NOAA Technical Memorandum NESDIS NGDC-60

DIGITAL ELEVATION MODELS OF PORT TOWNSEND, WASHINGTON: PROCEDURES, DATA SOURCES AND ANALYSIS

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Marine Geology and Geophysics Division
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Also available from the National Technical Information Service (NTIS)

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Digital Elevation Models of Port Townsend, Washington: Procedures, Data Sources and Analysis

1. Introduction

The National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), has developed two bathymetric–topographic digital elevation models (DEMs) of Port Townsend, Washington (Fig. 1). A 1/3 arc-second[1] DEM referenced to North American Vertical Datum of 1988 (NAVD 88) was carefully developed and evaluated. An NAVD 88 to mean high water (MHW) 1/3 arc-second conversion grid was then created to represent the relationship between NAVD 88 and MHW in the Port Townsend region. A 1/3 arc-second MHW DEM, combining the NAVD 88 DEM and the conversion grid, will be used as input for the Method of Splitting Tsunami (MOST) model developed by the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/) to simulate tsunami generation, propagation and inundation. The NAVD 88 DEM was generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 3). The MHW DEM will be used for tsunami inundation modeling, as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing both Port Townsend DEMs.

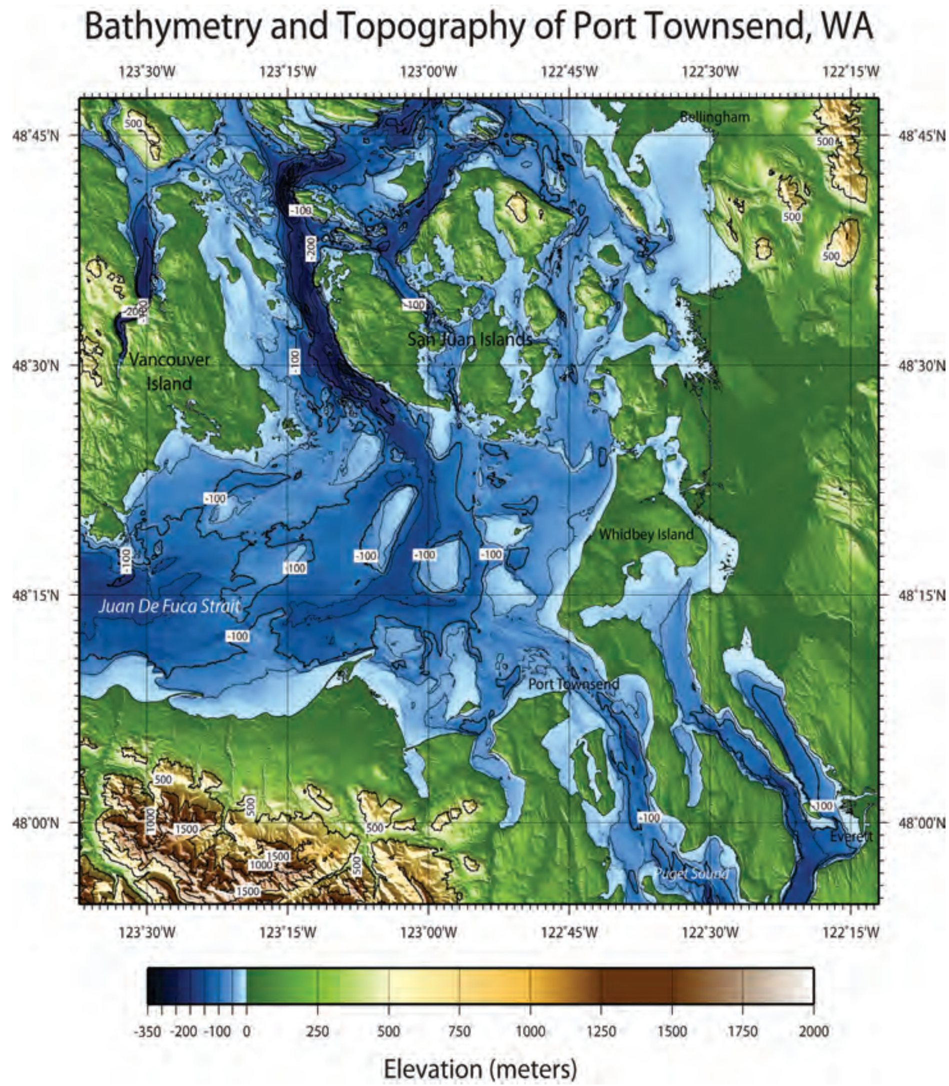

Figure 1. Shaded-relief image of the Port Townsend NAVD 88 1/3 arc-second DEM. Contour interval is 500 meters for topography and 50 meters for bathymetry. Image is in Mercator projection.

1. The Port Townsend DEMs are 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 Port Townsend, Washington, (48°6'59"N, 122°46'31"W) 1/3 arc-second of latitude is equivalent to 10.30 meters; 1/3 arc-second of longitude equals 6.90 meters.

2. Study Area

The Port Townsend, WA DEM spans an area of approximately 10,000 square kilometers and covers the Juan De Fuca Strait, Puget Sound, San Juan Islands, and Vancouver Island. Port Townsend is located 40 miles northwest of Seattle, on the tip of the Olympic Peninsula. The region offers a diverse variety of landscapes, which include mudflats, rocky shores, mountains, tidal-flats, and floodplains (Fig. 2). Areas such as Puget Sound are estuaries composed of a series of underwater basins and sills, which are the result of the Cascadia subduction zone and the Wisconsin Glaciation (http://www.tititudorancea.com/z/puget_sound.htm).

The last major subduction zone earthquake in this region was a magnitude 8.7 that occurred in the Cascadia subduction zone in 1700. The length of the fault rupture was approximately 1000 kilometers with an average slip of 20 meters. The geological record reveals that earthquakes with a moment magnitude of 8 or higher occur every 500 years on average and are often accompanied by tsunamis. Previous earthquakes are estimated to have occurred in 1310 AD, 810 AD, 400 AD, 170 BC, and 600 BC (http://www.cosmosmagazine.com/node/3437/full).

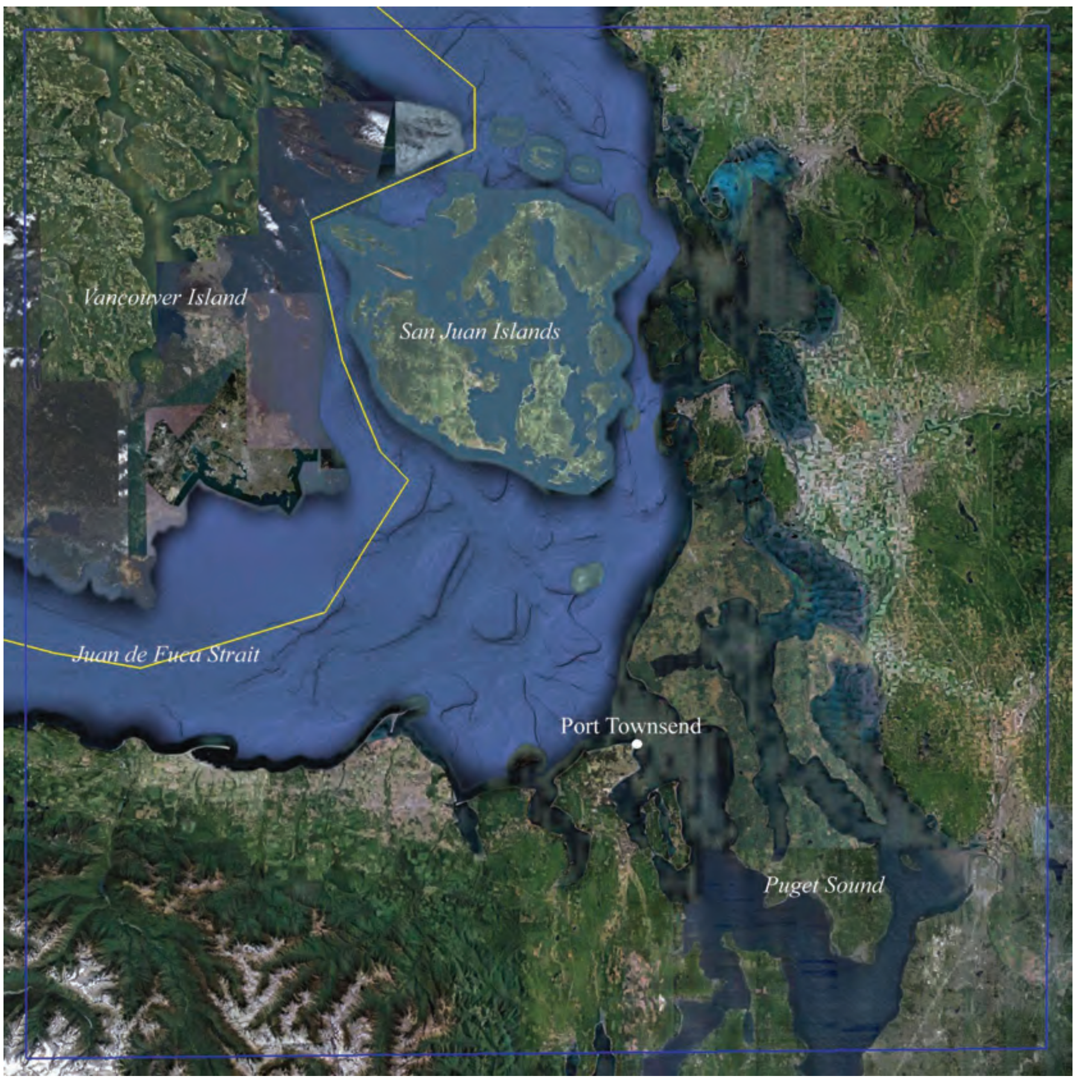

Figure 2. Google Earth imagery of the Port Townsend DEM region. Blue box denotes DEM boundary. Yellow boundary denotes the international boundary between the U.S. and Canada.

