals 6.922 meters.

2. Study Area

The La Push DEM covers the coastal region surrounding the town of La Push, Washington. Included within the DEM boundary are the Native American communities of the Makah, Quileute, and Ho tribes and the coastal town of Neah Bay to the north (Fig. 2). Nearly all the area covered by the DEM lies within the Olympic Coast National Marine Sanctuary boundary. The name La Push is derived from the Chinook translation of the French 'la bouche' meaning 'the mouth', as the town is located at the mouth of the Quillayute River.

The near shore region is subject to sediment deposition and transport, making the sea floor relatively shallow for upwards of 40 miles offshore. Farther from the coast, the shelf is cut by many submarine canyons that carry sediments to the deep ocean floor. Tectonic activity, such as earthquakes and volcanism, are relatively common in the region as the Juan de Fuca oceanic plate subducts underneath the continental North American plate (http://olympiccoast.noaa.gov/living/physical_environment/geo/welcome.html).

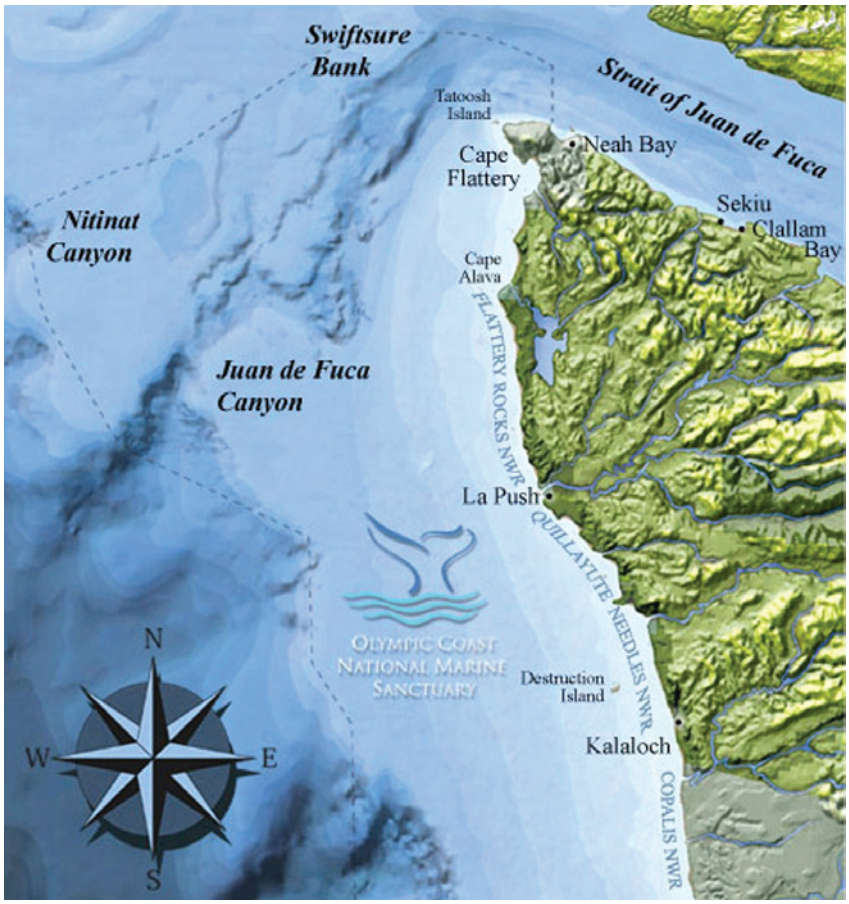

Figure 2. *Northern region of the Olympic Coast National Marine Sanctuary (http://olympiccoast.noaa.gov/visitor/vismap/welcome.html).*

3. METHODOLOGY

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

Table 1: PMEL specifications for the La Push, Washington DEM.

Grid Area	La Push, Washington
Coverage Area	124.35º to 125.05º W; 47.55º to 48.45º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System 1984 (WGS84)
Vertical Datum	Mean High Water (MHW)
Vertical Units	Meters
Grid Spacing	1/3 arc-second
Grid Format	ESRI Arc ASCII grid

3.1 Data Sources and Processing

Shoreline, bathymetric, topographic, and topographic–bathymetric 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) and Coastal Services Center (CSC); the Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX); the U.S. Geological Survey (USGS); the Puget Sound LiDAR Consortium (PSLC); the U.S. Army Corps of Engineers (USACE); and the Washington State Department of Transportation (WSDOT). Safe Software's (http://www.safe.com/) FME data translation tool package was used to shift datasets to WGS84 horizontal datum and to convert them into ESRI (http://www.esri.com/) ArcGIS shape files. The shape files were then displayed with ArcGIS to assess data quality and manually edit datasets. Vertical datum transformations to MHW were accomplished using FME, based upon data from the NOAA La Push, Quillayute River tide station. VDatum model software (http://nauticalcharts.noaa.gov/csdl/vdatum.htm) was not available for this area. Applied Imagery's Quick Terrain Modeler software (http://www.appliedimagery.com/) was used to edit and assess the quality of the LiDAR data.

