Digital Elevation Model for Garibaldi, Oregon: Procedures, Data Sources and Analysis

Prepared for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research by the NOAA National Geophysical Data Center (NGDC)
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1. Introduction

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

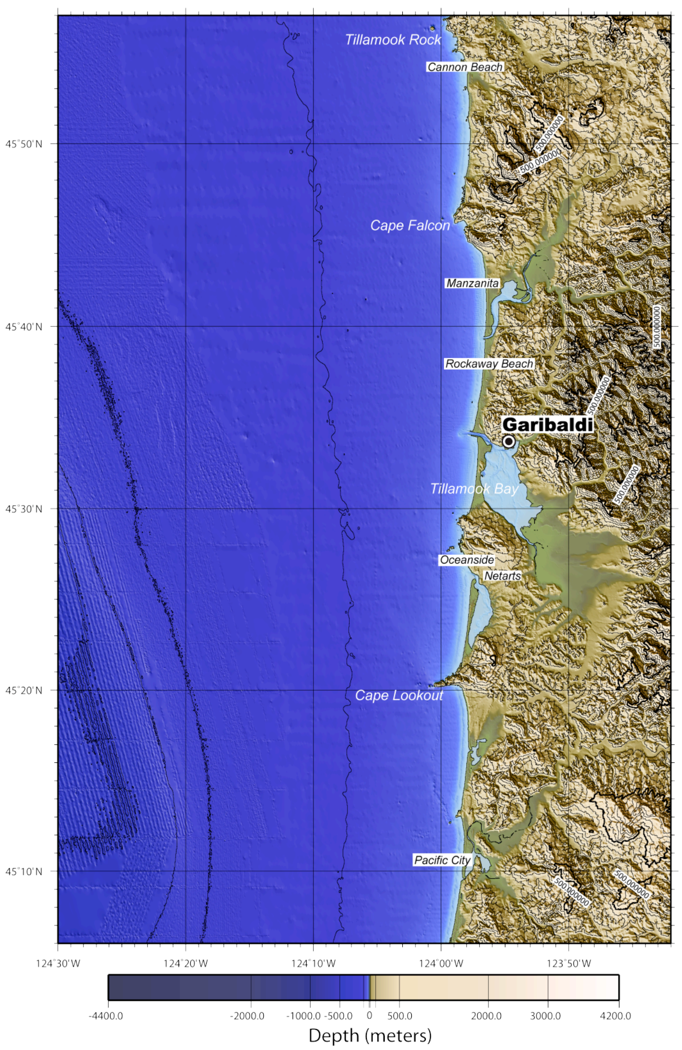

Figure 1. *Shaded relief image of the Garibaldi, Oregon DEM. Contour interval is 100 meters.*

1. The Garibaldi 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 Garibaldi, Oregon (45°33.6167′ N, 123°54.6833′ W) 1/3 arc-second of latitude is equivalent to 10.291 meters; 1/3 arc-second of longitude equals 7.229 meters.

2. STUDY AREA

The Garibaldi DEM covers the coastal region surrounding the town of Garibaldi, Oregon, located on the northern edge of Tillamook Bay. Included within the DEM boundary are the neighboring communities of Cannon Beach, Manzanita, and Rockaway Beach to the north and Oceanside, Netarts, and Pacific City to the south (Fig. 1). Garibaldi has a small population of approximately 1000 people, working primarily in the agricultural, fisheries, lumber, and recreation industries. The U.S. Coast Guard maintains a station in town.

Garibaldi lies near an active convergent tectonic zone (Fig. 2) making it especially vulnerable to seismically generated tsunamis. The Oregon Department of Geology and Mineral Industries (DOGAMI) has prepared a community tsunami plan in order to increase public awareness and safety of the threat of tsunamis.

> *"Tsunamis rank as one of the most dangerous natural disasters that could affect the Oregon coast. Although not frequent in occurrence, the damage caused by these catastrophic events is immediate and life threatening. The most destructive type of tsunami would be generated locally by a Cascadia subduction zone earthquake of magnitude of 8.0 to 9.0, or greater. Devastating tsunami waves would be expected to arrive along the Pacific Northwest coast including Oregon within 5 to 30 minutes after such an event, providing very little evacuation time" (http://www.coastalatlas.net/learn/topics/hazards/tsunami/index.asp).*

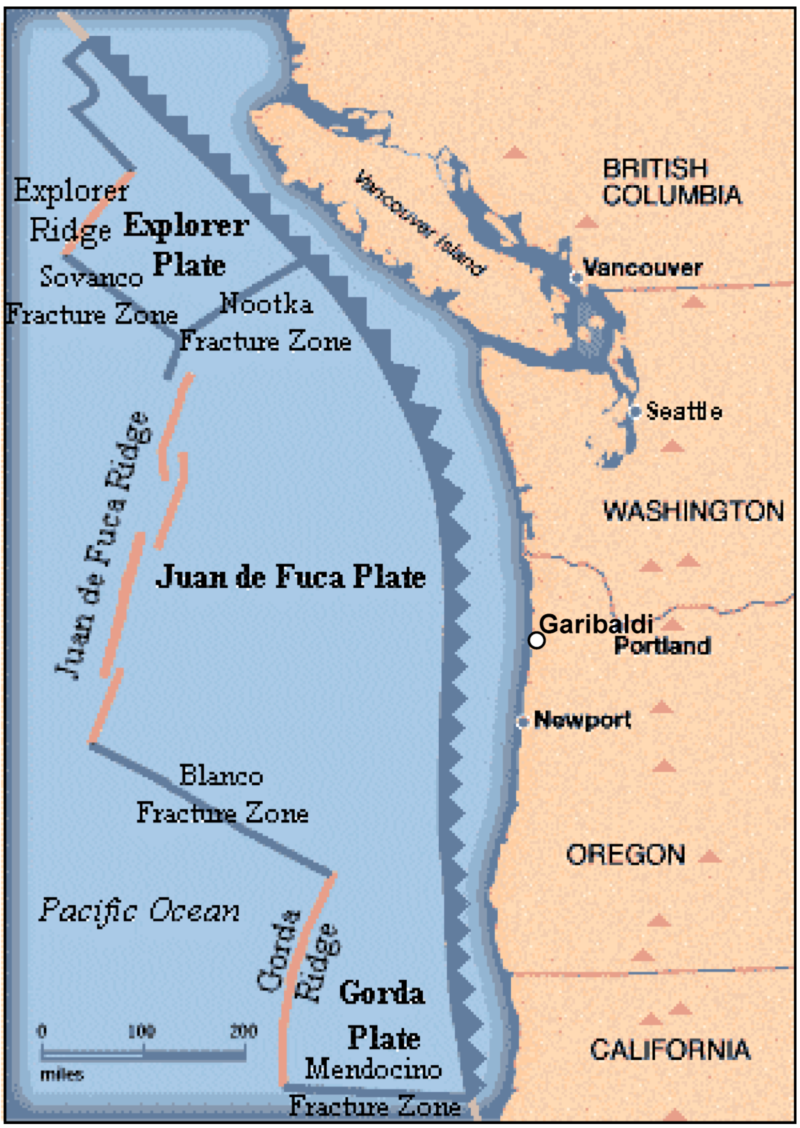

Figure 2. *Tectonic features along the Oregon-Washington coast. The leading edge of the Cascadia subduction zone is shown as dark blue triangles. (http://www.washington.edu/burkemuseum/geo_history_wa/Cascade%20Episode.htm).*

3. METHODOLOGY

The Garibaldi 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 Garibaldi, Oregon DEM.

Grid Area	Garibaldi, Oregon
Coverage Area	123.7º to 124.5º W; 45.1º to 45.95º 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, and topographic digital datasets (Fig. 3) were obtained from several U.S. federal 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 U.S. Army Corps of Engineers (USACE). Safe Software's (http://www.safe.com/) FME data translation tool package was used to shift datasets to WGS84 horizontal datum and to convert into ESRI (http://www.esri.com/) ArcGIS shape files. The shape files were then displayed with ArcGIS to assess data quality and manually edit datasets. Vertical datum transformations to MHW were accomplished using FME, based upon data from the local NOAA tide stations. 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.