3. Methodology

The Port Townsend NAVD 88 and MHW DEMs were 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 bathymetric and topographic digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North American Datum of 1983[2] (NAD 83) and NAVD 88. The resulting NAVD 88 DEM was then transformed to MHW using a conversion grid for modeling of maximum flooding (see section 3.3.4). Data were gathered in an area slightly larger (~5%) than the DEM extents. This data "buffer" ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1. PMEL specifications for the Port Townsend, WA DEMs.

Grid Area	Port Townsend, Washington
Coverage Area	123.62º to 122.20º W; 47.91º to 48.79º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datums	A. North American Vertical Datum of 1988 (NAVD 88) B. Mean High Water
Vertical Units	Meters
Cell Size	1/3 arc-second
Grid Format	ESRI Arc ASCII raster grid

2. The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (WGS 84) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEMs. 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. These DEMs are 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 DEMs, WGS 84 and NAD 83 geographic are identical and may be used interchangeably.

3.1 Data Sources and Processing

Shoreline, bathymetric, topographic, and bathymetric-topographic digital datasets (Fig. 3) were obtained from several U.S. federal, state, and international agencies including: NGDC; NOAA's Coastal Services Center (CSC) and Office of Coast Survey (OCS); USACE's Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX); the Canadian Hydrographic Service (CHS), the Canadian Digital Elevation Data (CDED); Washington State Department of Ecology (WSDE); Puget Sound Lidar Consortium (PSLC); and the U.S. Geological Survey (USGS). Safe Software's *FME* data translation tool package was used to shift datasets to NAD 83 geographic horizontal datum and to convert them into ESRI *ArcGIS* shapefiles or ASCII xyz files[3]. The shapefiles were then displayed with *ArcGIS* and the xyz files were displayed with Applied Imagery's *Quick Terrain Modeler* (*QT Modeler*) to assess data quality and manually edit datasets. Vertical datum transformations to NAVD 88 were accomplished using NOAA's *Vertical Datum* (*VDatum*) transformation tool. ESRI's online *World 2D* imagery was used to analyze and modify data. *QT Modeler* and Interactive Visualization System's *Fledermaus* software were used to evaluate processing and gridding techniques.

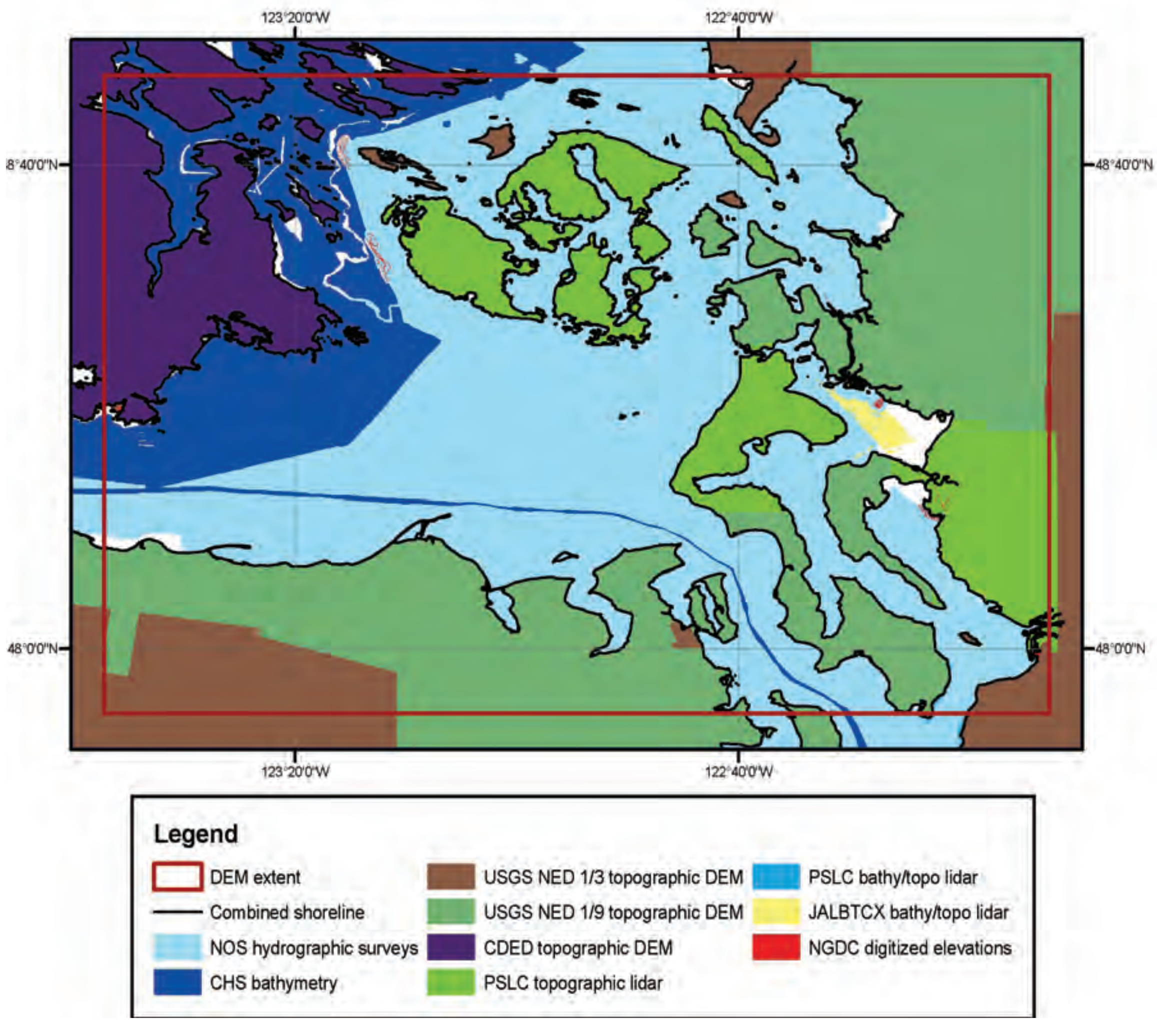

Figure 3. Source and coverage of datasets used in compiling the Port Townsend NAVD 88 DEM.

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

3.1.1 Shoreline

Shoreline datasets of the Port Townsend region were obtained from WSDE, CSC, and OCS (Table 2; Fig. 4). Shorelines from NOAA's OCS were obtained as Electronic Navigational Charts (ENCs)[4] and were evaluated but were not used because of inconsistencies in coverage and lower spatial resolutions. The two remaining datasets were edited and merged to develop a "combined shoreline" of the Port Townsend region.

Table 2. Shoreline datasets used in developing the Port Townsend NAVD 88 DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
WSDE	2001	vector shoreline	1:24,000	NAD 83 HARN State Plane WA South	Mean high water	http://www.ecy.wa.gov/services/gis/data/data.htm
CSC	1995	vector shoreline	1:24,000	NAD 83 geographic	Mean sea level	http://www.csc.noaa.gov/

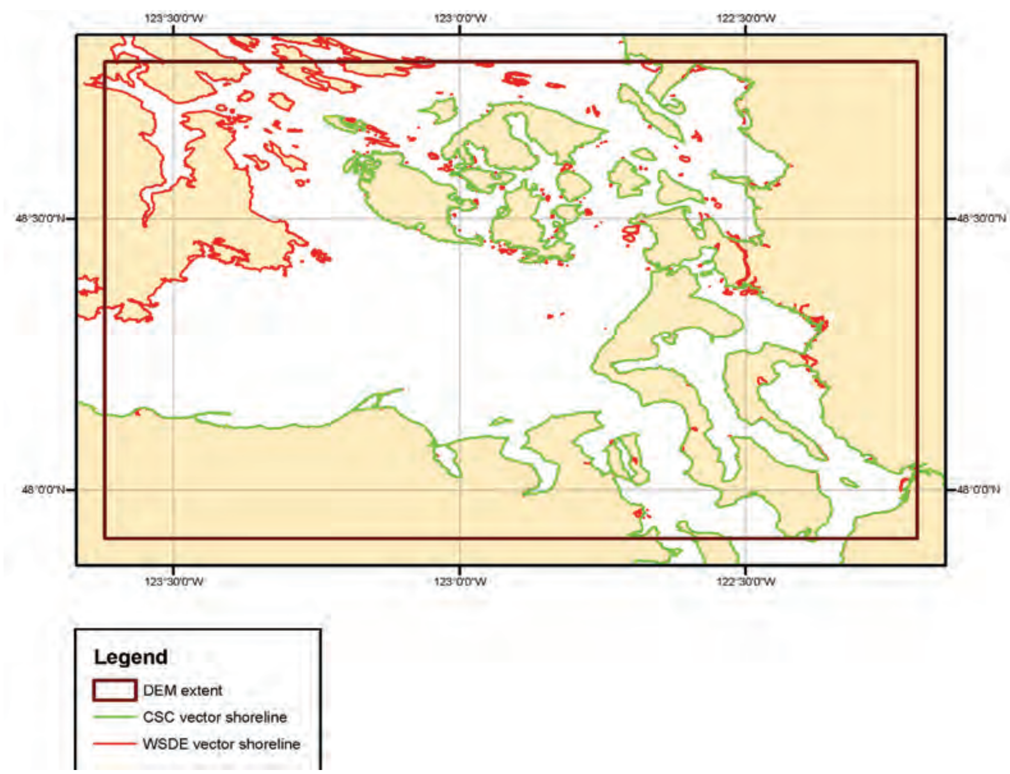

Figure 4. Digital shoreline datasets used in developing a combined shoreline of the Port Townsend region. Water areas shown in white. Land areas shown in beige.

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

1) **Washington State Department of Ecology**

The WSDE shoreline dataset includes Puget Sound, Hood Canal, the Strait of Juan de Fuca, and the Pacific coastline. In support of the Southwest Washington Coastal Erosion Study, WSDE edited, digitized, and updated the shoreline using USGS 7.5' quadrangles to define the mean high tide line between 2000-2010.