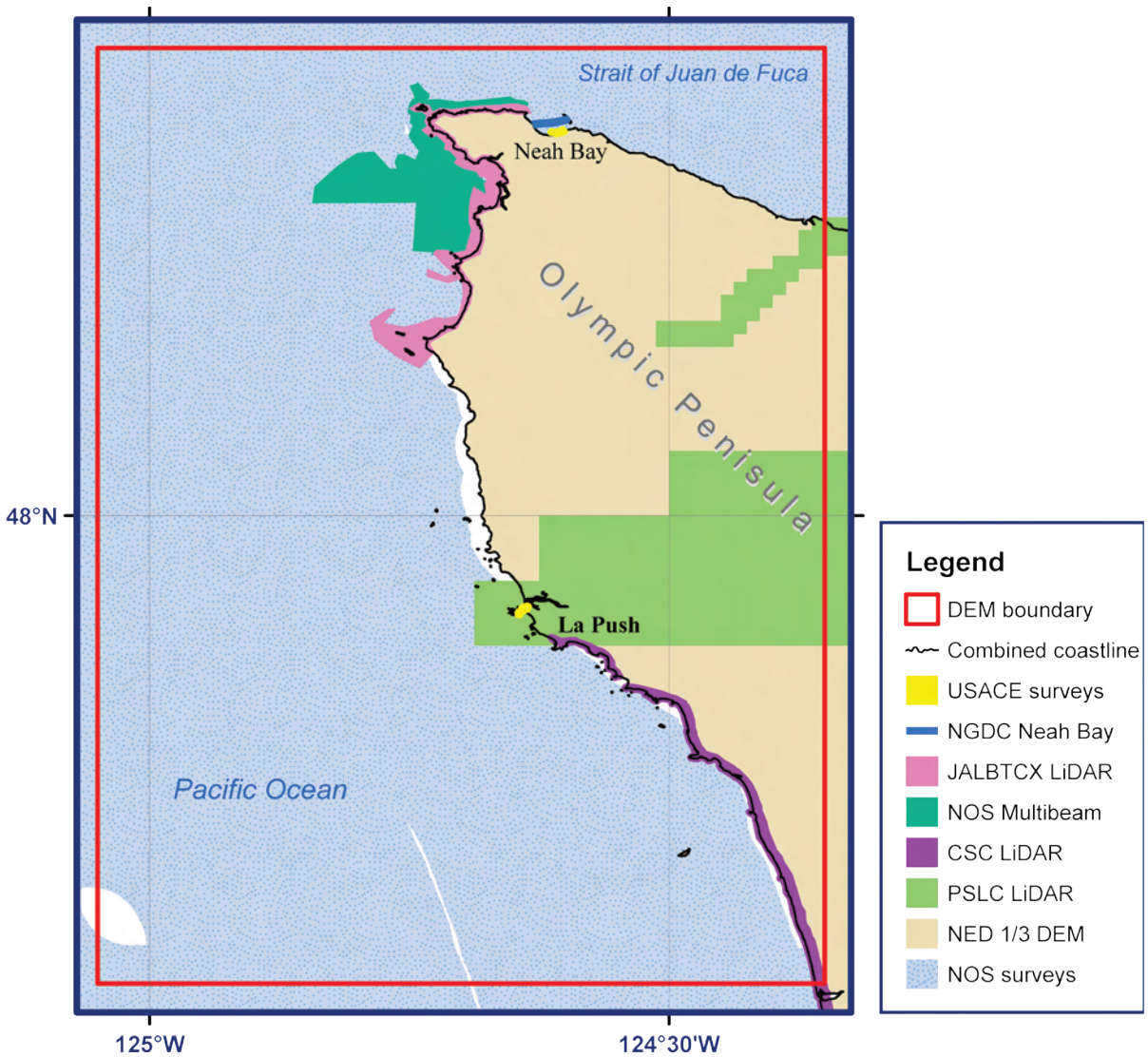

Figure 3. *Source and coverage of datasets used to compile the La Push DEM.*

3.1.1 Shoreline

Coastline datasets of the La Push region were obtained from the Washington State Department of Transportation (WSDOT) and NOAA's Office of Coast Survey electronic navigational charts (ENCs; Table 2; Fig. 4).

Table 2: Shoreline datasets available in the La Push, Washington region.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
OCS ENC	2006-2007	Coastline	1:40,000 to 1:176,253	WGS84 geographic	Mean High Water	http://nauticalcharts.noaa.gov/mcd/enc/index.htm
Washington State Dept. of Transportation	1995	Digitized hydrography	1:100,000	NAD83 geographic		http://www.wsdot.wa.gov/mapsdata/GeoDataCatalog/default.htm#georef
Washington State Dept. of Transportation	1996	Digitized hydrography	1:24,000	NAD83 geographic		http://www.wsdot.wa.gov/mapsdata/GeoDataCatalog/default.htm#georef

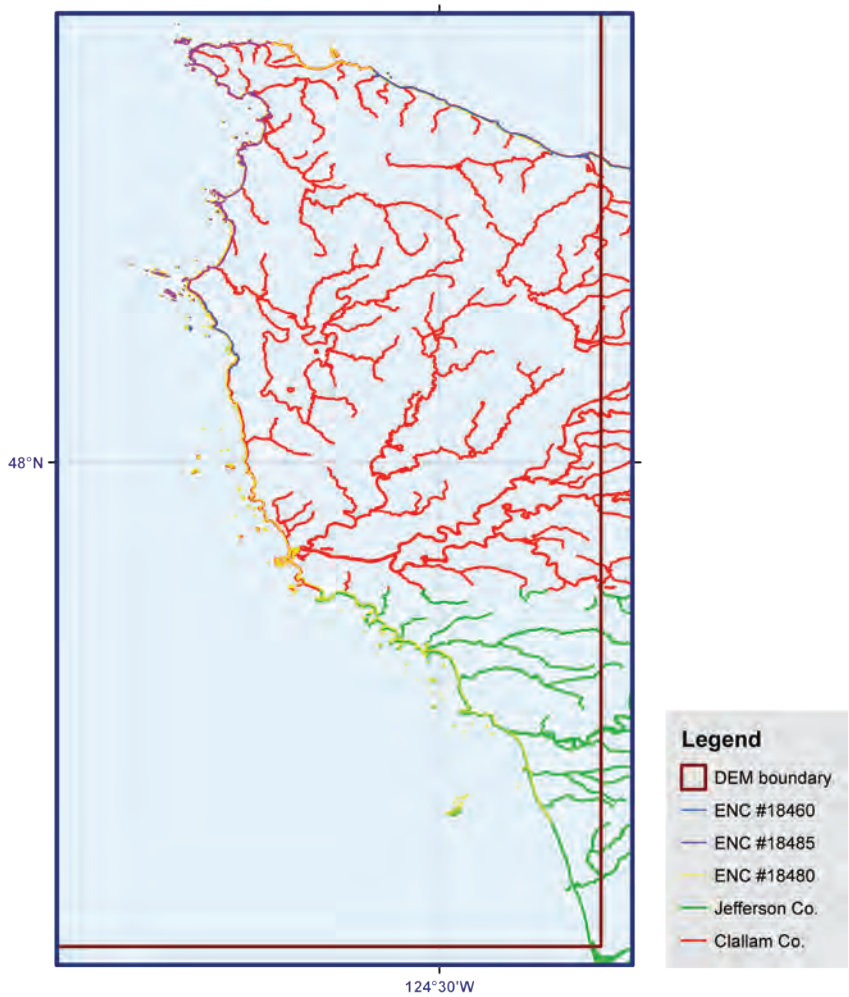

Figure 4. *Digital coastline datasets available in the La Push region. DEM boundary shown in brown.*

1) OCS electronic navigational chart

Three electronic navigational charts (ENCs) were available for the La Push area (#18460, 18480, and 18485) and were downloaded from NOAA's Office of Coast Survey website (http://nauticalcharts.noaa.gov/mcd/enc/index.htm). The ENCs are available in S-57 format and include coastline data files at Mean High Water. ENCs #18460 and 18480 were at a scale significantly smaller than the 1:24,000 WSDOT dataset. ENC #18485, at 1:40,000 scale, provided limited coverage in the Makah Bay region and did not reflect the NED topographic dataset as accurately as the WSDOT 1:24,000 dataset. Other nautical charts were available as georeferenced raster nautical charts (RNCs; digital images of the charts) and were used to QC bathymetric and topographic datasets.

2) Washington State Department of Transportation 1:100,000

The Washington State Department of Transportation (http://www.wsdot.wa.gov/) has developed a hydrography dataset for entire state of Washington. The dataset is derived from 1:100,000 scale USGS topographic maps, though, while offering complete coverage of the DEM area, did not provide as much resolution as the 1:24,000 scale WSDOT coastline.

3) Washington State Department of Transportation 1:24,000

The Washington State Department of Transportation has also developed a more detailed hydrography dataset from 7.5 minute USGS topographic quads (1:24,000 scale). This dataset is divided by county and available from the WSDOT web site. Clallam and Jefferson County hydrography data, which fully cover the La Push region, were downloaded and edited in ArcMap to remove inland water bodies and rivers.

The WSDOT 1:24,000 scale coastlines of Jefferson and Clallam counties were merged to create a 'combined coastline' of the La Push area. River inlets were included in the 'combined coastline' where digital bathymetric data was present. Modifications to the coastline include adjustments to fit most recent topographic and topographic–bathymetric data. In addition, the breakwater at Neah Bay and the jetties to the north and south of the Quillayute River entrance at La Push (Fig. 4) were added as they were not represented in the 1:24,000 WSDOT coastlines. All modifications were done using ArcMap editing tools.

Figure 5. *Aerial photo of La Push at Quillayute River entrance (http://apps.ecy.wa.gov/shorephotos/index.html).*

3.1.2 Bathymetry

Bathymetric datasets used in the compilation of the La Push DEM include 26 NOS hydrographic surveys, two USACE surveys located at the La Push and Neah Bay harbors, and an NOS shallow-water multibeam sonar survey that covers Makah Bay (Table 3; Fig. 6).