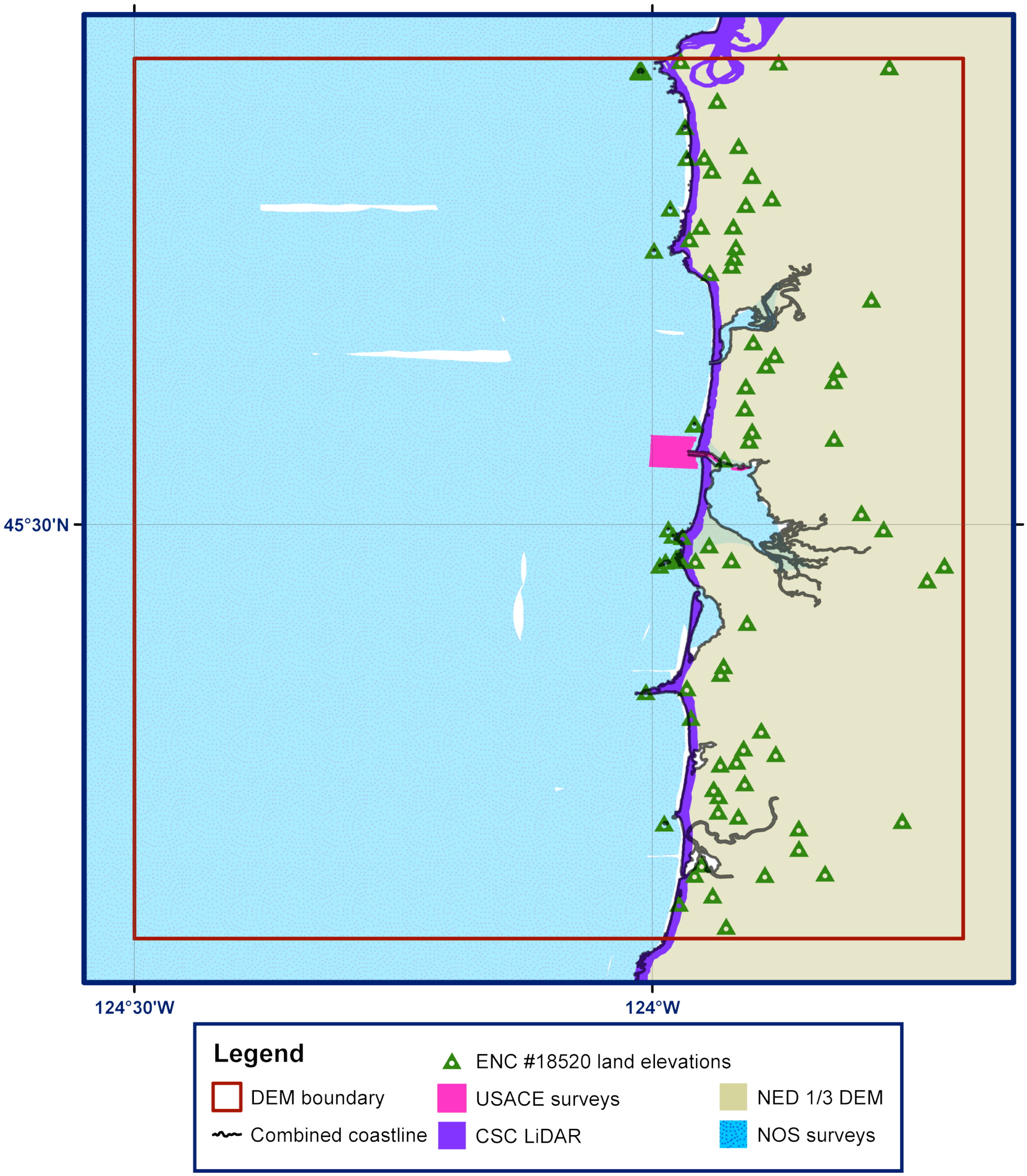

Figure 3. *Source and coverage of datasets used to compile the Garibaldi DEM.*

3.1.1 Shoreline

Coastline datasets of the Garibaldi region were obtained from NOAA's Coastal Services Center (CSC) and Office of Coast Survey Electronic Navigational Chart (ENC) #18520 (Table 2, Fig. 4). The ENC was not used in compiling a combined coastline for the Garibaldi DEM as it did not provide enough detail of coastal features, at a 1:185,238 scale, for developing a coastline for a one-third arc-second DEM. NGDC created a partial shoreline from CSC coastal LiDAR data.

Table 2: Shoreline datasets used in compiling the Garibaldi DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
CSC historical shoreline	1922-1974	digitized T-sheets	1:5,000 to 1:24,000	NAD83 geographic	Mean High Water	http://www.csc.noaa.gov/shoreline/data.html
NGDC/CSC LiDAR derived shoreline		Contour		WGS84 geographic	Mean High Water	

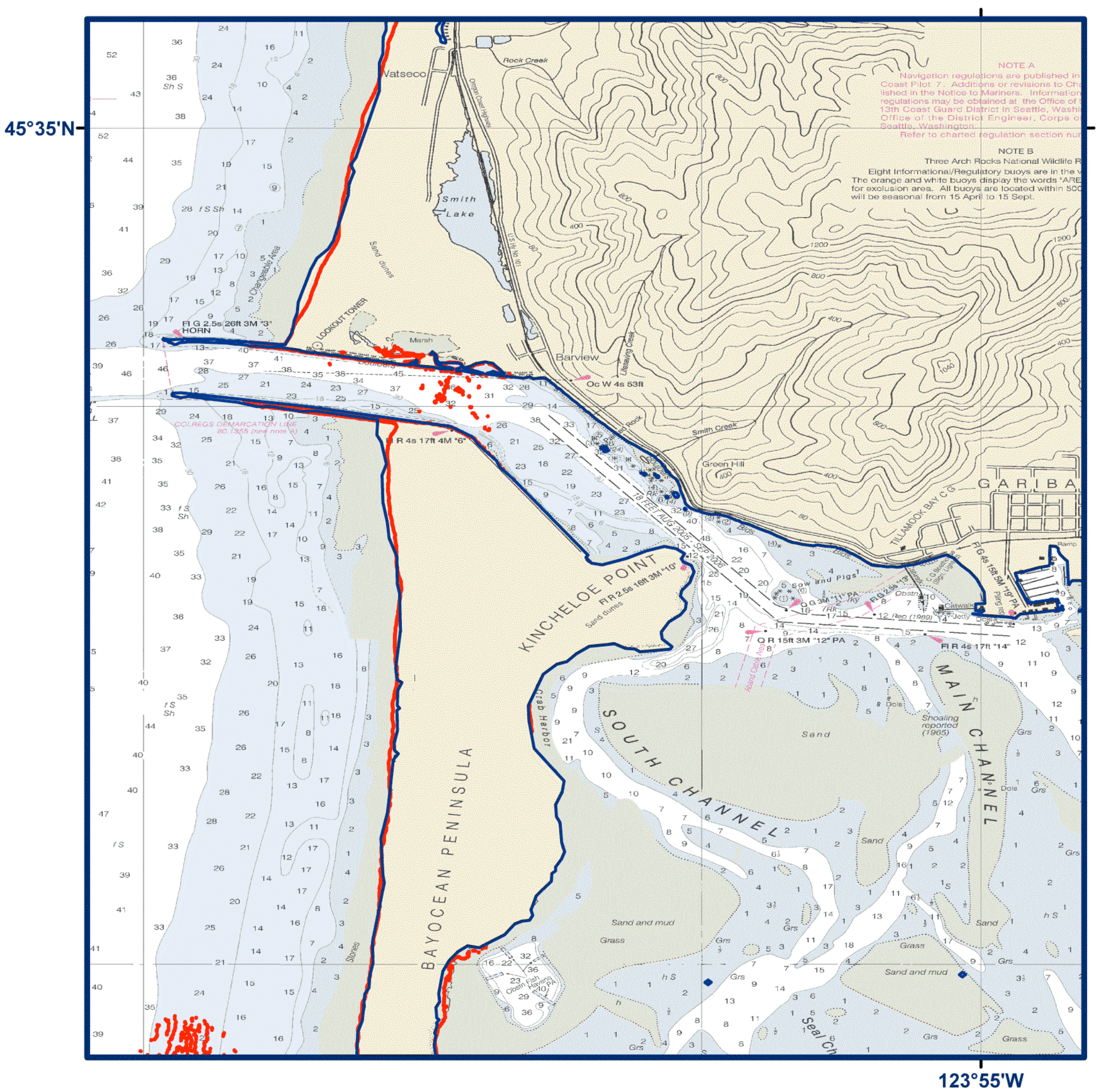

***Figure 4**. Coastlines at entrance to Tillamook Bay. NGDC's CSC LiDAR derived coastline shown in red and the CSC historical coastline in blue. RNC #18558 in background.*

1) Coastal Services Center historical shoreline

The CSC historical shoreline was downloaded from the CSC website. It was used in the bays and inlets where topographic LiDAR was not present. The historical shoreline provided more detail in these areas than the ENC #18520 extracted coastline. Features such as pilings, docks, and piers were edited out of the coastline dataset using ArcMap and by referencing the more detailed small scale RNCs for Tillamook Bay and Nehalem River (charts #18558 and #18556).

2) NGDC/Coastal Services Center LiDAR derived contour shoreline

In order to accurately represent the coastal topographic data, NGDC processed the most recent high resolution topographic LiDAR dataset available from CSC to create a zero elevation coastline at Mean High Water vertical datum. The zero contour line incorporated major off-shore rock features and the jetties located at the entrance to Tillamook Bay.