2) **NOAA's Coastal Services Center**

NOAA's CSC compiled a vector shoreline using multi-temporal collection of NOAA coastal survey maps (T-sheets) ranging from 1901-1995. Where T-sheets were unavailable, NOAA's Extracted Vector Shoreline (EVS) was used to compile seamless shoreline coverage throughout the region.

The WSDE and CSC shoreline datasets were merged using *ArcCatalog* and used to create a "combined shoreline" of the Port Townsend region. The combined shoreline was modified to include large offshore rocks, breakwaters, harbors, and small inlets as shown on the larger-scale RNCs, USGS quadrangles and ESRI's *World 2D* imagery (e.g., Fig 5). ESRI's *World 2D* imagery was used to identify piers and docks, which were removed from the combined shoreline, and to reflect the most current coastal morphology. The combined shoreline was clipped to 0.05 degrees larger than the DEM boundary to allow for interpolation along the edges of the DEMs.

Figure 5. Combined shoreline of Port Townsend Harbor (green line) shown with ESRI World 2D Imagery. Piers are not included in the shoreline as water can flow beneath them, but large rocks and breakwaters were included as they are solid structures.

3.1.2 Bathymetry

Bathymetric datasets available for use in the compilation of the Port Townsend DEMs include 133 NOS hydrographic surveys; CHS multibeam bathymetry, and NGDC digitized bathymetry. (Table 3; Fig. 6).

Table 3. Bathymetric datasets used in compiling the Port Townsend DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1887 to 2006	NOS hydrographic survey soundings	Ranges from 5 meters to 1.2 kilometers (varies with scale of survey, depth, traffic and probability of obstructions)	NAD 83 geographic, NAD 83 UTM Zone 10 North	MLW and MLLW (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
CHS	2010	Gridded data	~10 meters	WGS 84 geographic	Assumed MSL (meters)	http://www.dfo-mpo.gc.ca/index-eng.htm
NGDC	2010	digitized points	n/a	WGS 84 geographic	NAVD 88	

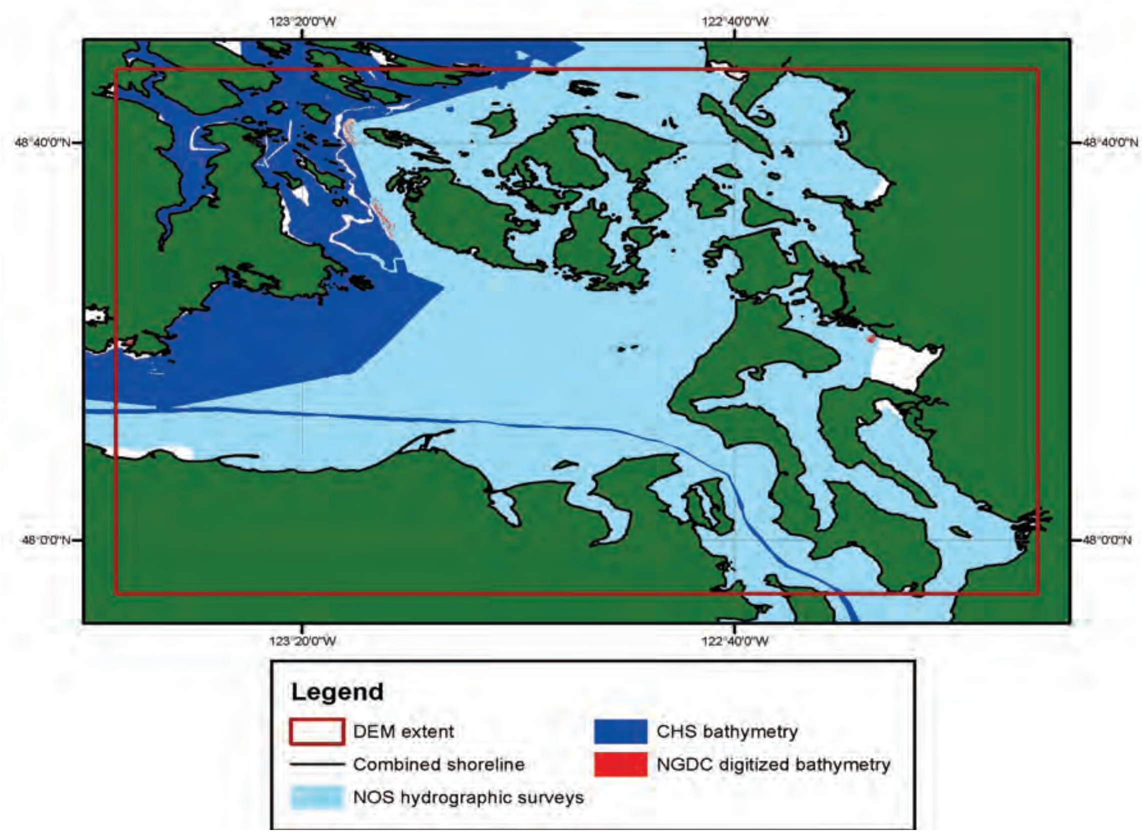

Figure 6. Source and coverage of bathymetric datasets used in compiling the Port Townsend DEMs.

1) National Ocean Service hydrographic survey data

A total of 133 NOS hydrographic surveys conducted between 1887 and 2006 were available for use in developing the Port Townsend DEMs. Surveys were extracted as xyz files using *GEODAS*[5] from NGDC's online NOS hydrographic database with a buffer 0.05 degrees (~5%) larger than the Port Townsend DEM area to support data interpolation along grid edges. The downloaded digital hydrographic survey data were vertically referenced to mean low water (MLW) or mean lower low water (MLLW) and horizontally referenced to NAD 83 geographic and NAD 83 UTM Zone 10 North (Table 4; Fig. 7). The most recent surveys were provided to NGDC by NOS, retrieved from the NGDC multibeam database. These surveys were provided as bathymetric attributed grids (BAG). The horizontal and vertical datums of the BAG data are NAD 83 UTM Zone 10 North and in MLLW respectively (Table 4).

Data point spacing for the NOS surveys varied by scale. In general, small scale surveys had greater point spacing than large scale surveys. All NOS survey data were converted to NAVD 88 using the *VDatum* transformation tool (see Sec. 3.2.1). The data were then converted to shapefiles using *FME* software and displayed in ESRI *ArcMap* and reviewed for digitizing errors and edited as necessary. The surveys were also compared to other bathymetric datasets, the combined shoreline, NOAA RNCs, and USGS 7.5' quadrangles. Older surveys were clipped to remove soundings that have been superseded by more recent NOS surveys and multibeam data.

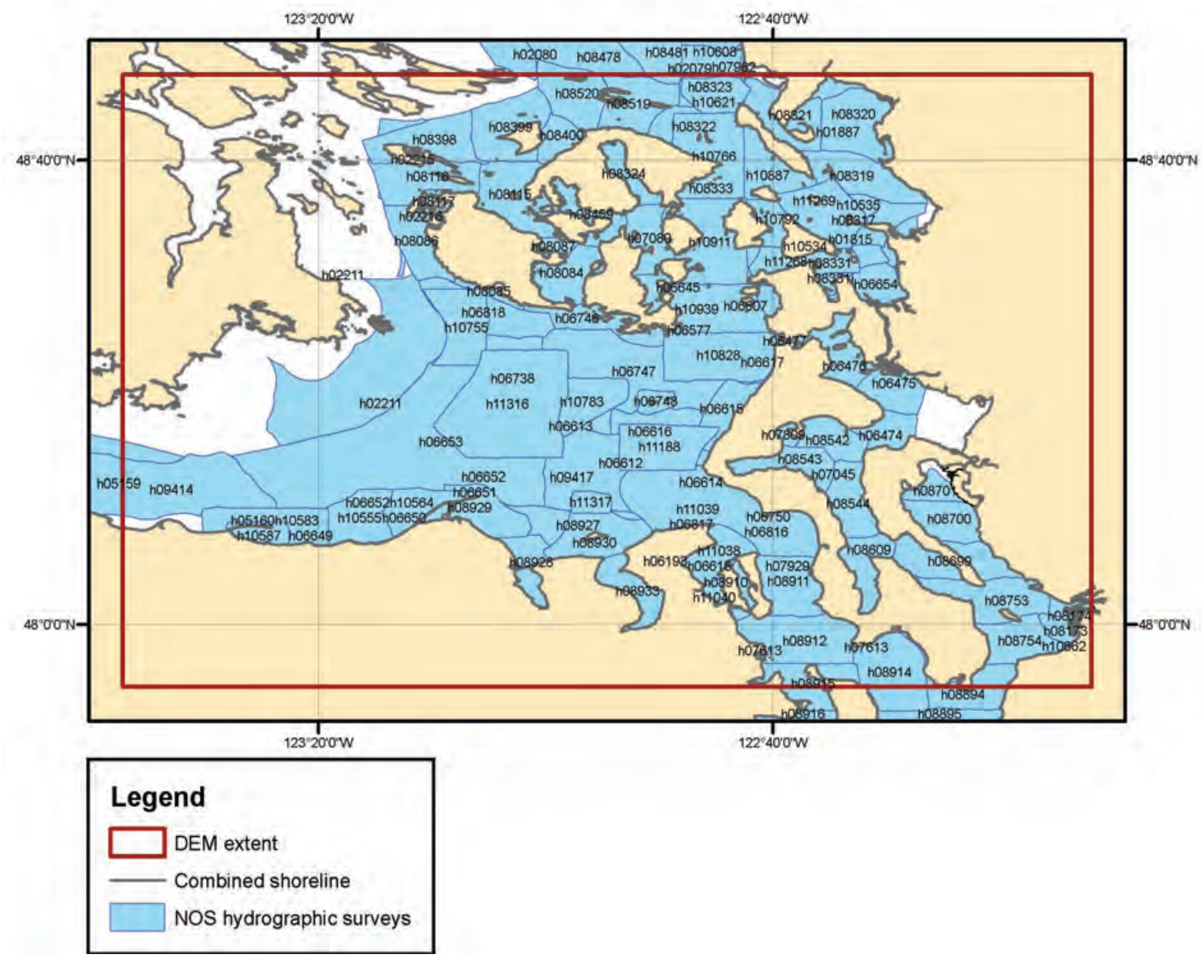

Figure 7. Digital NOS hydrographic survey coverage in the Port Townsend region. Several older surveys were not used as they have been superseded by more recent surveys.