Table 3: Bathymetric datasets used in compiling the La Push DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NOS	1891 to 2001	Hydrographic survey soundings	Ranges from 10 m to 1 km (varies with scale of survey, depth, traffic, and probability of obstructions)	NAD27 or NAD83 geographic	Mean Low Water or Mean Lower Low Water	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
USACE	2006	Hydrographic survey profiles	Profiles 50 to 200 meters long, spaced 50 meters apart, with point spacing < 1 meter	NAD83 Washington State Plane North	Mean Lower Low Water	
NOS	2003	Shallow water multibeam sonar	10 meters	NAD83 geographic	Mean Lower Low Water	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html

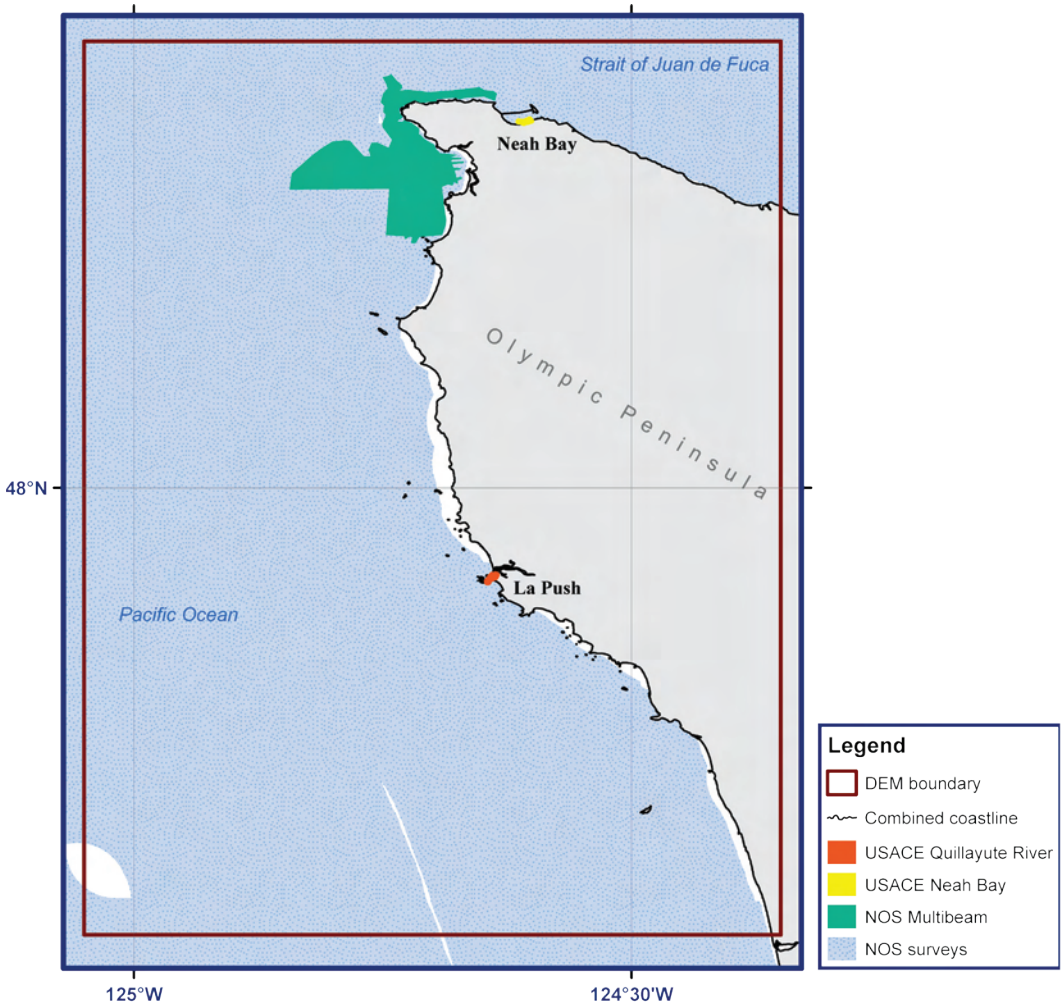

Figure 6. *Spatial coverage of bathymetric datasets used to compile the La Push DEM.*

1) NOS hydrographic survey data

A total of 26 NOS hydrographic surveys conducted between 1893 and 2001 were utilized in developing the La Push DEM (Table 4; Fig. 7). The hydrographic survey data were originally vertically referenced to Mean Lower Low Water (MLLW) or Mean Low Water (MLW) and horizontally referenced to either NAD27 or NAD83 datums.

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). The data were then converted to WGS84 and MHW using FME software, an integrated collection of spatial extract, transform, and load tools for data transformation (http://www.safe.com). The surveys were subsequently clipped to a polygon 0.05 degree (~5%) larger than the La Push 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 the topographic, bathymetric, and topographic–bathymetric datasets, the combined coastline, and NOS raster nautical charts (RNCs). The surveys were clipped to remove soundings that overlap the more recent USACE survey at Neah Bay, and where soundings from older surveys have been superseded by more recent NOS surveys. Five additional NOS surveys were located within the DEM boundary but were not used due to inconsistencies with more recent, overlapping data.

Table 4: Digital NOS hydrographic surveys used in compiling the La Push DEM.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum*
H02170	1893	80,000	mean low water	undetermined
H02869	1907	50,000	mean lower low water	undetermined
H04735	1927	80,000	mean lower low water	NAD27
H05068	1930	40,000	mean lower low water	NAD27
H05069	1930	20,000	mean lower low water	NAD27
H05070	1930	20,000	mean lower low water	NAD27
H05107	1930	20,000	mean lower low water	NAD27
H05108	1930	20,000	mean lower low water	NAD27
H05109	1930	20,000	mean lower low water	NAD27
H05110	1930	40,000	mean lower low water	NAD27
H05111	1930/42	40,000/20,000	mean lower low water	NAD27
H05114	1930	120,000	mean lower low water	NAD27
H05146	1931	20,000	mean lower low water	NAD27
H05148	1931	40,000	mean lower low water	NAD27
H05155	1931	20,000	mean lower low water	NAD27
H05156	1931	20,000	mean lower low water	NAD27
H05157	1931	40,000	mean lower low water	NAD27
H07036	1945	5,000	mean lower low water	NAD27
H07037	1945	10,000	mean lower low water	NAD27
H08241	1955	5,000	mean lower low water	NAD27
H08242	1955	10,000	mean lower low water	NAD27
H09413	1974	80,000	mean lower low water	NAD27
H09415	1974	40,000	mean lower low water	NAD27
H09416	1974	40,000	mean lower low water	NAD27
H09418	1974	80,000	mean lower low water	NAD27
H11086	2001	5,000	mean lower low water	NAD83