The two coastline datasets were merged to create a ‘combined coastline’. River inlets were left in the combined coastline where digital bathymetric data was present. Modifications to the coastline included adjustments to fit the most recent topographic data. At Wells Cove on Cape Lookout, the combined coastline was adjusted to fit the NED topographic DEM (Fig. 5). Additionally the jetty at the entrance to Tillamook Bay was extended to match RNC #18558. All modifications were done using ArcMap editing tools.

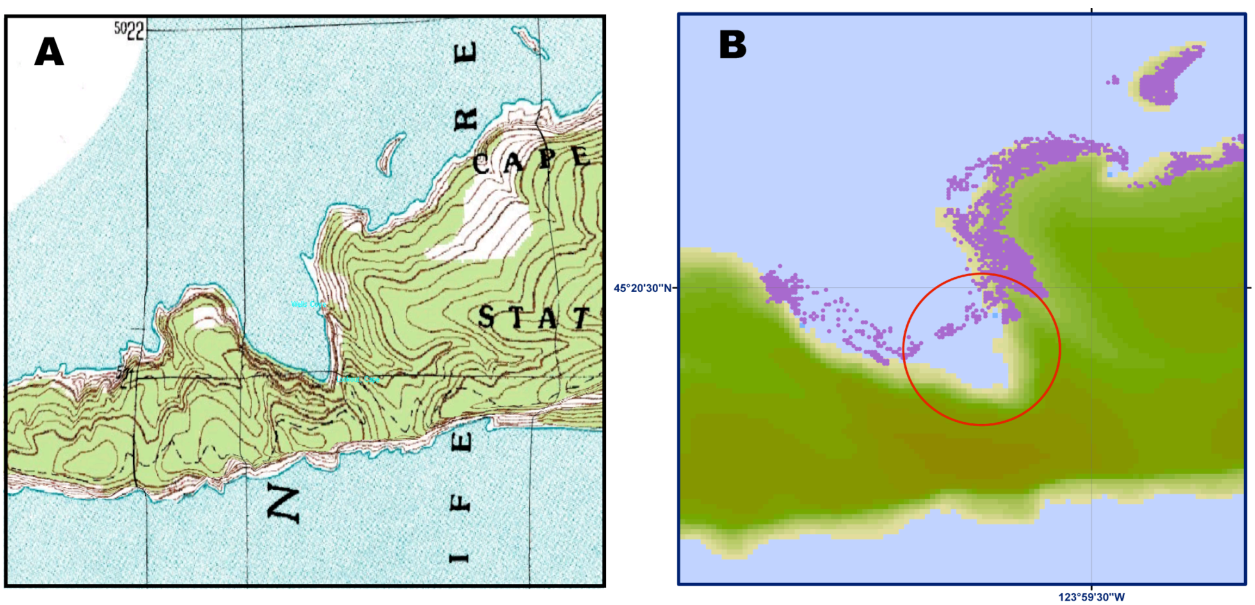

Figure 5. *Wells Cove at Cape Lookout. A) USGS topographic map of Cape Lookout showing Wells Cove. B) Red circle highlighting gap in CSC LiDAR, shown in purple, where ‘combined coastline’ was modified to fit NED DEM, shown as green/brown.*

3.1.2 Bathymetry

Bathymetric datasets used in the compilation of the Garibaldi DEM (Fig. 6) include 23 NOS hydrographic surveys and three USACE surveys located at the entrance to Tillamook Bay (Table 3).

Table 3: Bathymetric datasets used in compiling the Garibaldi DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NOS	1926 to 1987	Hydrographic survey soundings	Ranges from 10 m to 1 km (varies with scale of survey, depth, traffic, and probability of obstructions)	NAD13, NAD27, or NAD83 geographic	Mean Lower Low Water	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
USACE	2005 to 2006	Hydrographic survey	10 to 35 meters	NAD83 Oregon State Plane North (feet)	Mean Lower Low Water	https://www.nwp.usace.army.mil/op/nwh/xyzcoastal.asp

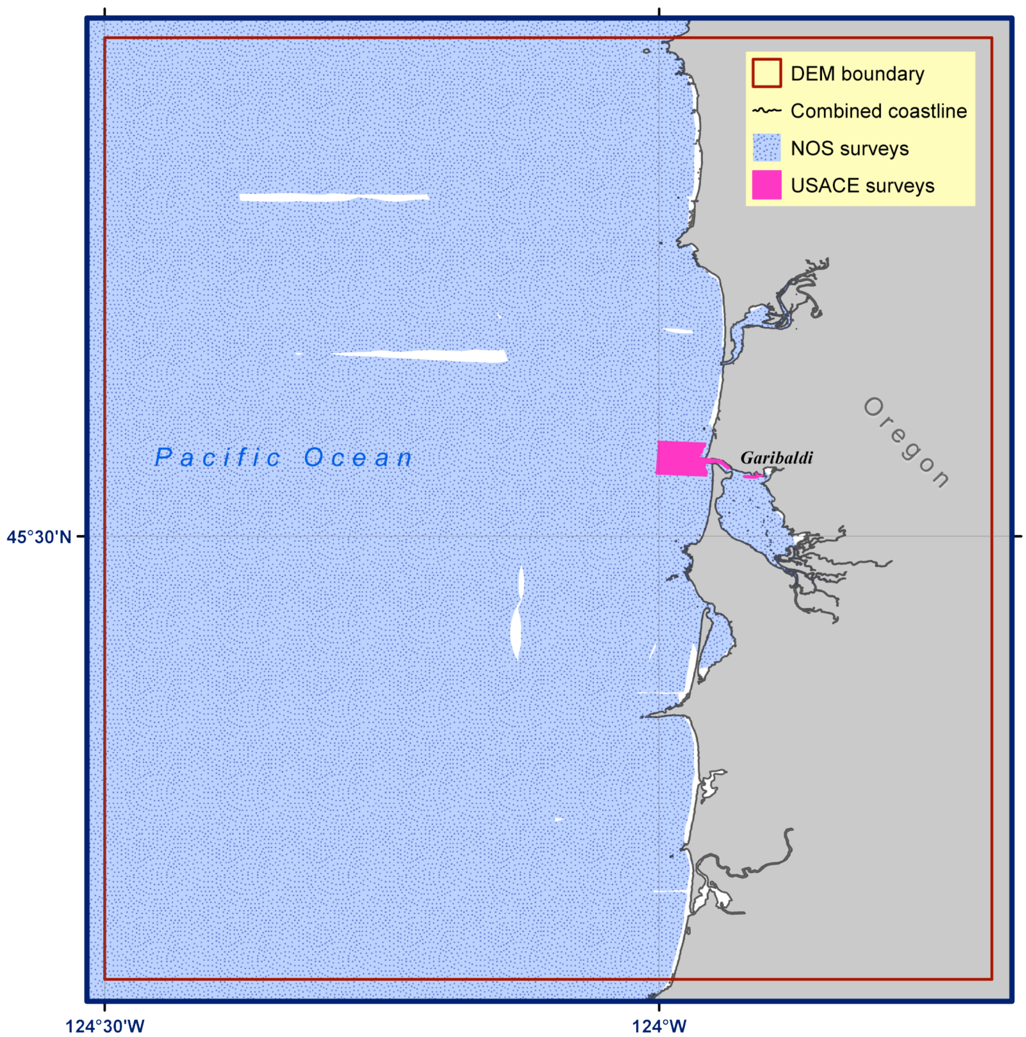

Figure 6. *Spatial coverage of bathymetric datasets used to compile the Garibaldi DEM.*

1) NOS hydrographic survey data

A total of 27 NOS hydrographic surveys conducted between 1877 and 1987 were available for inclusion in the Garibaldi DEM (Table 4; Fig. 7). Four of the NOS surveys located within the DEM boundary were not used due to inconsistencies with neighboring surveys and more recent overlapping data. The hydrographic survey data were originally vertically referenced to Mean Lower Low Water (MLLW) and horizontally referenced to NAD13, 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 Garibaldi 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 other bathymetric and topographic datasets, the combined coastline, and NOS raster nautical charts (RNCs). The surveys were clipped to remove soundings that overlap the more recent USACE surveys at the entrance to Tillamook Bay, and where soundings from older surveys have been superseded by more recent NOS surveys.