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

Table 4. Digital NOS hydrographic surveys in the Port Townsend region.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
F00399	1994	5,000	Mean Lower Low Water	North American Datum of 1983
H01815[+]	1887	20,000	Mean Low Water	North American Datum of 1983
H01887	1888	10,000	Mean Lower Low Water	North American Datum of 1983
H02049	1890	20,000	Mean Low Water	North American Datum of 1983
H02079	1889	20,000	Mean Low Water	North American Datum of 1983
H02080	1891	20,000	Mean Low Water	North American Datum of 1983
H02211	1894	40,000	Mean Lower Low Water	North American Datum of 1983
H02215	1894	10,000	Mean Lower Low Water	North American Datum of 1983
H02216	1894	10,000	Mean Lower Low Water	North American Datum of 1983
H05158	1931	20,000	Mean Lower Low Water	North American Datum of 1983
H05159	1931	40,000	Mean Lower Low Water	North American Datum of 1983
H05160	1931	10,000	Mean Lower Low Water	North American Datum of 1983
H05659	1935	20,000	Mean Lower Low Water	North American Datum of 1983
H05709	1935	20,000	Mean Lower Low Water	North American Datum of 1983
H06193	1937	5,000	Mean Lower Low Water	North American Datum of 1983
H06474	1939	10,000	Mean Lower Low Water	North American Datum of 1983
H06475	1939	10,000	Mean Lower Low Water	North American Datum of 1983
H06476	1939	10,000	Mean Lower Low Water	North American Datum of 1983
H06477	1939	5,000	Mean Lower Low Water	North American Datum of 1983
H06577	1940	10,000	Mean Lower Low Water	North American Datum of 1983
H06607	1940	10,000	Mean Lower Low Water	North American Datum of 1983
H06612	1941	20,000	Mean Lower Low Water	North American Datum of 1983
H06613	1941	20,000	Mean Lower Low Water	North American Datum of 1983
H06614	1941	10,000	Mean Lower Low Water	North American Datum of 1983
H06615	1941	10,000	Mean Lower Low Water	North American Datum of 1983
H06616	1941	10,000	Mean Lower Low Water	North American Datum of 1983
H06617	1941	10,000	Mean Lower Low Water	North American Datum of 1983
H06618	1940	5,000	Mean Lower Low Water	North American Datum of 1983
H06645	1940	10,000	Mean Lower Low Water	North American Datum of 1983
H06649	1940	10,000	Mean Lower Low Water	North American Datum of 1983
H06650	1940	10,000	Mean Lower Low Water	North American Datum of 1983
H06651	1941	10,000	Mean Lower Low Water	North American Datum of 1983
H06652	1941	20,000	Mean Lower Low Water	North American Datum of 1983
H06653	1943	40,000	Mean Lower Low Water	North American Datum of 1983
H06654	1940	10,000	Mean Lower Low Water	North American Datum of 1983
H06738	1942	20,000	Mean Lower Low Water	North American Datum of 1983
H06746	1943	10,000	Mean Lower Low Water	North American Datum of 1983
H06747	1941	20,000	Mean Lower Low Water	North American Datum of 1983
H06748	1941	10,000	Mean Lower Low Water	North American Datum of 1983
H06750	1941	10,000	Mean Lower Low Water	North American Datum of 1983

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
H06757	1942	5,000	Mean Lower Low Water	North American Datum of 1983
H06816	1943	10,000	Mean Lower Low Water	North American Datum of 1983
H06817	1943	10,000	Mean Lower Low Water	North American Datum of 1983
H06818	1943	20,000	Mean Lower Low Water	North American Datum of 1983
H07045	1945	20,000	Mean Lower Low Water	North American Datum of 1983
H07080	1947	10,000	Mean Lower Low Water	North American Datum of 1983
H07099	1947	10,000	Mean Lower Low Water	North American Datum of 1983
H07168	1946	10,000	Mean Lower Low Water	North American Datum of 1983
H07613	1948	10,000	Mean Lower Low Water	North American Datum of 1983
H07809	1951	10,000	Mean Lower Low Water	North American Datum of 1983
H07929	1944	10,000	Mean Lower Low Water	North American Datum of 1983
H07962	1953	10,000	Mean Lower Low Water	North American Datum of 1983
H08084	1955	10,000	Mean Lower Low Water	North American Datum of 1983
H08085	1953	10,000	Mean Lower Low Water	North American Datum of 1983
H08086	1955	10,000	Mean Lower Low Water	North American Datum of 1983
H08087	1953	5,000	Mean Lower Low Water	North American Datum of 1983
H08115	1954	10,000	Mean Lower Low Water	North American Datum of 1983
H08116	1954	10,000	Mean Lower Low Water	North American Datum of 1983
H08117	1957	5,000	Mean Lower Low Water	North American Datum of 1983
H08173	1954	5,000	Mean Lower Low Water	North American Datum of 1983
H08174	1955	10,000	Mean Lower Low Water	North American Datum of 1983
H08317	1956	10,000	Mean Lower Low Water	North American Datum of 1983
H08319	1956	10,000	Mean Lower Low Water	North American Datum of 1983
H08320	1956	10,000	Mean Lower Low Water	North American Datum of 1983
H08321	1956	10,000	Mean Lower Low Water	North American Datum of 1983
H08322	1956	10,000	Mean Lower Low Water	North American Datum of 1983
H08323	1956	10,000	Mean Lower Low Water	North American Datum of 1983
H08324	1957	10,000	Mean Lower Low Water	North American Datum of 1983
H08331	1955	10,000	Mean Lower Low Water	North American Datum of 1983
H08331I	1955	10,000	Mean Lower Low Water	North American Datum of 1983
H08333	1955	10,000	Mean Lower Low Water	North American Datum of 1983
H08398	1957	10,000	Mean Lower Low Water	North American Datum of 1983
H08399	1957	10,000	Mean Lower Low Water	North American Datum of 1983
H08400	1957	10,000	Mean Lower Low Water	North American Datum of 1983
H08459	1958	10,000	Mean Lower Low Water	North American Datum of 1983
H08478	1959	30,000	Mean Lower Low Water	North American Datum of 1983
H08481	1959	10,000	Mean Lower Low Water	North American Datum of 1983
H08518	1960	10,000	Mean Lower Low Water	North American Datum of 1983
H08519	1960	10,000	Mean Lower Low Water	North American Datum of 1983
H08520	1960	10,000	Mean Lower Low Water	North American Datum of 1983
H08542	1962	10,000	Mean Lower Low Water	North American Datum of 1983

NOS Survey ID	***Year of Survey***	***Survey Scale***	***Original Horizontal Datum***	***Original Vertical Datum***
H08543	1960	10,000	Mean Lower Low Water	North American Datum of 1983
H08544	1960	10,000	Mean Lower Low Water	North American Datum of 1983
H08609	1961	10,000	Mean Lower Low Water	North American Datum of 1983
H08699	1962	10,000	Mean Lower Low Water	North American Datum of 1983
H08700	1962	10,000	Mean Lower Low Water	North American Datum of 1983
H08701	1962	10,000	Mean Lower Low Water	North American Datum of 1983
H08753	1963	10,000	Mean Lower Low Water	North American Datum of 1983
H08754	1966	10,000	Mean Lower Low Water	North American Datum of 1983
H08894	1966	10,000	Mean Lower Low Water	North American Datum of 1983
H08895	1966	10,000	Mean Lower Low Water	North American Datum of 1983
H08910	1966	10,000	Mean Lower Low Water	North American Datum of 1983
H08911	1966	10,000	Mean Lower Low Water	North American Datum of 1983
H08912	1966	10,000	Mean Lower Low Water	North American Datum of 1983
H08914	1967	10,000	Mean Lower Low Water	North American Datum of 1983
H08915	1966	10,000	Mean Lower Low Water	North American Datum of 1983
H08916	1969	10,000	Mean Lower Low Water	North American Datum of 1983
H08927	1967	20,000	Mean Lower Low Water	North American Datum of 1983
H08928	1967	10,000	Mean Lower Low Water	North American Datum of 1983
H08929	1967	10,000	Mean Lower Low Water	North American Datum of 1983
H08930	1967	10,000	Mean Lower Low Water	North American Datum of 1983
H08933	1967	10,000	Mean Lower Low Water	North American Datum of 1983
H09038	1969	10,000	Mean Lower Low Water	North American Datum of 1983
H09414	1974	40,000	Mean Lower Low Water	North American Datum of 1983
H09417	1974	40,000	Mean Lower Low Water	North American Datum of 1983
H09743	1978	10,000	Mean Lower Low Water	North American Datum of 1983
H10072	1982	10,000	Mean Lower Low Water	North American Datum of 1983
H10534	1994	10,000	Mean Lower Low Water	North American Datum of 1983
H10535	1994	10,000	Mean Lower Low Water	North American Datum of 1983
H10555	1994	10,000	Mean Lower Low Water	North American Datum of 1983
H10564	1995	10,000	Mean Lower Low Water	North American Datum of 1983
H10583	1995	10,000	Mean Lower Low Water	North American Datum of 1983
H10587	1995	5,000	Mean Lower Low Water	North American Datum of 1983
H10608	1995	10,000	Mean Lower Low Water	North American Datum of 1983
H10621	1996	10,000	Mean Lower Low Water	North American Datum of 1983
H10626	1995	10,000	Mean Lower Low Water	North American Datum of 1983
H10662	1995	5,000	Mean Lower Low Water	North American Datum of 1983
H10755	1997	10,000	Mean Lower Low Water	North American Datum of 1983
H10766	1998	10,000	Mean Lower Low Water	North American Datum of 1983
H10783	1998	10,000	Mean Lower Low Water	North American Datum of 1983
H10792	2000	10,000	Mean Lower Low Water	North American Datum of 1983
H10828	1999	n/a	Mean Lower Low Water	North American Datum of 1983