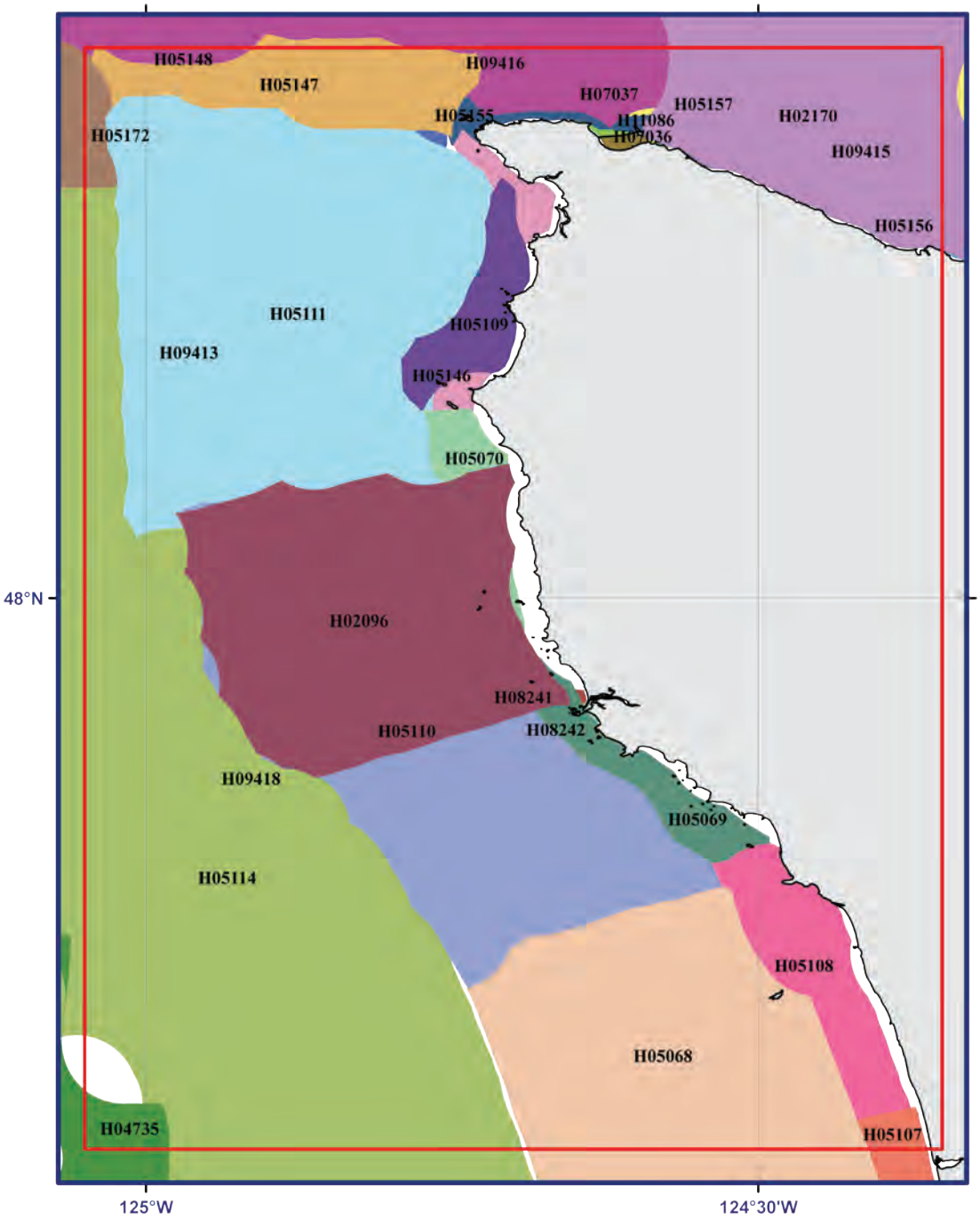

Figure 7. *Digital NOS hydrographic survey coverage in the La Push region. Some older surveys were not utilized as they have been superseded by more recent surveys. DEM boundary in red.*

2) U.S. Army Corps of Engineers hydrographic surveys

The USACE, La Push District provided NGDC with two recent bathymetric surveys located in Neah Bay and in the Quillayute River entrance at the La Push harbor (Fig. 8). The surveys were collected in 2006, and referenced to NAD83 Washington State Plane North and Mean Lower Low Water (MLLW) datums. The files were converted to WGS84 and MHW using FME. Point spacing averages less than 1 meter along profiles 50 to 200 meters long and averaging 50 meters apart.

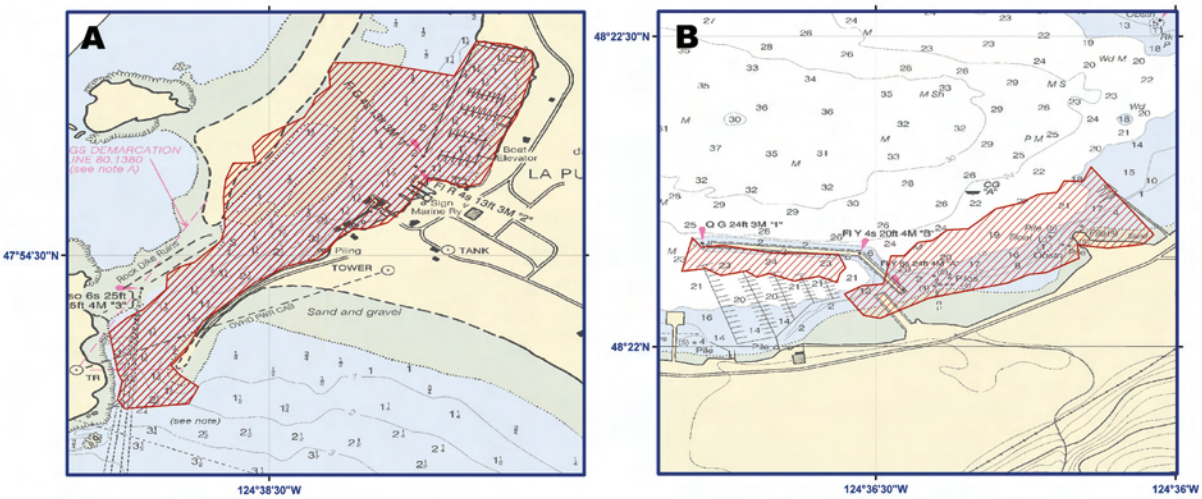

Figure 8. *Digital USACE hydrographic survey coverage in the La Push region. Surveys shown in red, with RNCs as background. (A). Quillayute River entrance survey. (B). Neah Bay survey.*

3) NOS shallow water multibeam survey

NOAA's NOS conducted a shallow water multibeam sonar survey in Makah Bay and to the north around Cape Flattery (Fig. 9). The survey was downloaded from the NGDC hydrographic survey website (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) in ASCII xyz gridded format in NAD83 geographic at 10-meter resolution and referenced to MLLW. This dataset provided dense bathymetric coverage in the area, particularly around the small islands and rocks off Cape Flattery.