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

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum*
H04612	1926	20,000	mean lower low water	NAD13
H04613	1926	20,000	mean lower low water	NAD13
H04614	1926	20,000	mean lower low water	undetermined
H04635	1926	40,000	mean lower low water	NAD13
H04636	1926	80,000	mean lower low water	NAD13
H04637	1926	40,000	mean lower low water	NAD13
H04638	1926	80,000	mean lower low water	NAD27
H04745	1927	20,000	mean lower low water	NAD13
H04746	1927	20,000	mean lower low water	NAD13
H04747	1927	20,000	mean lower low water	NAD13
H04754	1927	80,000	mean lower low water	NAD27
H04755	1927	40,000	mean lower low water	NAD13
H04756	1927	40,000	mean lower low water	NAD13
H08346	1956	10,000	mean lower low water	NAD27
H08368	1957	5,000	mean lower low water	NAD27
H08369	1956/57	5,000	mean lower low water	NAD27
H08370	1957	10,000	mean lower low water	NAD27
H08371	1957	10,000	mean lower low water	NAD27
H08372	1957	10,000	mean lower low water	NAD27
B00019	1985	50,000	mean lower low water	NAD83
B00020	1985	50,000	mean lower low water	NAD83
B00115	1987	50,000	mean lower low water	NAD83
B00116	1987	50,000	mean lower low water	NAD83

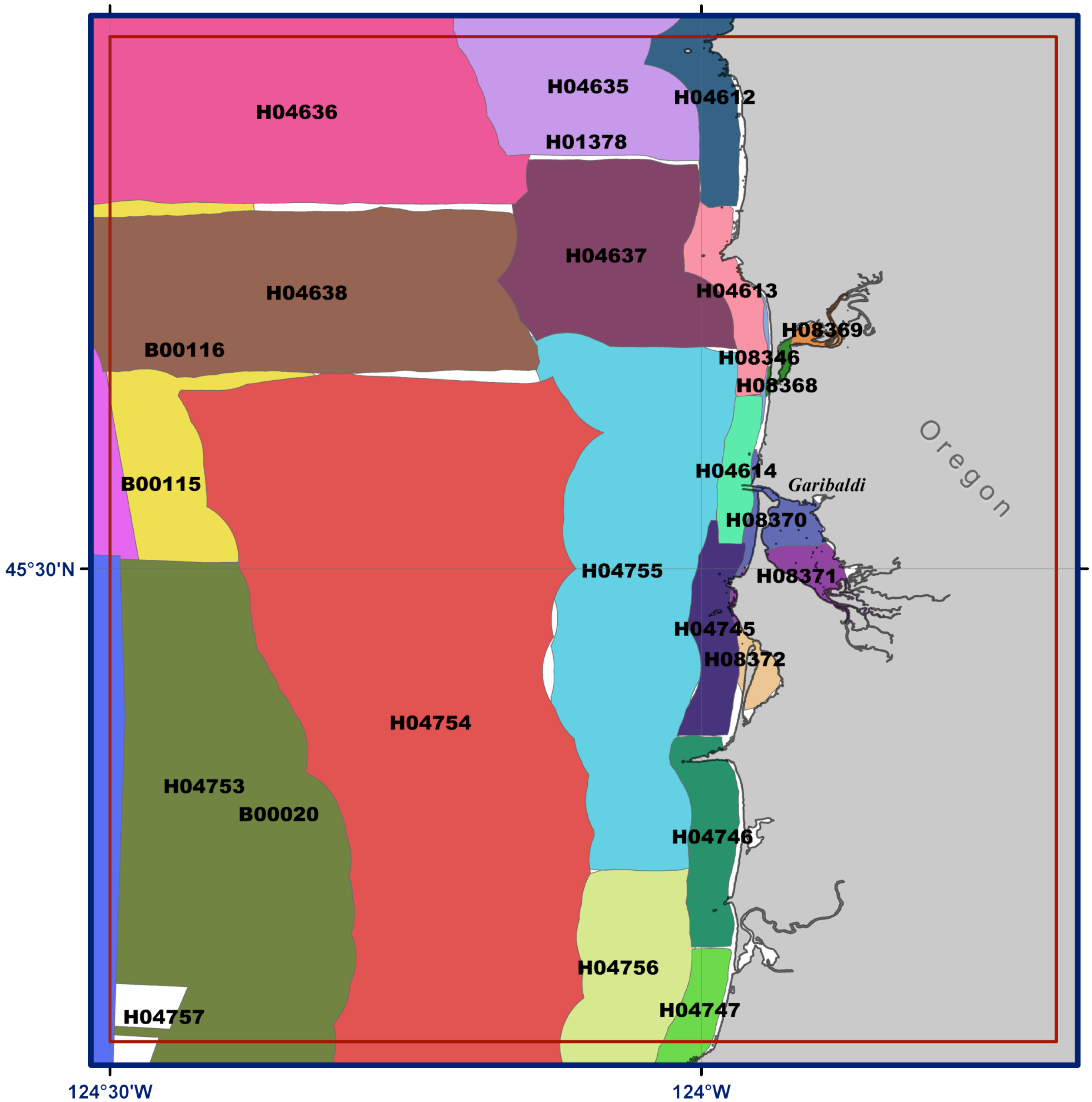

Figure 7. *Digital NOS hydrographic survey coverage in the Garibaldi region. Some older surveys were not used as they have been entirely superseded by more recent surveys. DEM boundary in red.*

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

The USACE, Garibaldi District provided NGDC with three recent bathymetric surveys located at the entrance to Tillamook Bay (Fig. 8). The surveys were collected in 2005 and 2006, and are referenced to Mean Lower Low Water (MLLW) vertical datum. The files were converted to WGS84 and MHW using FME. Point spacing averages 10 to 35 meters.

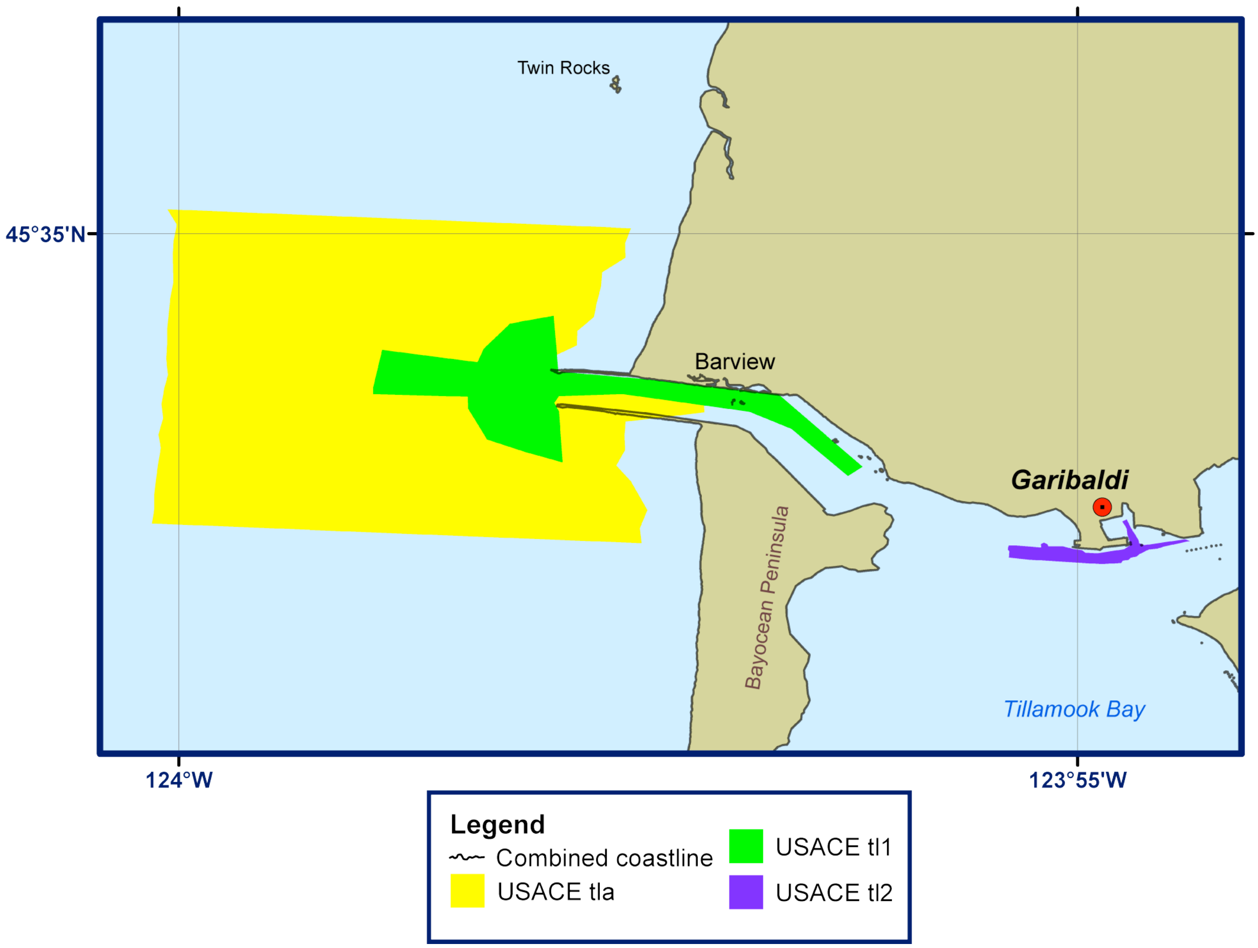

Figure 8. *Digital USACE hydrographic survey coverage.*

3.1.3 Topography

Topographic datasets in the Garibaldi region were obtained from NOAA's Coastal Services Center (CSC), Office of Coast Survey (OCS), and the U.S. Geological Survey (USGS; Table 5; Fig. 9).