NOS Survey ID	***Year of Survey***	***Survey Scale***	***Original Horizontal Datum***	***Original Vertical Datum***
H10887	1999	10,000	Mean Lower Low Water	North American Datum of 1983
H10911	1999	10,000	Mean Lower Low Water	North American Datum of 1983
H10939	1999	20,000	Mean Lower Low Water	North American Datum of 1983
H11038	2001	10,000	Mean Lower Low Water	North American Datum of 1983
H11039	2002	20,000	Mean Lower Low Water	North American Datum of 1983
H11040	2002	5,000	Mean Lower Low Water	North American Datum of 1983
H11188	2002	10,000	Mean Lower Low Water	North American Datum of 1983
H11268	2003	10,000	Mean Lower Low Water	North American Datum of 1983
H11269	2004	10,000	Mean Lower Low Water	North American Datum of 1983
H11316	2004	20,000	Mean Lower Low Water	North American Datum of 1983
H11317	2004	10,000	Mean Lower Low Water	North American Datum of 1983
H11371*	2005	20,000	Mean Lower Low Water	NAD 83 UTM Zone 10 North
H11375*	2005	10,000	Mean Lower Low Water	NAD 83 UTM Zone 10 North
H11419*	2005	10,000	Mean Lower Low Water	NAD 83 UTM Zone 10 North
H11420*	2005	10,000	Mean Lower Low Water	NAD 83 UTM Zone 10 North
H11552*	n/a	10,000	Mean Lower Low Water	NAD 83 UTM Zone 10 North
H11553*	n/a	10,000	Mean Lower Low Water	NAD 83 UTM Zone 10 North
H11556*	2006	5,000	Mean Lower Low Water	NAD 83 UTM Zone 10 North
H11631*	n/a	n/a	Mean Lower Low Water	NAD 83 UTM Zone 10 North
H11632*	n/a	n/a	Mean Lower Low Water	NAD 83 UTM Zone 10 North
H11748*	n/a	n/a	Mean Lower Low Water	NAD 83 UTM Zone 10 North
H11750*	n/a	n/a	Mean Lower Low Water	NAD 83 UTM Zone 10 North
H11751*	n/a	n/a	Mean Lower Low Water	NAD 83 UTM Zone 10 North

* denotes BAG survey
$^{+}$ denotes excluded survey

2) Canadian Hydrographic Service Multibeam Bathymetry

Canadian multibeam bathymetry was provided by Rob Hare of CHS. A Memorandum Of Understanding (MOU) was signed by NOAA and CHS giving NOAA clearance to integrate CHS bathymetry into the Port Townsend DEMs in support of improved tsunami forecasting and warning. Surveys are in WGS 84 geographic, which NGDC gridded at a cell size of 1 arc-second (Fig. 8) and are in an assumed MSL vertical datum. Depth anomalies were manually removed in Fledermaus (e.g., Fig. 9).

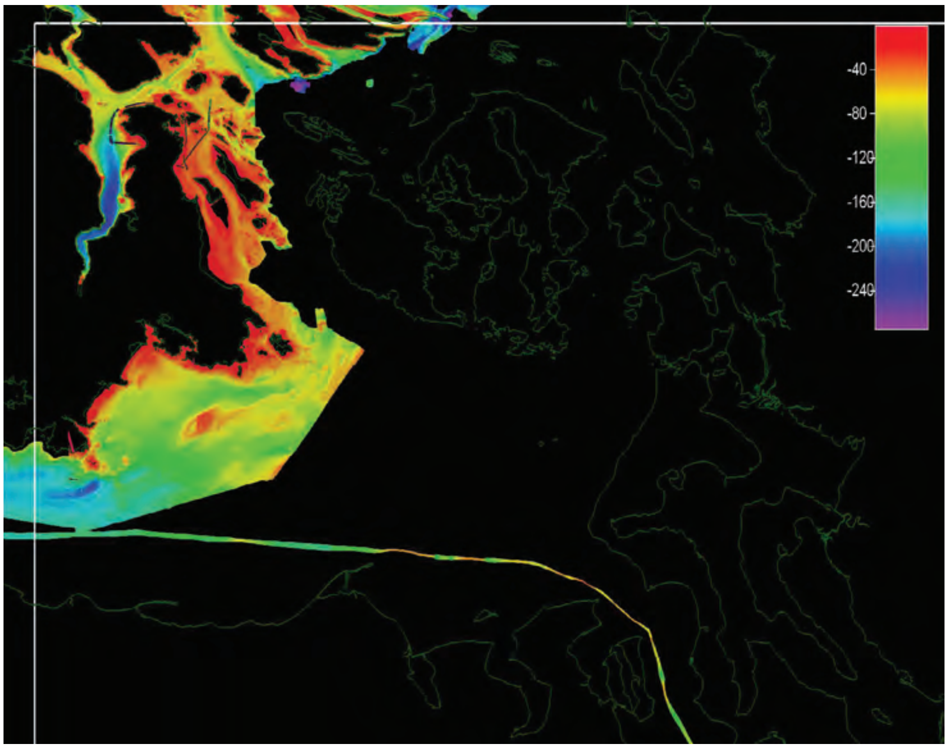

Figure 8. Color image of the CHS multibeam bathymetry provided by the Canadian Hydrographic Service. DEM boundary in white and combined coastline in green.

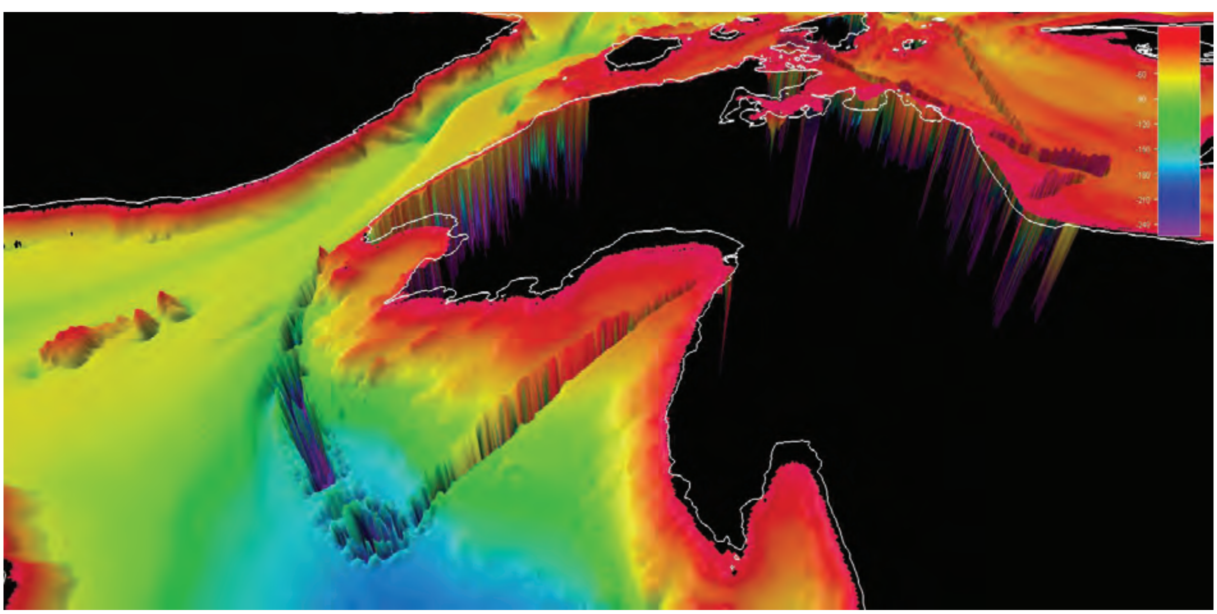

Figure 9. Examples of gross anomalies in the CHS multibeam bathymetry. Spikes were manually removed using Fledermaus.

3) NGDC-digitized depths

NGDC digitized bathymetric values in areas where bathymetric data were sparse and inconsistent with corresponding RNCs and satellite imagery. Figure 10 illustrates how digitized depths were used to represent the seabed of Port Townsend Harbor. Elevation values were assigned to points based on RNCs, satellite imagery, and peripheral datasets and were referenced to the NAVD 88 vertical datum.

Figure 10. NGDC digitized points in Port Townsend Harbor.

3.1.3 Topography

The topographic datasets used to build the Port Townsend DEMs include: USGS NED 1/3 and 1/9 arc-second DEMs, PSLC, and CDED (Table 5; Fig. 11). NGDC also digitized elevation points to represent breakwaters, jetties, levees, and harbors that were not resolved in the topographic datasets.