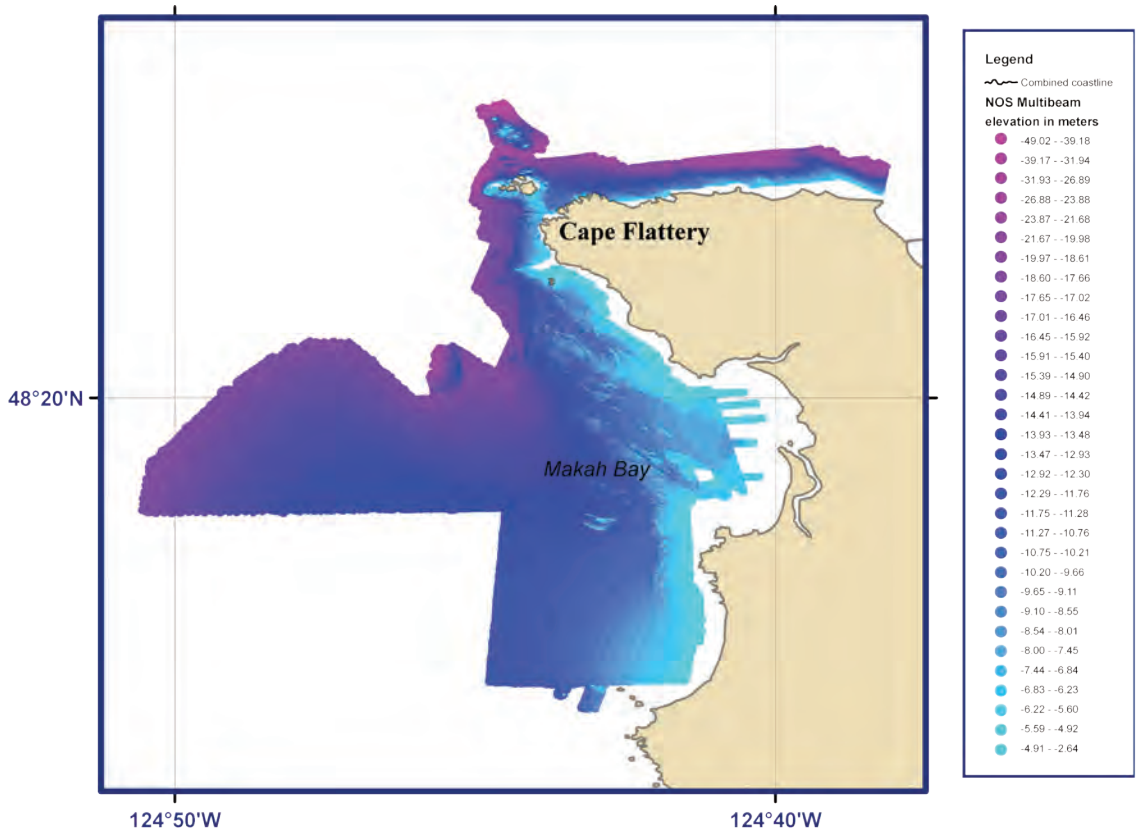

Figure 9. *Coverage of NOS shallow-water multibeam sonar survey H11083. The high resolution multibeam survey covers the near-shore region of Makah Bay and around Cape Flattery.*

3.1.3 Topography

Topographic datasets in the La Push region were obtained from NOAA's Coastal Services Center (CSC), the Puget Sound LiDAR Consortium (PSLC), and the U.S. Geological Survey (USGS; Table 5; Fig. 10). NGDC digitized the breakwater as Neah Bay as it was not represented in any dataset.

Table 5: Topographic datasets used in compiling the La Push DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
CSC	2002	Coastal LiDAR	~6 meters	NAD83 geographic	NAVD88 (meters)	http://maps.csc.noaa.gov/TCM/
PSLC	2005	LiDAR	~2 meters	NAD83 Washington State Plane North (feet)	NAVD88 (feet)	http://pugetsoundlidar.ess.washington.edu/
PSLC	2001	Bare-earth DEMs	~2 meters	NAD83 Washington State Plane North (feet)	NAVD88 (feet)	http://pugetsoundlidar.ess.washington.edu/
USGS	1999-2000	NED DEM	1/3 arc-second	NAD83 geographic	NAVD88 (meters)	http://ned.usgs.gov/
NGDC	2007	Digitized breakwater	< 10 meters	WGS84 geographic	MHW	

Figure 10. *Source and coverage of topographic datasets used to compile the La Push DEM.*

1) Coastal Services Center topographic LiDAR

NOAA's Coastal Services Center provided NGDC with topographic LiDAR datasets in NAD83 geographic horizontal datum and NAVD88 vertical datum for the coastal area south of La Push (Fig. 11). These data have point spacing approximately 6 meters apart and extend 50 to 525 meters inland from the coastline. These data were not processed to bare earth and at higher elevations were inconsistent with the NED bare-earth DEMs. The LiDAR data were therefore 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.

Figure 11. *Spatial coverage of CSC topographic LiDAR datasets used to compile the La Push DEM.*

2) Puget Sound topographic LiDAR data

The Puget Sound LiDAR Consortium (PSLC) provided NGDC with a topographic LiDAR dataset for northern coastal Clallam County (Fig. 10). The LiDAR data had been processed to bare earth and supplied in tiles covering approximately 1 km^2 each. Data were in NAD83 State Plane Washington North and NAVD88 (feet).

The LiDAR data files contained position and elevation values for both land and water areas. FME was used in initial processing to remove elevation values less than zero. The LiDAR files were then evaluated and edited using QT Modeler to remove points remaining over water.

3) Puget Sound topographic LiDAR DEMs

PSLC also provided NGDC with bare-earth topographic LiDAR DEMs of southwestern Clallam County (Fig. 10). Each DEM covers 5 km^2 with a grid cell spacing of ~2 meters. DEMs were in NAD83 State Plane Washington North and NAVD88 (feet). Elevations in open-water areas reflect gridding interpolation from nearby shoreline values and were removed by clipping to the combined coastline.

4) USGS NED topographic DEM

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

5) NGDC Neah Bay breakwater

As no topographic representation of the breakwater at Neah Bay was available, NGDC digitized this feature as a line segment with an elevation of 1 meter (Fig. 12). The line segment was then converted to points at less than 10 meter intervals to ensure representation of the breakwater in the La Push DEM.

Figure 12. *Aerial photo of breakwater at Neah Bay (http://apps.ecy.wa.gov/shorephotos/index.html).*

The NED DEM and both PSLC LiDAR datasets, all processed to bare earth, did not match up in elevation. One possible cause is LiDAR returns from forest canopy not being fully eliminated in PSLC bare-earth processing. The effect is a 'step' of up to 30 meters in the terrain surface when gridded at 1 arc-second for quality control. As a result of the elevation discrepancy between datasets, only two of the fourteen PSLC DEMs were used in developing the La Push DEM: those closest to the town of La Push. NED data at La Push were not as consistent as the PSLC DEMs, which were closer to matching the USACE hydrographic survey data and contained more accurate elevation values along both the north and south jetties and the entrance to the La Push harbor. To reduce the differences in elevation between the NED and PSLC data, a 75-meter buffer or data gap was created in the NED DEM by outlining the PSLC data. Gridding interpolation across the gap, when building the final La Push DEM, produced a more gradual "slope" rather than an artificial "step".

3.1.4 Topography–Bathymetry

One topographic–bathymetric dataset was available from the Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX), covering the northern portion of the La Push DEM from Cape Alava to Neah Bay (Fig. 13, Table 6).

Table 6: Topographic–bathymetric dataset used in compiling the La Push DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*
JALBTCX LiDAR	2005	Coastal LiDAR	< 5 meters	WGS84 UTM Zone 10	MLLW (meters)

1) JALBTCX topographic–bathymetric LiDAR

The JALTBCX LiDAR dataset provided topographic–bathymetric coverage for the coastal and near shore regions north of La Push. These data were obtained in WGS84 UTM Zone 10 horizontal datum and MLLW. FME was used to re-project the xyz data to WGS84 geographic and to MHW. Point spacing varied from less than 5 meters with full coverage at the shoreline to more sparse farther from shore, where ‘clumps’ of data surrounded rocks and kelp.

As with the CSC topographic LiDAR datasets, a discontinuity between the NED DEM and the JALBTCX dataset created an artificial ‘berm’ along the coastline in preliminary grids. This effect is interpreted to have resulted from the JALBTCX LiDAR data having not been processed to bare earth and higher elevations therefore reflect returns from tree tops rather than land surface. In order to minimize this effect, elevation values greater than 10 meters were removed from the JALBTCX dataset using ArcMap. This elevation filtering was not done off shore so as to retain elevations located on rocks and islets not present in the NED DEM.