Table 5: Topographic datasets used in compiling the Garibaldi DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
CSC	2002	Topographic coastal LiDAR	~6 meters	NAD83 geographic	NAVD88 (meters)	http://maps.csc.noaa.gov/TCM/
USGS	1999-2000	NED DEM	1/3 arc-second	NAD83 geographic	NAVD88 (meters)	http://ned.usgs.gov/
OCS ENC #18520	1998 to 2005	Extracted land elevation points		WGS84 geographic	MHW	http://chartmaker.ncd.noaa.gov/MCD/enc/index.htm

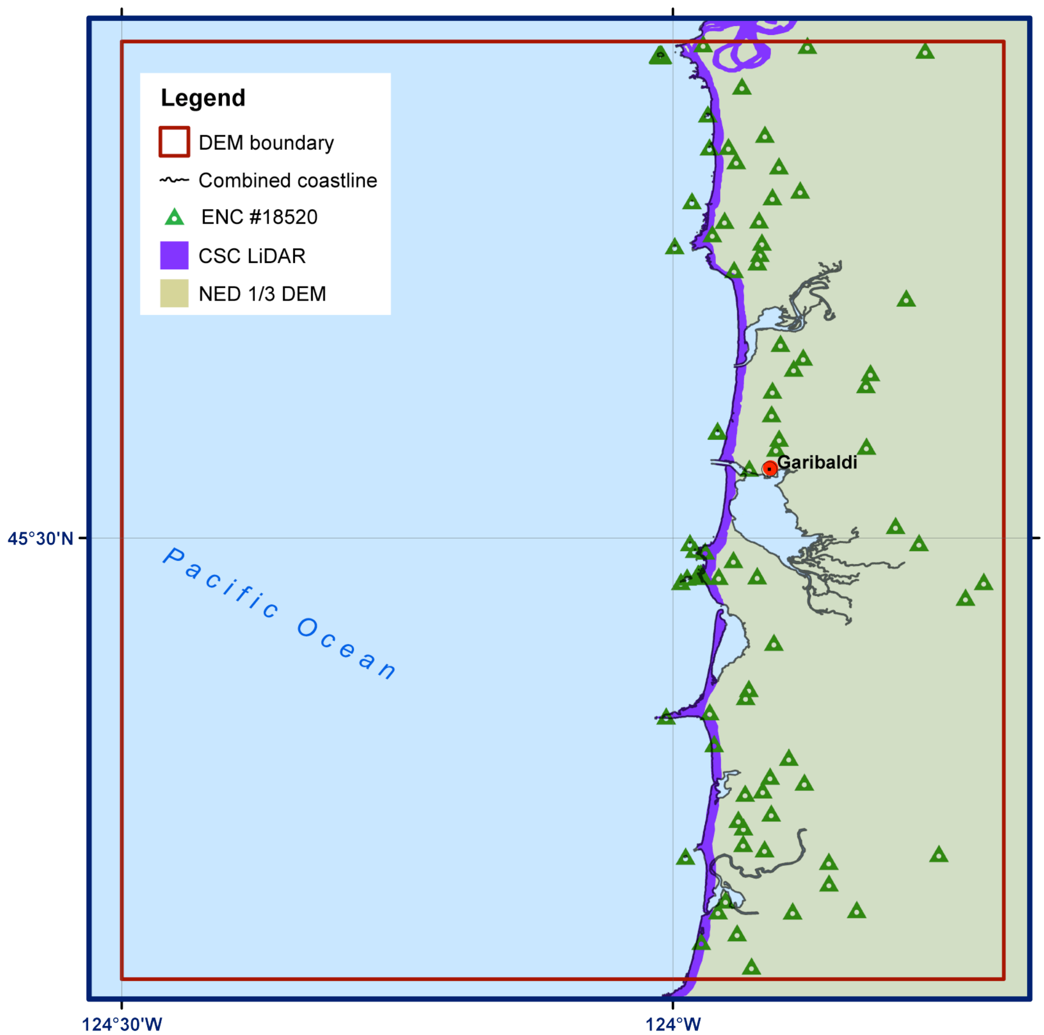

Figure 9. *Source and coverage of topographic datasets used to compile the Garibaldi DEM.*

1) Coastal Services Center topographic LiDAR

NGDC downloaded the topographic LiDAR dataset from the CSC website in NAD83 geographic horizontal datum and NAVD88 vertical datum for the entire Pacific coast near Garibaldi (Fig. 10). These data have point spacing approximately 5 meters apart and extend 50 to 800 meters inland from the coastline. As these data were not processed to bare earth, the data were filtered using FME to remove points with elevations less than 0 meters and greater than 50 meters. This process removed some water surface returns from offshore areas (Fig. 11) and inland high-elevation forested areas while retaining high-resolution coastal elevations. The combined coastline was also used to clip the remaining positive elevation values that lay over water.