Table 5. Topographic datasets used in compiling the Port Townsend DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
USGS NED	1999-2007	DEMs	1/3 and 1/9 arc-seconds	NAD 83 geographic	NAVD 88	http://ned.usgs.gov
PSLC	2009	Lidar	~1 meter	NAD 83 WA State Plane North	NAVD 88	http://pugetsoundlidar.ess.washington.edu/
CDED	2007	DEM	~8 meters	NAD 83 geographic	MSL	http://www.geobase.ca/data/cded/index.html
NGDC	2010	digitized points	n/a	WGS 84 geographic	NAVD 88	

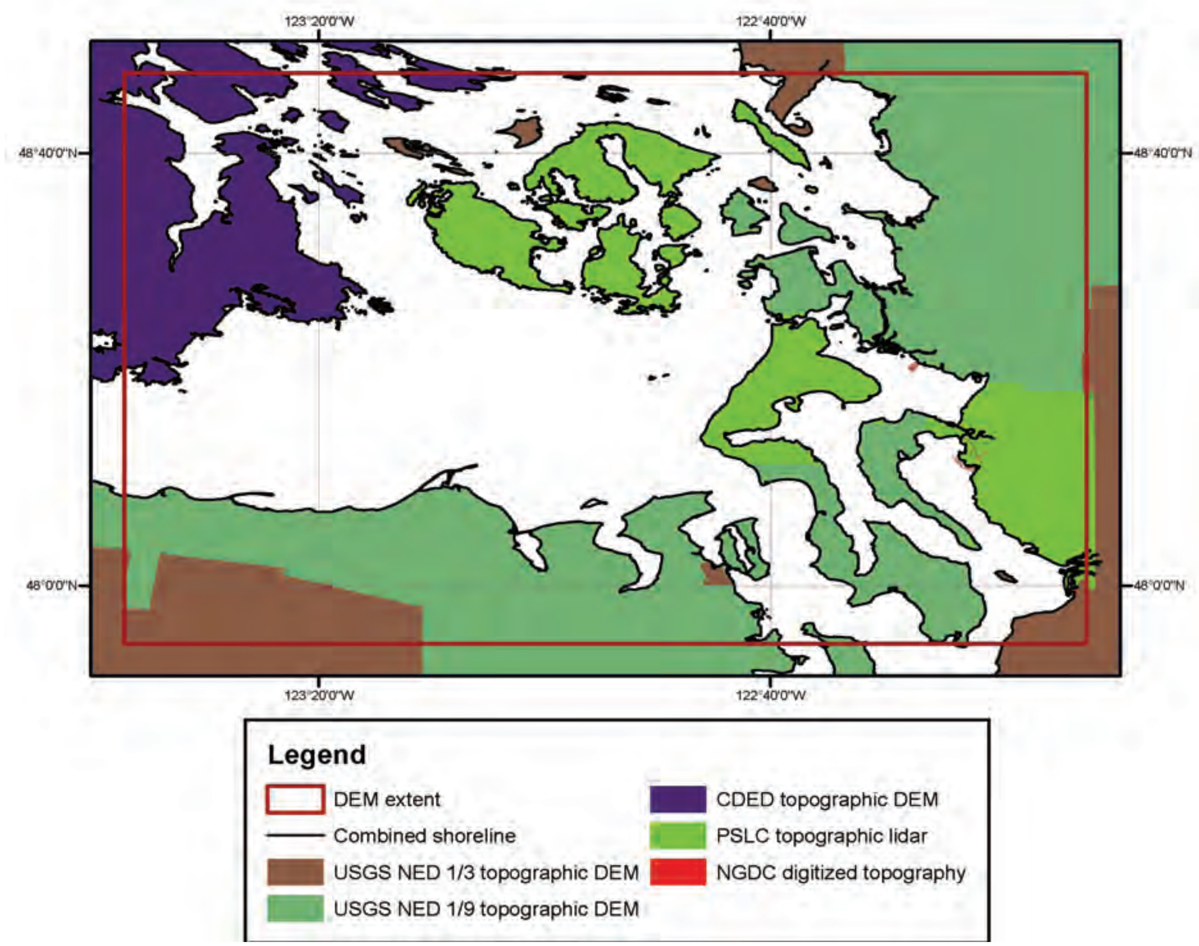

Figure 11. Source and coverage of topographic datasets used in compiling the Port Townsend DEMs.

1) United States Geological Survey National Elevation Dataset 1/3 arc-second topographic DEM

The USGS National Elevation Dataset (NED) provides complete 1/3 arc-second coverage of the Port Townsend region[6]. The dataset is available for download as raster DEMs in NAD 83 geographic horizontal datum and NAVD 88 vertical datum (meters). The bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution (see the USGS Seamless web site for specific source information: http://seamless.usgs.gov). The dataset was derived from USGS quadrangle maps and aerial photographs based on topographic surveys and topographic lidar. The NED DEM included "zero" elevation values over the open ocean, which were removed from the dataset by clipping to the "combined shoreline".

NGDC used the NED 1/3 arc-second DEM in those regions where the NED 1/3 is derived from the higher resolution NED 1/9 data. In addition, the NED 1/3 was used where no NED 1/9, CDED, or lidar data existed (Fig. 12).

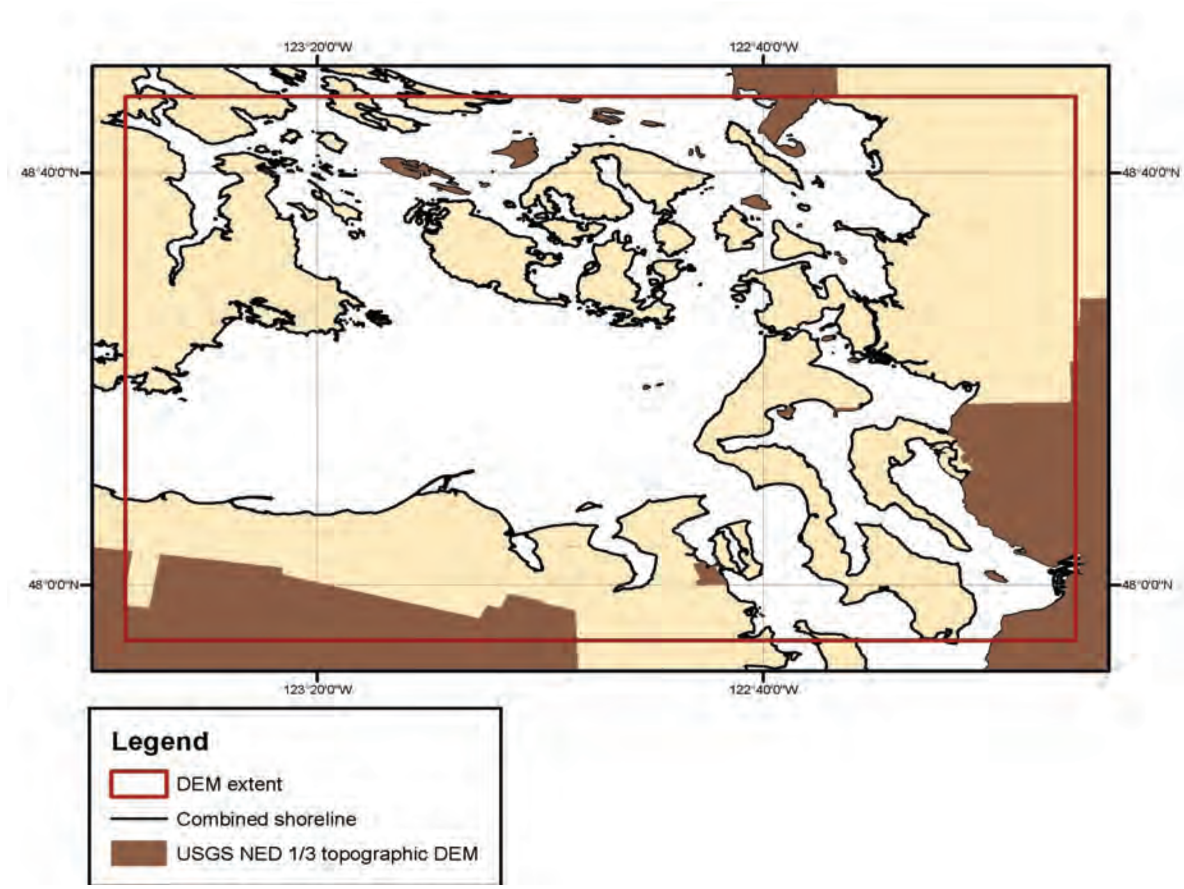

Figure 12. Coverage of the NED 1/3 arc-second topographic DEM used in building the Port Townsend DEMs. This dataset was used only where higher resolution topography was unavailable.

6. 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 NAVD 88, 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 web site]

2) United States Geological Survey National Elevation Dataset 1/9 arc-second topographic DEM

The USGS provides limited high-resolution NED 1/9 arc-second DEMs, derived from 3 meter point spacing lidar data. Data are in NAD 83 geographic coordinates and NAVD 88 vertical datum (meters), and are available for download as raster DEMs. The horizontal accuracy is 3 meters and the vertical accuracy, depending on the source data, is less than 22 centimeters. The NED 1/9 DEM included "zero" elevation values over the open ocean, which were removed by clipping to the "combined shoreline".

In areas where recent lidar surveys have been conducted, the lidar superseded the older NED 1/9 arc-second DEM, primarily in the San Juan Islands (Fig. 11). In addition, the NED 1/9 contained sections of anomalous elevation values that were manually removed from the dataset (e.g., Fig. 13).

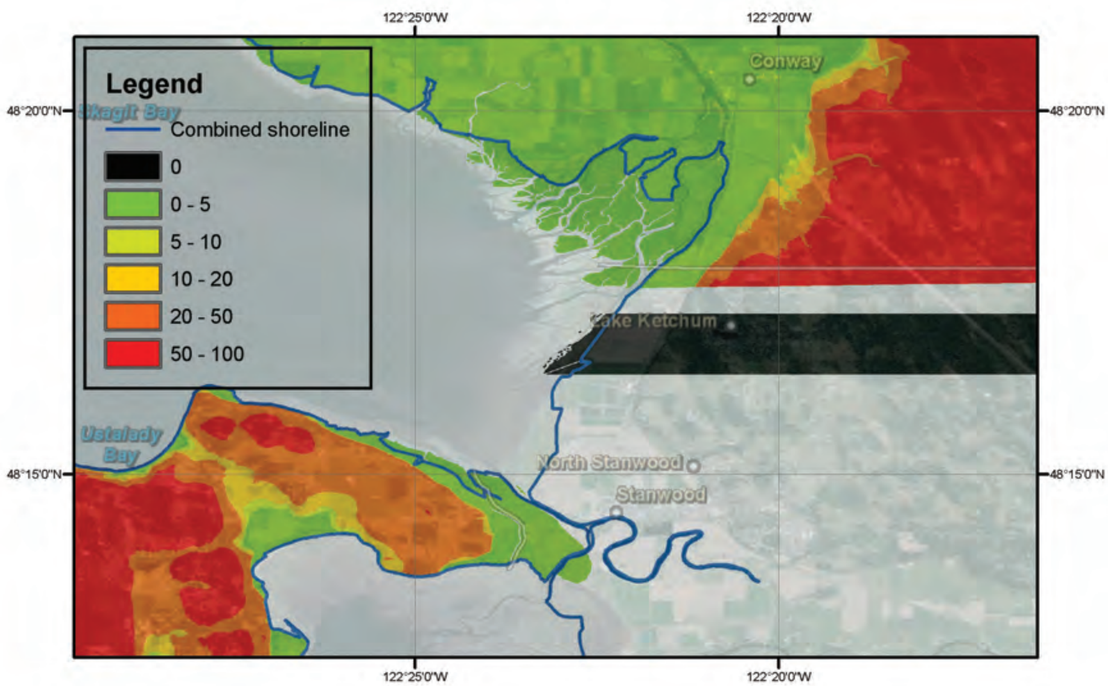

Figure 13. Image of the NED 1/9 arc-second topographic DEM draped over ESRI's World 2D Imagery. NGDC deleted anomalous elevation values of "0" shown in black.