Figure 13. *Spatial coverage of JALBTCX topographic–bathymetric LiDAR dataset used to compile the La Push DEM.*

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the La Push DEM were originally referenced to a number of vertical datums including Mean Lower Low Water (MLLW), Mean Low Water (MLW), and North American Vertical Datum of 1988 (NAVD88). All datasets were transformed to MHW to provide the worst-case scenario for inundation modeling. Units were converted from feet to meters as appropriate.

1) Bathymetric data

The NOS hydrographic surveys, the USACE surveys, and the NOS multibeam sonar survey were transformed from MLLW and MLW to MHW, using FME software, by adding a constant derived from La Push Pier tide station #9442396 (Table 7).

2) Topographic data

The USGS NED 1/3 arc-second DEM, the PSLC LiDAR datasets, and the CSC coastal LiDAR data were originally referenced to NAVD88. As the La Push Pier tide station did not reference vertical datum NAVD88, conversion to MHW, using FME software, was accomplished by adding a constant offset of -1.882 meters (Table 7). This constant was derived by calculating the difference between MHW and NAVD88 at both Neah Bay and Sekiu tide stations and averaging the values.

3) Topographic–Bathymetric data

The JALBTCX topographic–bathymetric LiDAR data were transformed from MLLW to MHW by adding a constant offset of -2.43 meters using FME.

Table 7. *Relationship between Mean High Water and other vertical datums in the La Push region.*

Vertical datum	*Difference to MHW*
NAVD88*	-1.882 meters
MLW	-2.002 meters
MLLW	-2.43 meters

* Datum relationship determined by values from tide station #9443090 Neah Bay and #9443361 Sekiu.

3.2.2 Horizontal datum transformations

Datasets used to compile the La Push DEM were originally referenced to WGS84 UTM Zone 10, NAD83 Washington State Plane North, NAD83 geographic, or NAD27 geographic horizontal datums. The relationships and transformational equations between these horizontal datums are well established. All data were converted to a horizontal datum of WGS84 geographic using FME software.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting ESRI shape files 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:

- Presence of extensive small streams and inland water bodies in the WSDOT 1:24,000 hydrography dataset, which had to be removed.
- Inconsistencies between the NED, CSC, PSLC and JALBTCX topographic data. These inconsistencies could result from forest canopy returns in the datasets. The La Push region, located on the Olympic Peninsula in Washington State, has large areas of dense forest canopy inland and stretching close to the shoreline. Coastal LiDAR data were clipped to remove higher elevations from suspected forest canopy.
- Data values over the ocean and rivers in the NED and PSLC LiDAR topographic data. Each dataset required automated clipping to the combined coastline.
- Digital, measured bathymetric values from NOS surveys date back over 100 years. More recent data, such as the USACE hydrographic surveys differed from older NOS data by as much as 10 meters. The older NOS survey data were excised where more recent bathymetric data exists.

3.3.2 Smoothing of bathymetric data

The NOS hydrographic surveys are generally sparse at the resolution of the 1/3 arc-second La Push 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 this low resolution dataset, and to provide effective interpolation into the coastal zone, a 1 arc-second-spacing 'pre-surface' bathymetric grid was generated using GMT, an NSF-funded share-ware software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/).

The NOS hydrographic point data, in xyz format, were clipped to remove overlap with the JALBTCX topographic–bathymetric LiDAR data, then combined with the USACE soundings and the NOS multibeam data into a single file, along with points extracted from the combined coastline—to provide a buffer along the entire coastline. In the Cape Alava region, NOS survey H05146 soundings were not clipped to the topographic–bathymetric LiDAR data in order to more accurately reflect the depths on the tidal flats and in areas with heavy kelp (Fig. 14).

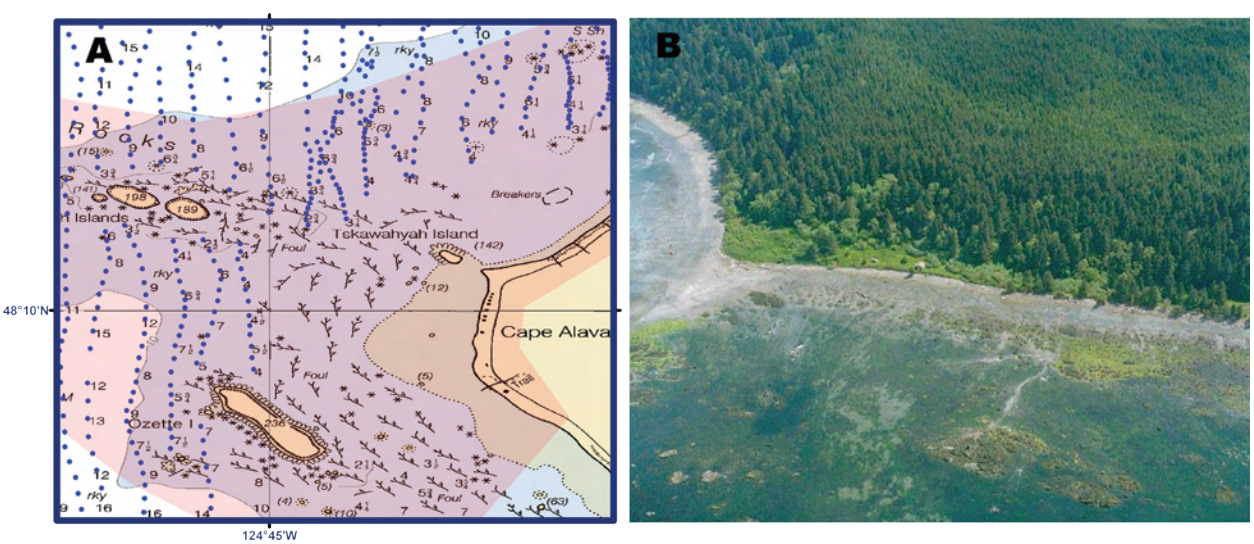

Figure 14. *Tidal flats at Cape Alava. (A) Kelp and other features fouling the coastal zone as shown on nautical chart #18485. Pink shaded area represents JALBTCX topographic–bathymetric LiDAR data, with NOS survey H05146 represented by blue dots. (B) Aerial photo of Cape Alava (http://apps.ecy.wa.gov/shorephotos/index.html).*

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 La Push 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), converted to a shape file, and then exported as an xyz file for use in the final gridding process (see Table 8).