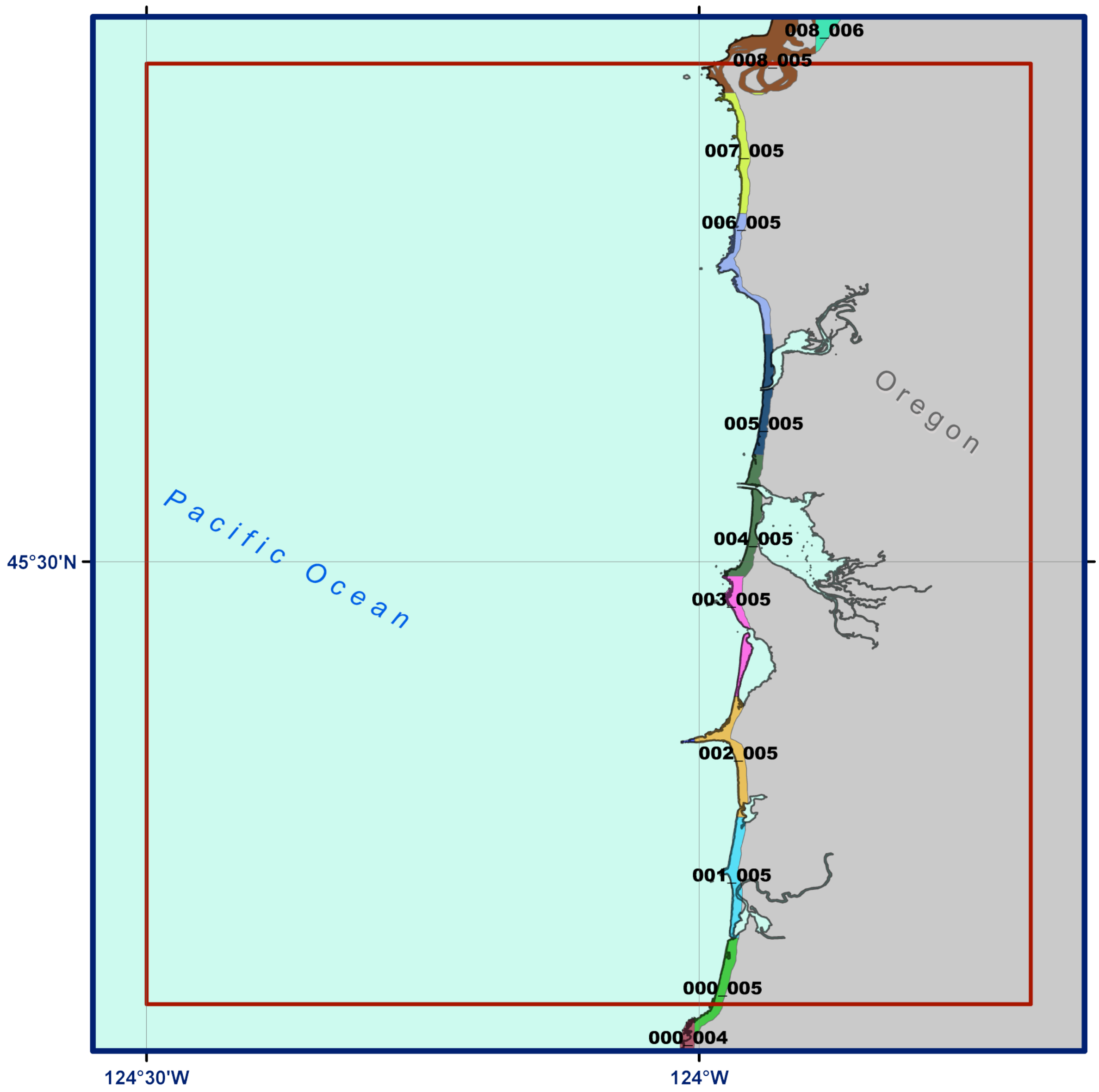

Figure 10. *CSC topographic dataset used to compile the Garibaldi DEM.*

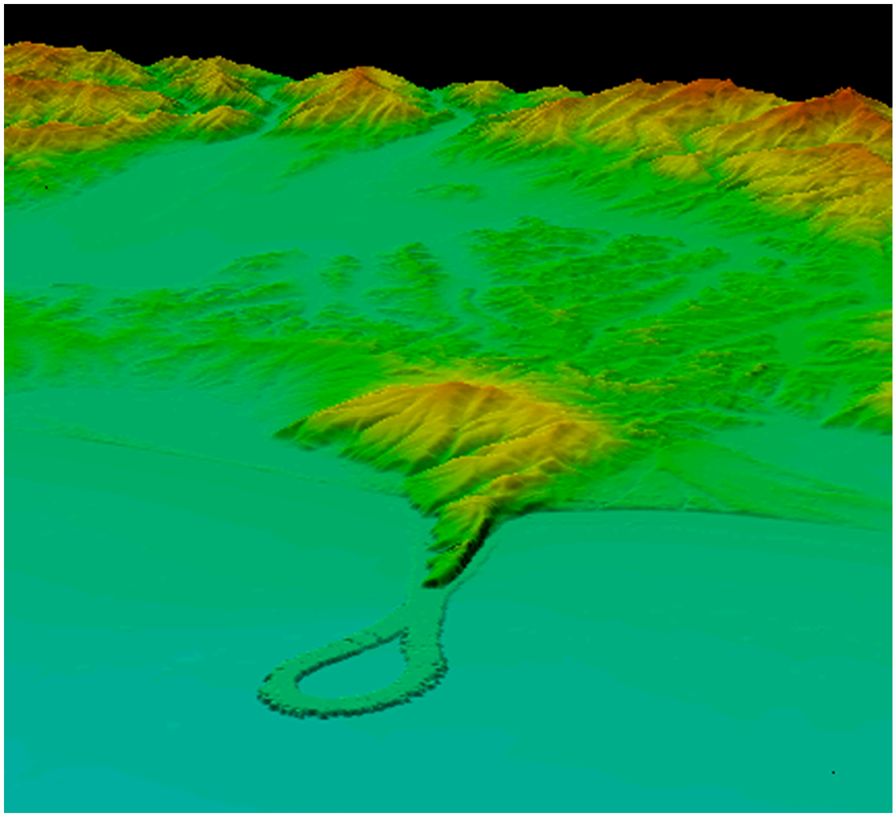

Figure 11. *A preliminary 1 arc-second grid surface of the Garibaldi region. A false looping peninsula off the end of Cape Lookout generated by water surface returns in the unedited CSC LiDAR data.*

2) USGS NED topographic DEM

The U.S. Geological Survey (USGS) National Elevation Dataset (NED; http://ned.usgs.gov/) provided complete 1/3 arc-second coverage of the Garibaldi region[2]. Data are in NAD83 geographic coordinates and NGVD88 vertical datum (meters), and are available for download as 2 raster DEMs. The extracted bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution. See the USGS Seamless web site for specific source information (http://seamless.usgs.gov/). The dataset was derived from USGS quadrangle maps and aerial photographs based on topographic surveys; it has been revised using data collected in 1999 and 2000. The NED DEMs 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]

3) OCS Electronic navigational chart data

An extracted land elevation point file from ENC #18520 was used to provide elevation values for major off shore rock formations. As no topographic representation of Tillamook Rock was available, NGDC also digitized points with an elevation of 30 meters to augment the single ENC land elevation point on the rock. Adding the points resulted in a feature that more closely resembles the actual rock formation (Fig. 12).

Figure 12. *The Tillamook Rock Lighthouse. Courtesy of TC3 Jason Wesley (http://www.uscg.mil/D13/units/gruastoria/photo_gallery.htm).*

In merging the NED DEMs and the CSC LiDAR the resulting surface included a slight “berm” where the two datasets met. This effect is most likely due to the LiDAR data, which was not processed to bare earth. The substantial vegetation coverage in the areas directly inland from the coast resulted in LiDAR returns of generally higher elevation values than the NED DEM. In order to reduce this effect, the CSC LiDAR was filtered in FME to remove elevations greater than 50 meters.

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Garibaldi DEM were originally referenced to a number of vertical datums including Mean Lower Low Water (MLLW), 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 and the USACE surveys were transformed from MLLW to MHW, using FME software, by adding a constant derived from the Garibaldi tide station (Table 6).

2) **Topographic data**

   The USGS NED 1/3 arc-second DEMs, and the CSC LiDAR data were originally referenced to NAVD88. Conversion to MHW, using FME software, was accomplished by adding a constant offset of -2.102 meters (Table 6) derived from averaging the values from the two closest tide stations to the Garibaldi tide station referencing NAVD88, Depoe Bay #9435827 and Astoria, Tongue Point #9439040.

Table 6. *Relationship between Mean High Water and other vertical datums in the Garibaldi region.*

Vertical datum	*Difference to MHW*
NAVD88	-2.102 meters
MLW	-1.859 meters
MLLW	-2.263 meters

* Datum relationships determined by values from tide station #9437540 at Garibaldi.

3.2.2 Horizontal datum transformations

Datasets used to compile the Garibaldi DEM were originally referenced to NAD83, NAD83 Oregon State Plane North, NAD83 geographic, NAD27 geographic, or WGS84 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 using FME software.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting ESRI shape files were checked in ESRI ArcMap for 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 CSC historical coastline dataset, which had to be removed. The dataset also had piers, docks , and pilings that were deleted.
- Inconsistencies between the NED and CSC datasets. The cause of these inconsistencies could be the result of LiDAR data not being processed to bare earth.
- Data values over the ocean and rivers in the NED and CSC LiDAR 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 USACE 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 Garibaldi DEM: in both deep water and in some areas close to shore, the NOS survey data have point spacing up to 1900 m apart (Fig. 13). In order to reduce the effect of artifacts in the form of lines of “pimples” in the DEM due to this low resolution dataset and to provide effective interpolation into the coastal zone, a 1 arc-second-spacing ‘pre-surface’ or grid was generated using GMT, an NSF-funded share-ware software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/).

The NOS hydrographic point data, in xyz format, were clipped to remove overlap with the topographic LiDAR data and USACE soundings then combined into a single xyz file, along with points extracted from the combined coastline. Applying a -0.5 meter value to the coastline ensured that coastal bays and rivers would have negative elevation values in the final DEM.

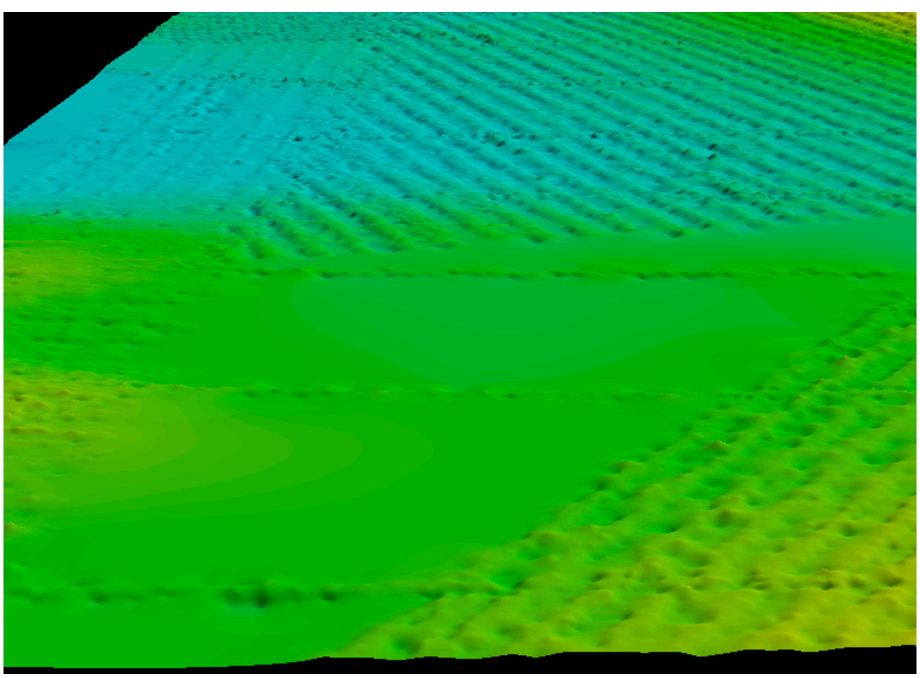

Figure 13. *Detail image of the bathy ‘pre-surface’ in the southwest corner of the DEM boundary. Ridges are present in the original data values in deep water NOS survey data, shown as closely spaced lines.*

These point data were then median-averaged using the GMT tool ‘blockmedian’ to create a 1 arc-second grid 0.05 degrees (~5%) larger than the Garibaldi DEM gridding region. The GMT tool ‘surface’ was applied to interpolate 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. 14), converted to a shape file, and then exported as an xyz file for use in the final gridding process (see Table 7). Outliers occurred where soundings from older surveys were located near offshore rock features digitally represented in more recent surveys. These older soundings were subsequently deleted.