3) Puget Sound Lidar Consortium Lidar

PSLC is an informal group of local agency staff and federal research scientists devoted to developing public domain high-resolution lidar products for the Puget Sound region. Although PSLC provides extensive lidar coverage around the boundaries of the Port Townsend DEMs, the NED 1/9 arc-second topographic DEM integrates PSLC lidar collected prior to 2005. Lidar surveys conducted in 2009 for the San Juan Islands and the town of Everett were used in the Port Townsend DEMs.

Although the NED 1/9 topographic DEM integrates PSLC lidar prior to 2005, it contained anomalous values and data gaps over Whidbey Island and Snohomish County (e.g., Fig. 14). In these areas, PSLC lidar from 2001 and 2003 respectively, were used in the Port Townsend DEMs. Data are in NAD 83 Washington State Plane North projected coordinates and NAVD88 vertical datum (meters), and have a vertical accuracy of ~1 meter.

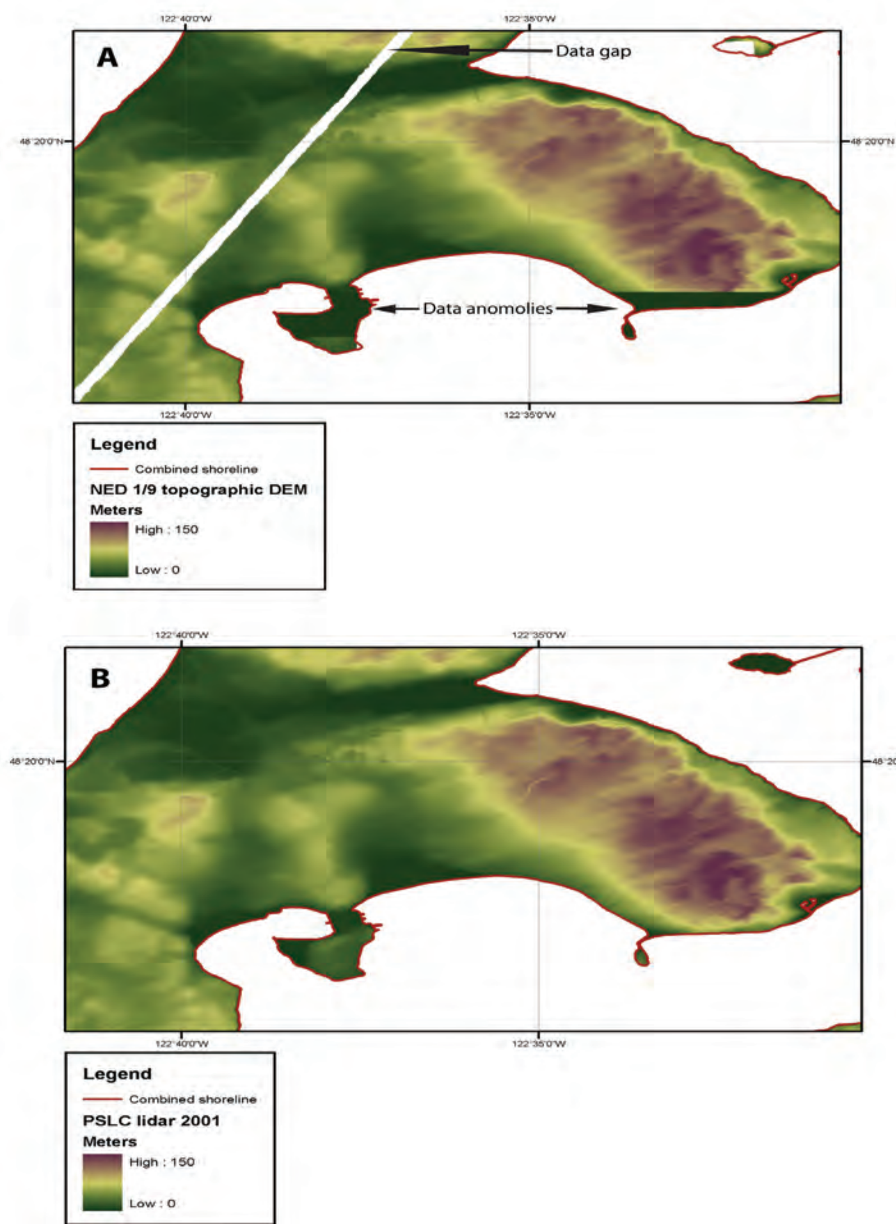

Figure 14. A. Data gaps and anomalies over Whidbey Island in the NED 1/9 arc-second DEM. B. PSLC lidar of the same region.

4) Canadian Digital Elevation Dataset

CDED consist of an ordered array of ground elevations at regularly spaced intervals at scales of 1:50,000 and 1:250,000. For the region surrounding Vancouver Island, the grid spacing is 0.75 arc-seconds at the 1:50,000 scale (Fig. 15). Data are in NAD 83 geographic coordinates, referenced to MSL (meters), and are available for download as raster DEMs. The extracted elevations have a vertical accuracy of +/- 5 to 10 meters depending on the source data resolution. See the CDED web site for specific source information (http://www.geobase.ca/geobase/en/data/cded/index.html).

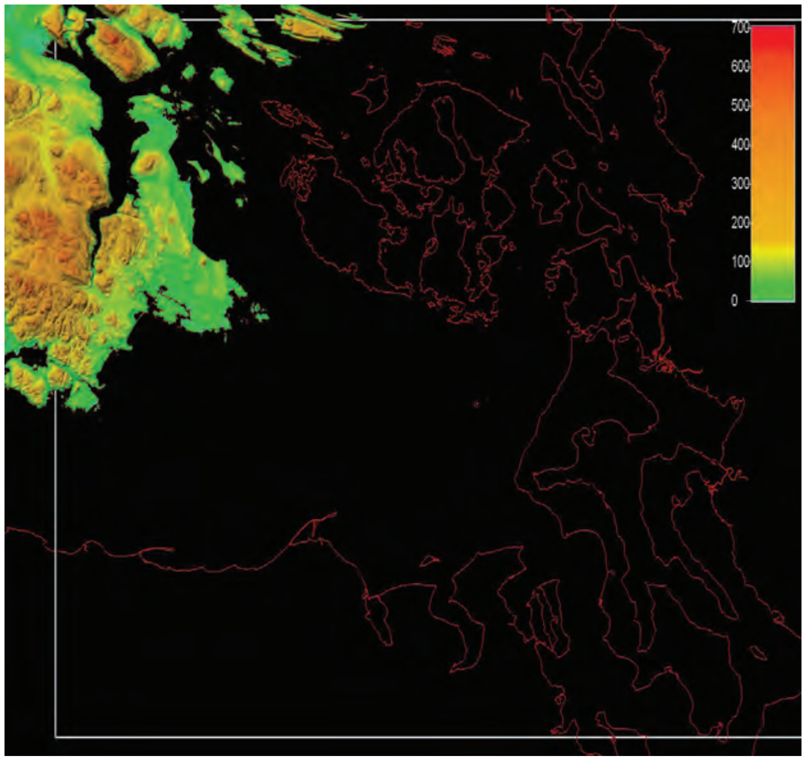

Figure 15. Color shaded-relief image of the CDED topographic DEM. DEM extent in white and combined shoreline in red.

5) NGDC digitized elevations

After inspecting the topographic datasets available for the Port Townsend DEMs, many breakwaters, jetties, and levees were either not represented or were unresolved in the topographic datasets. NGDC digitized these features with point spacings of 10 meters using USGS topographic quadrangles, RNCs, and ESRI's *World 2D* imagery as references.

In Stanwood, WA, NGDC digitized levees with point spacings of 10 meters and fixed elevation values of 3.8 meters at NAVD 88 vertical datum, as indicated in the NED 1/9 topographic DEM. The levees prevent this lowland area from flooding at high tide (Fig. 16).