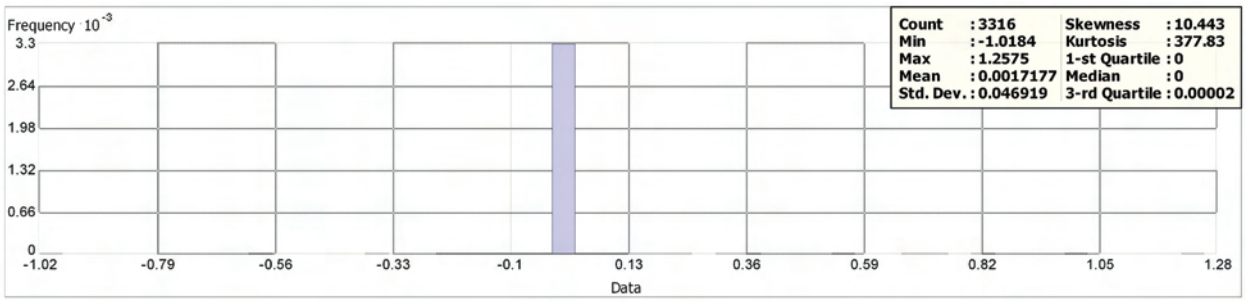

Figure 15. *Histogram of the differences between NOS hydrographic survey H09413 and the 1 arc-second pre-surfaced bathymetric grid.*

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 La Push DEM. MB-System is an NSF-funded share-ware software application specifically designed to manipulate submarine multibeam sonar data, though it can utilize a wide variety of data types, including generic xyz data. The MB-System tool 'mbgrid' 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 PSLC bare-earth LiDAR data. Least weight was given to the pre-surfaced 1 arc-second bathymetric grid. Gridding was performed in northern and southern halves. The resulting Arc ASCII grids were seamlessly merged in ArcCatalog to create the final 1/3 arc-second La Push DEM.

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

Dataset	*Relative Gridding Weight*
JALBTCX topographic–bathymetric coastal LiDAR	100
NOS shallow-water multibeam sonar survey	100
USACE bathymetry	100
CSC topographic coastal LiDAR	100
PSLC topographic bare-earth LiDAR	1000
USGS NED topographic DEM	10
NOS hydrographic surveys: bathymetric soundings	10
NGDC breakwater	100
Combined coastline	10
Pre-surfaced bathymetric grid	1

3.4 Quality Assessment of the DEM

3.4.1. Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the La Push DEM is dependent upon the datasets used to determine corresponding DEM cell values. Topographic features have an estimated accuracy of about 10 meters: PSLC, CSC and JALBTCX topographic LiDAR data have an accuracy of approximately 6 meters; NED topography is accurate to within about 10 meters. 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 subaerial 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 the morphologic change that occurs in this dynamic region.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the La Push 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 PSLC, JALBTCX and CSC LiDAR data, and up to 7 meters for NED topography. Bathymetric areas have an estimated accuracy of between 0.1 meters and 5% of water depth. Those values were derived from the wide range of input data sounding measurements from the early 20th century to recent, GPS-navigated sonar surveys. Gridding interpolation to determine values between sparse, poorly-located NOS soundings degrades the vertical accuracy of elevations in deep water.

3.4.3 Slope maps and 3-D perspectives

ESRI ArcCatalog was used to generate a slope grid from the La Push 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. Three-dimensional viewing of the UTM-transformed DEM was accomplished using ESRI ArcScene (e.g., Fig. 17). Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 1 shows a color image of the 1/3 arc-second La Push DEM in its final version.

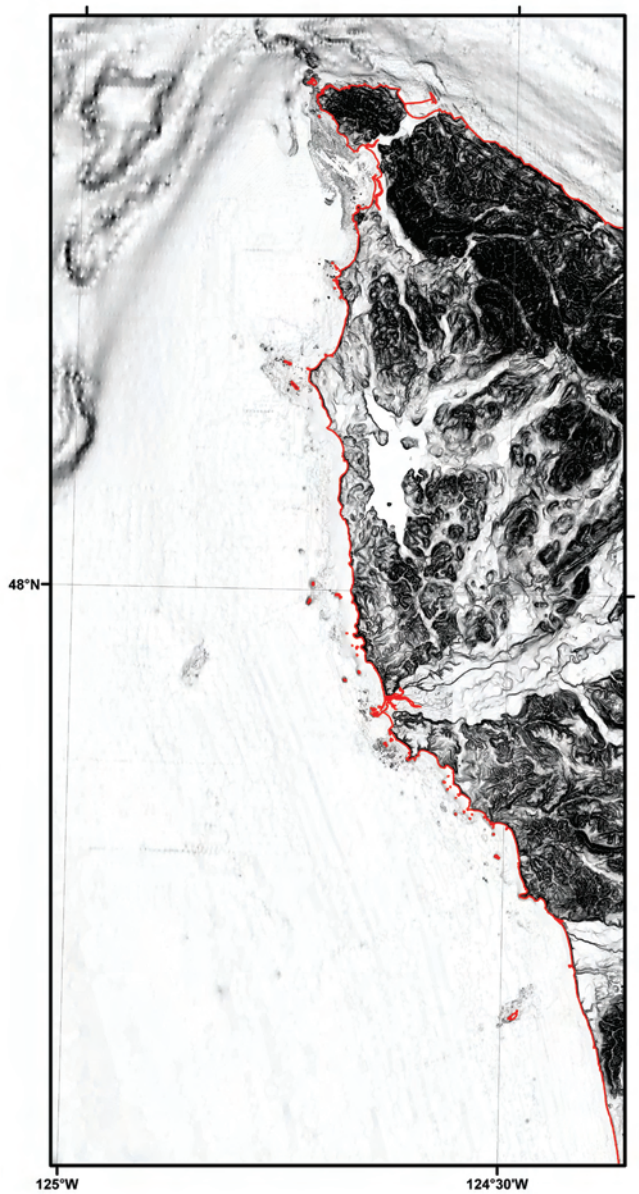

Figure 16. *Slope map of the La Push DEM. Flat-lying slopes are white; dark shading denotes steep slopes; combined coastline in red.*

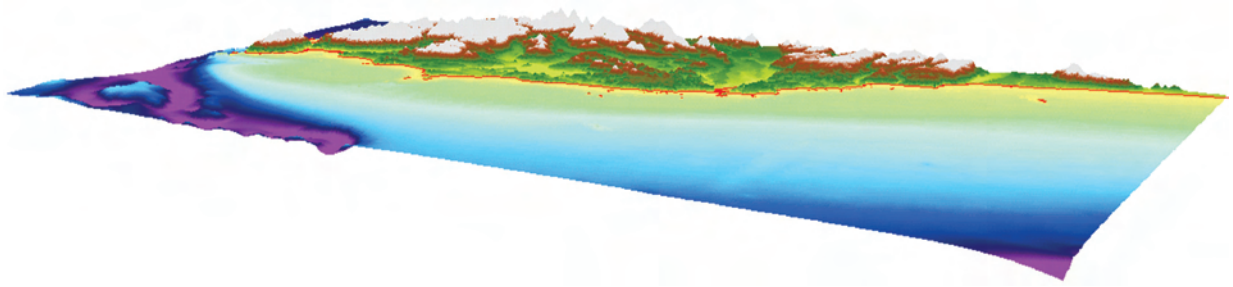

Figure 17. *Perspective view from the southwest of the La Push DEM. Combined coastline in red; vertical exaggeration–times 5.*

3.4.4 Comparison with source data files

To ensure grid accuracy, the La Push 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 PSLC topographic LiDAR survey file and the La Push DEM is shown in Figure 18. Differences cluster around zero, with only a handful of soundings, in regions of steep topography, exceeding 1.5-meter discrepancy from the DEM.