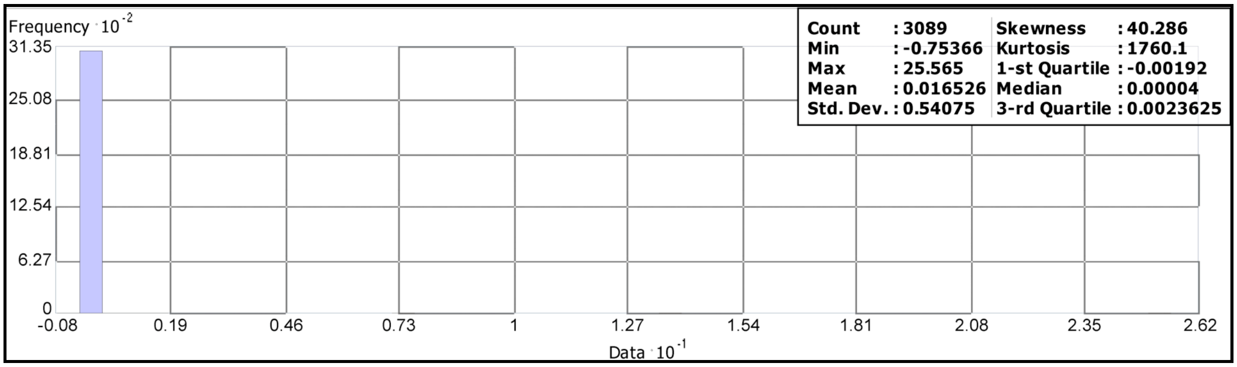

Figure 14. *Histogram of the difference between NOS hydrographic survey H04746 and the 1 arc-second pre-surfaced bathymetric grid.*

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 Garibaldi DEM. MB-System is an NSF-funded share-ware software application specifically designed to manipulate submarine multibeam sonar data, though it can use a wide variety of data types, including generic xyz data. The MB-System tool ‘mbgrid’ applied a tight spline tension to the xyz data, and interpolated values for cells without data. The data hierarchy used in the ‘mbgrid’ gridding algorithm, as relative gridding weights, is listed in Table 7. Greatest weight was given to the CSC LiDAR, the ENC land elevations, and the NED topographic data. Least weight was given to the pre-surfaced 1 arc-second bathymetric grid. Gridding was performed in quarters with a single cell overlap. The resulting Arc ASCII grids were seamlessly merged in ArcCatalog to create the final 1/3 arc-second Garibaldi DEM.

Table 7. Data hierarchy used to assign gridding weight in MB-System.

Dataset	*Relative Gridding Weight*
USACE bathymetry	100
CSC topographic LiDAR	1000
USGS NED topographic DEM	1000
NOS hydrographic surveys: bathymetric soundings	100
ENC land elevations	1000
Combined coastline	100
Pre-surfaced bathymetric grid	10

3.4 Quality Assessment of the DEM

3.4.1. Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Garibaldi DEM is dependent upon the datasets used to determine corresponding DEM cell values. Topographic features have an estimated accuracy of up to 10 meters: CSC 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 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 the morphologic change that occurs in this dynamic region.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the Garibaldi 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 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 Garibaldi DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 15). 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. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 16 shows a color image in perspective of the 1/3 arc-second Garibaldi DEM in its final version.

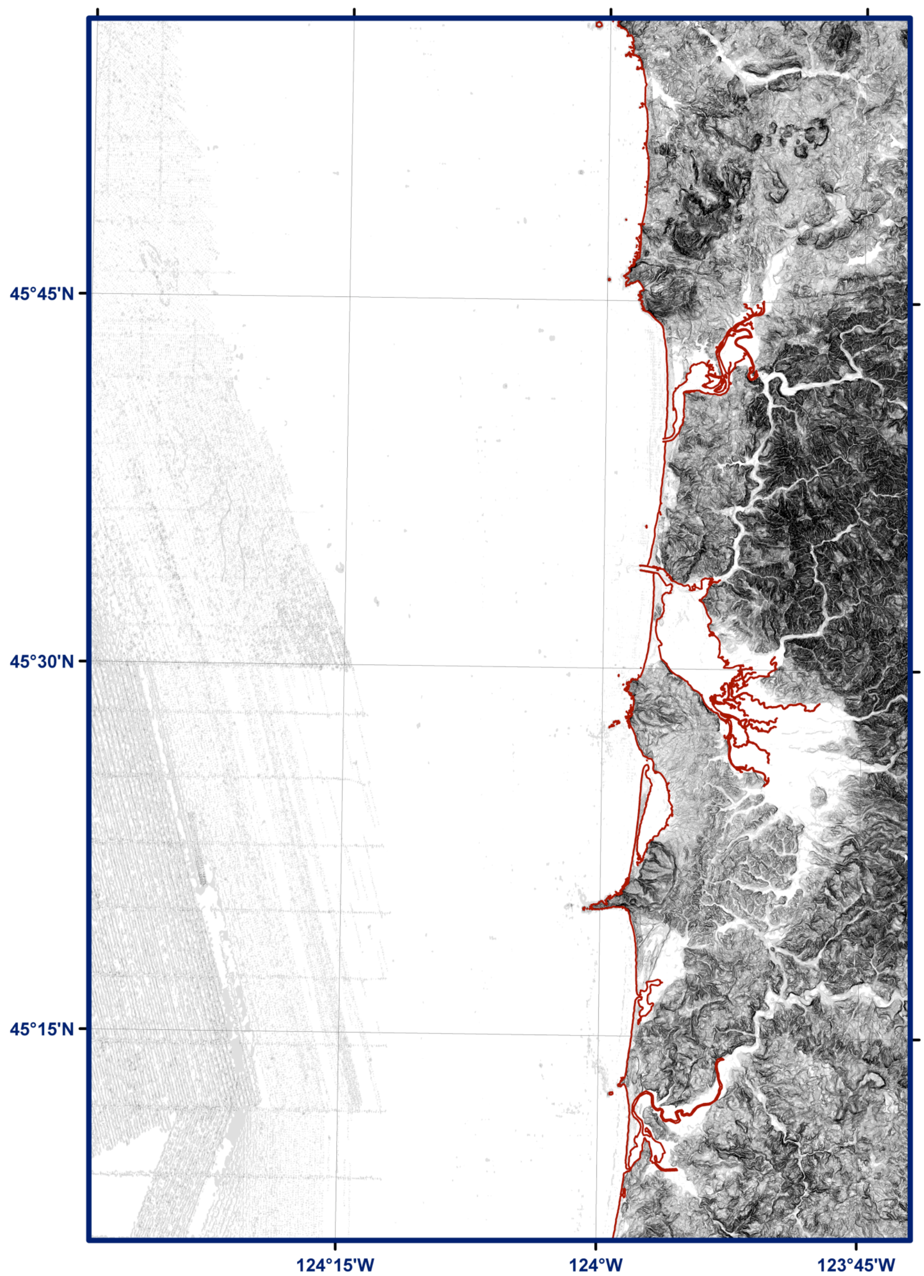

Figure 15. *Slope map of the Garibaldi DEM. Flat-lying slopes are white; dark shading denotes steep slopes; combined coastline in red.*

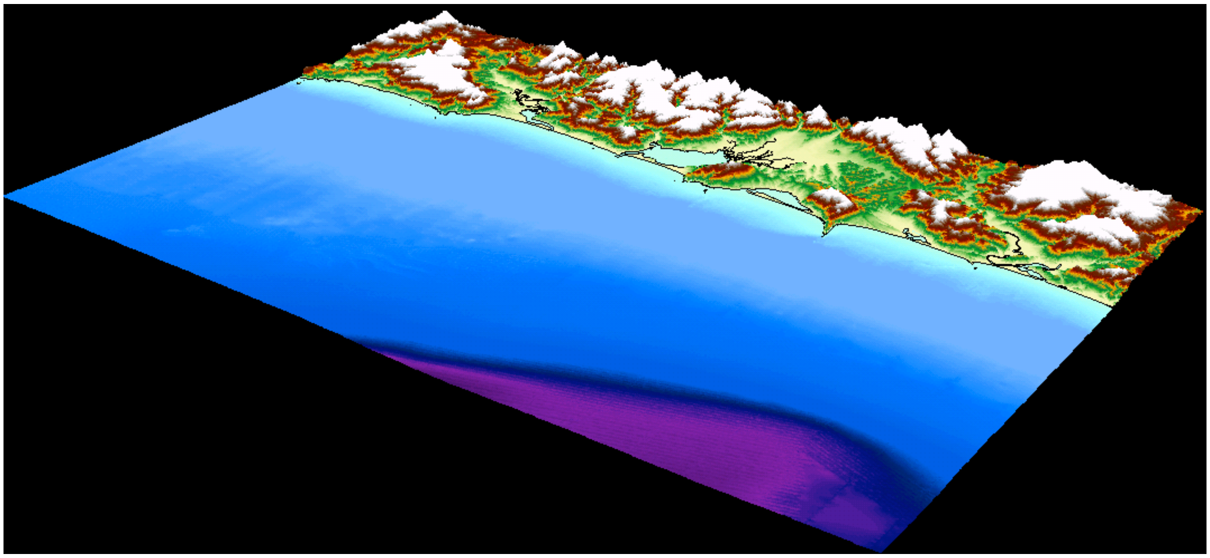

Figure 16. *Perspective view from the southwest of the one third arc-second Garibaldi DEM. Combined coastline in black; vertical exaggeration–times 3.*

3.4.4 Comparison with source data files

To ensure grid accuracy, the Garibaldi DEM was compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas (i.e., had the greatest weight and did not significantly overlap other data files with comparable weight). A histogram of the difference between a CSC topographic LiDAR survey file and the Garibaldi 1/3 arc-second DEM is shown in Figure 17. Differences cluster just below zero, with elevations, in heavily forested areas and near offshore rocks, exceeding 8 meters from the DEM.

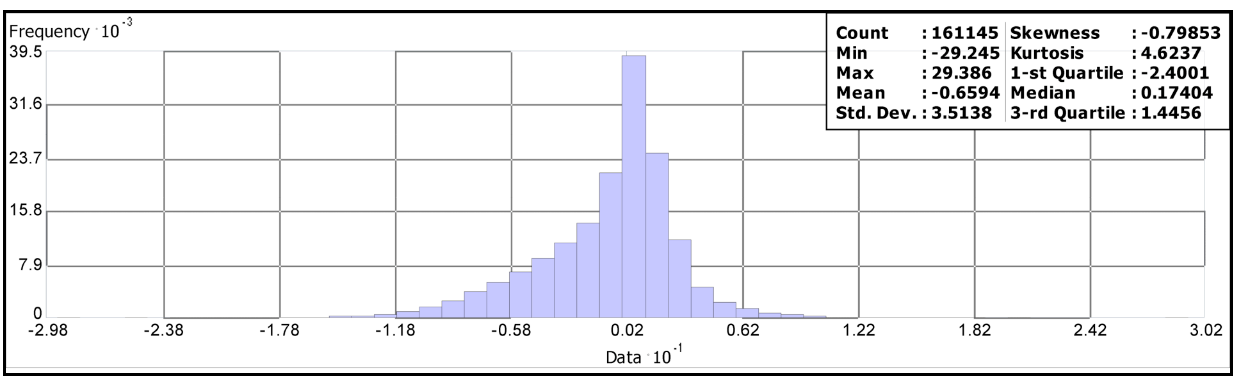

Figure 17. *Histogram of the difference between CSC LiDAR survey 007_005 and the Garibaldi DEM.*

3.4.5 Comparison with NGS geodetic monuments

The elevations of 408 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 (sub-mm accuracy) and elevations in NAVD88 (in meters). Elevations were shifted to MHW vertical datum (see Table 6) for comparison with the Garibaldi DEM (see Fig. 19 for monument locations). Differences between the Garibaldi DEM and the NGS geodetic monument elevations range from -88 to 216 meters (Fig. 18). Large negative differences occur where the NGS monument position varied from matching elevation in NED DEMs, generally at monuments located on offshore rock features. The largest positive difference occurs at an older monument last recorded in 1933. Prior to 1977, a view point was constructed on the site.

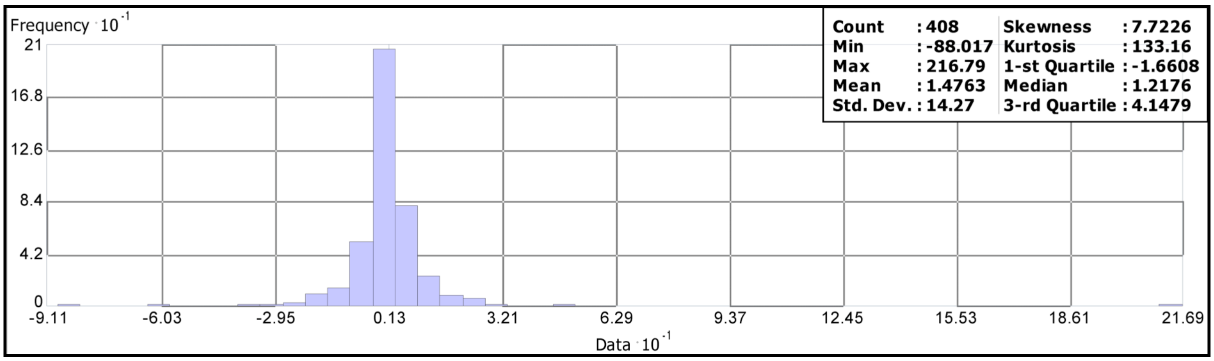

Figure 18. *Histogram of the differences between NGS geodetic monument elevations and the Garibaldi DEM.*

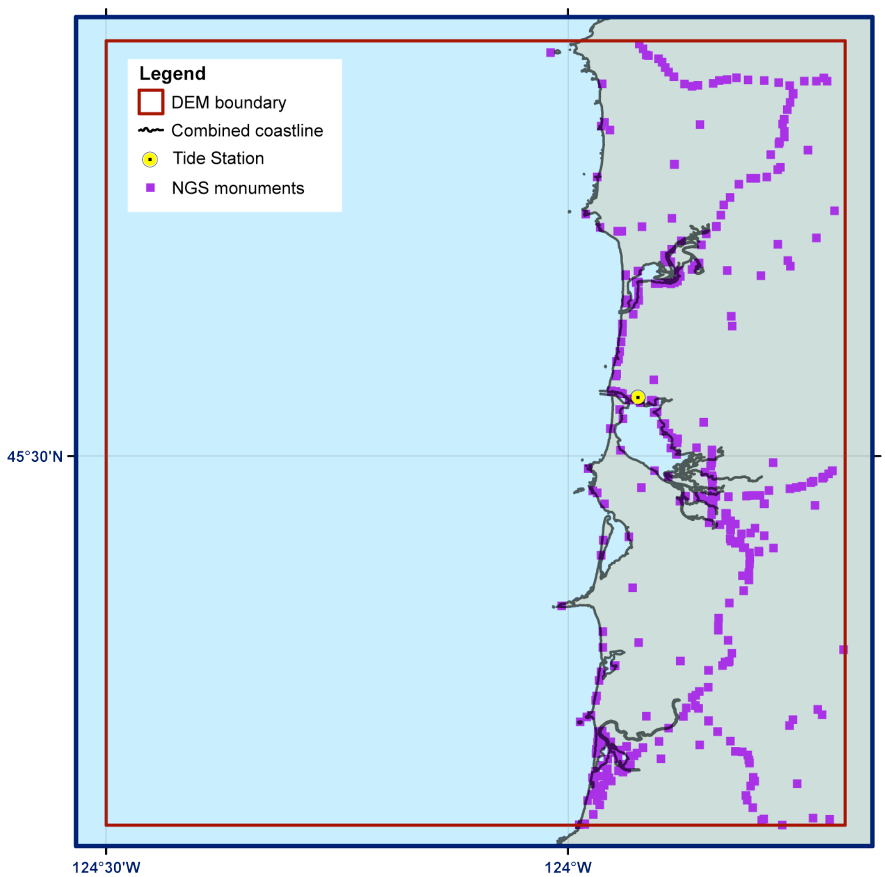

Figure 19. *Location of NGS monuments and the NOAA tide station in the Garibaldi region. NGS monument elevations were used to evaluate the DEM.*

4. Summary and Conclusions

A bathymetric–topographic digital elevation model of the Garibaldi, Oregon 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, and academic institutions were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI ArcGIS, FME, GMT, MB-System and Quick Terrain Modeler software.

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

- Conduct bathymetric–topographic LiDAR surveys on coastline between Seaside and Pacific City, Oregon.
- Conduct hydrographic survey near shore areas.
- Conduct topographic LiDAR surveying of entire region.
- Process CSC LiDAR data to bare earth.

5. Acknowledgments

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6. References

Nautical Chart #18520, 8th Edition, 2007. Yaquina Head to Columbia River; Netarts Bay. Scale 1:185,238. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18556, 25th Edition, 2004. Nehalem River. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18558, 38th Edition, 2006.Tillamook Bay. Scale 1:50,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing and Visualization Software

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

FME 2007 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/

NASA WorldWind 1.4, developed at NASA Ames Research Center, http://worldwind.arc.nasa.gov/index.html.