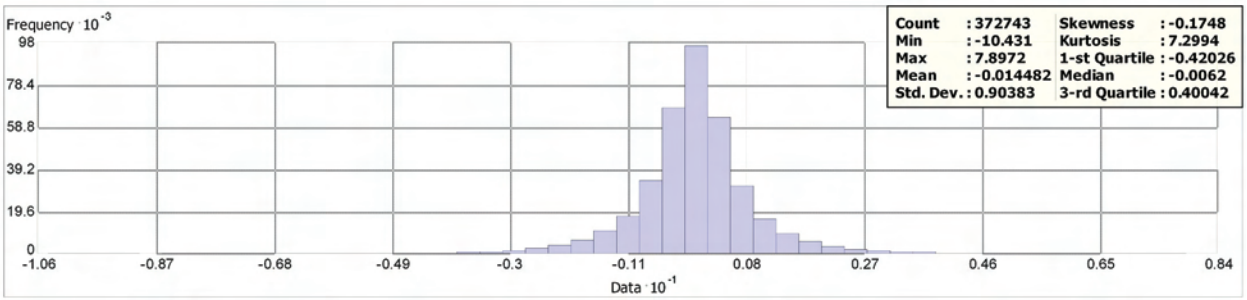

Figure 18. *Histogram of the differences between one PSLC LiDAR survey and the La Push DEM.*

3.4.5 Comparison with NGS geodetic monuments

The elevations of 260 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 NAD83 (typically sub-mm accuracy) and elevations in NAVD88 (in meters). Elevations were shifted to MHW vertical datum (see Table 7) for comparison with the La Push DEM (see Fig. 20 for monument locations). Differences between the La Push DEM and the NGS geodetic monument elevations range from -61 to 58 meters, with the majority of them being within ± 12 meters range. Negative values indicate that the monument elevation is less than the DEM (Fig. 19). Only 15 monuments out of 260 total showed significant deviations from the DEM. Such discrepancies are caused by the rough terrain in La Push area, where significant changes in local relief could happen on the scale of less then 10 meters.

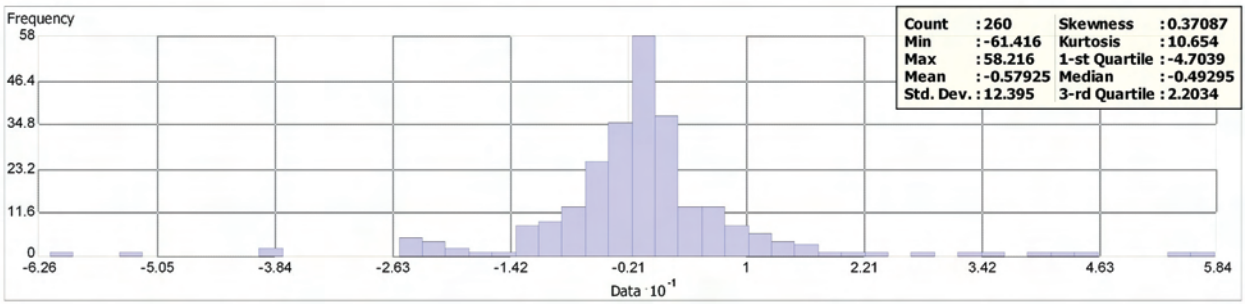

Figure 19. *Histogram of the differences between NGS geodetic monument elevations and the La Push DEM.*

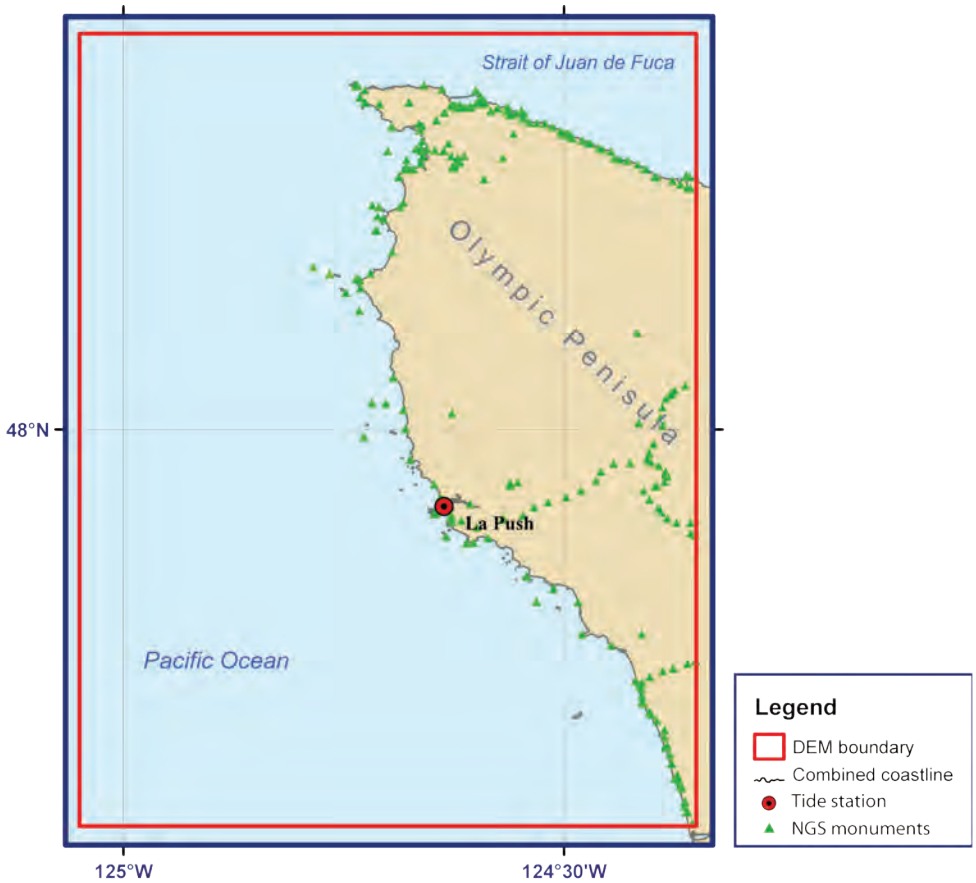

Figure 20. *Location of NGS geodetic monuments and the NOAA La Push tide station. NGS monument elevations were used to evaluate the DEM.*

4. Summary and Conclusions

A topographic–bathymetric digital elevation model of the La Push, Washington 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 La Push DEM, based on NGDC's research and analysis, are listed below:

- Conduct topographic–bathymetric LiDAR surveys for coastline between La Push and Cape Alava.
- Conduct hydrographic surveys for near-shore areas.
- Complete topographic LiDAR surveying of entire region.
- Process CSC and JALBTCX coastal LiDAR data to bare earth.

5. Acknowledgments

The creation of the La Push DEM was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Chris Chamberlin and Vasily Titov (PMEL), Lonnie Reid-Pell (USACE, Seattle District), and Diana Martinez (Puget Sound Regional Council).

6. References

Nautical Chart #18460, 13th Edition, 2006. Strait of Juan de Fuca Entrance. Scale 1:100,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18480, 31st Edition, 2006. Approaches to Strait of Juan de Fuca. Scale 1:176,253. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18484, 12th Edition, 2006. Neah Bay. Scale 1:10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18485, 16th Edition, 2007. Cape Flattery. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Haugerud, R.A., 1999, Digital elevation model (DEM) of Cascadia, latitude 39N-53N, longitude 116W-133W, U.S. Geological Survey Open-file Report 99-369, http://geopubs.wr.usgs.gov/open-file/of99-369/

Intelmann, Steven S., Jonathan Beaudoin and Guy R. Cochrane, 2006, Normalization and Characterization of Multibeam Backscatter: Koitlah Point to Point of the Arches, Olympic Coast National Marine Sanctuary - Survey HMPR-115-2004-03, (http://olympiccoast.noaa.gov/research/mapping/hmpr_115_2004_03/cruisereport_files/hmpr-115-2004-03_report.pdf)

7. Data Processing Software

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

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

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

GMT v. 4.1.4 – Generic Mapping Tools, shareware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/

MB-System v. 5.1.0, shareware developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System/

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