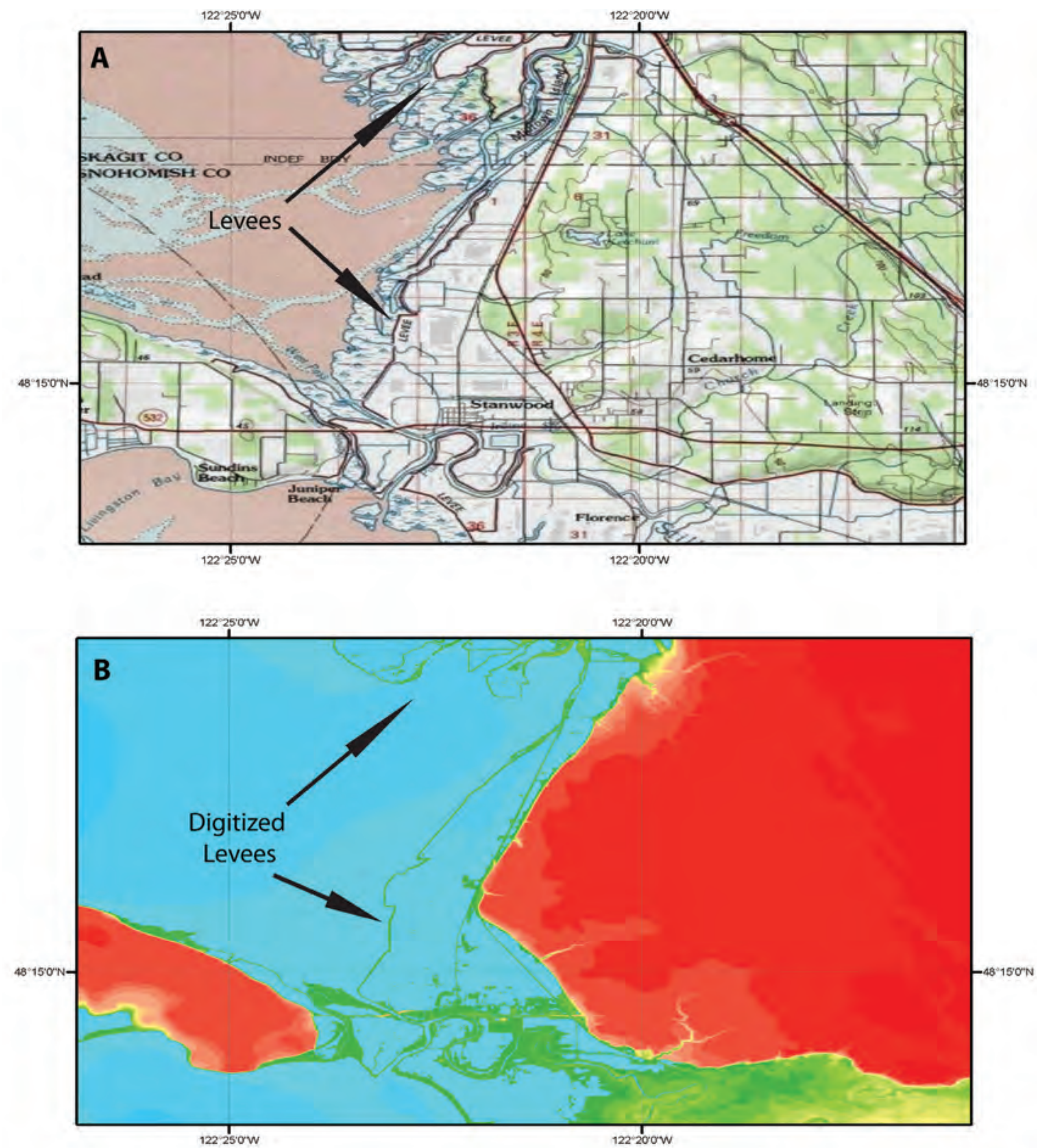

Figure 16. A. USGS topographic quadrangle indicating levees along the banks of Stanwood, WA.
B. Color image of the Port Townsend MHW DEM. Many levees were not represented in the topographic datasets and were digitized by NGDC.
Elevation values below zero are colored blue even though the levees prevent these areas from flooding at high tide.

3.1.4 *Bathymetry-topography*

Bathymetric-topographic lidar obtained from PSLC and JALBTCX provide bare-earth coverage of the coasts of Possesion Sound and Skagit Bay respectively, (Table 6). The surveys were conducted in 2001 and 2004 and have a vertical accuracy of approximately +/- 1 meter. Horizontal and vertical datums for the PSLC dataset are WGS 84 Washington State Plane North projected coordinates and MLLW respectively. Horizontal and vertical datums for the JALBTCX datset are NAD 83 Washington State Plane North projected coordinates and NAVD 88 respectively. The PSLC dataset was converted to NAVD 88 using the *VDatum* transformation tool (see Sec. 3.2.1).

Table 6. Bathymetric-topographic datasets used in compiling the Port Townsend DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Vertical Datum*	*Original Horizontal Datum/Coordinate System*	*URL*
PSLC	2001	lidar	~1 meter	MLLW (meters)	WGS 84 WA State Plane North	http://pugetsoundlidar.ess.washington.edu/
JALBTCX	2004	lidar	~1 meter	NAVD88 (feet)	NAD 83 WA State Plane North	http://rocky2.ess.washington.edu/data/raster/bluegreen/

1) **PSLC bathymetric-topographic lidar**

Bathymetric-topographic lidar collected in 2001 was obtained from PSLC and covers the coast of Possesion Sound (Fig. 17). Data are in WGS 84 Washington State Plane North projected coordinates and MLLW vertical datum (meters). The vertical accuracy is ~1 meter. NGDC converted the data from MLLW to NAVD 88 using the *VDatum* transformation tool (see Sec. 3.2.1).

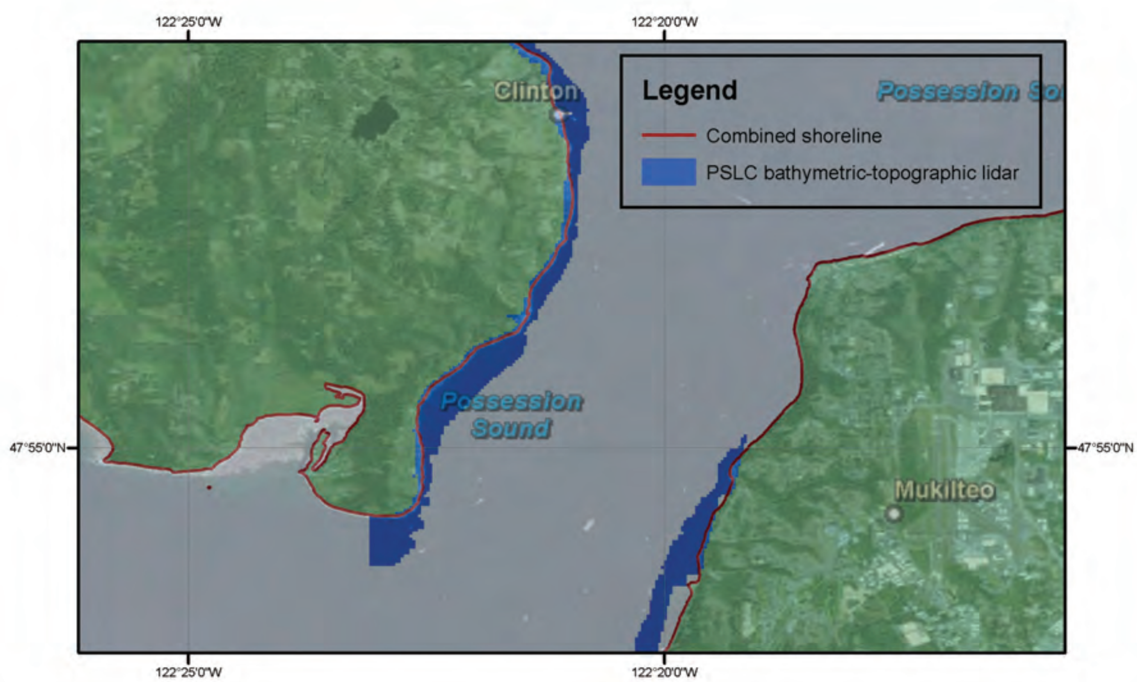

Figure 17. Coverage of PSLC bathymetric-topographic lidar.

2) JALBTCX bathymetric-topographic lidar

Bathymetric-topographic lidar collected in 2004 was obtained from JALBTCX and covers areas of Skagit Bay (Fig. 18). Data are in NAD 83 Washington State Plane North projected coordinates and NAVD 88 vertical datum (feet). The vertical accuracy is ~1 meter. Lidar is particularly useful in lowland areas such as Skagit Bay because of the wide tidal ranges that expose and cover the intertidal zone.

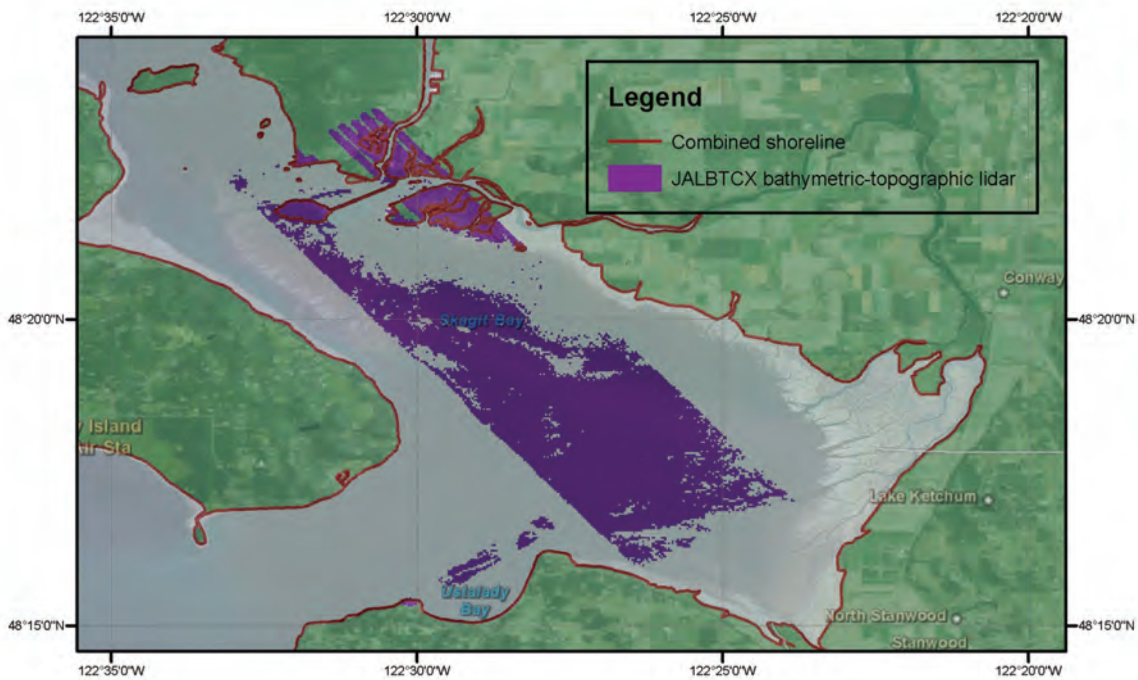

Figure 18. Coverage of JALBTCX bathymetric-topographic lidar. Lidar is particularly useful in lowland areas such as Skagit Bay because of the wide tidal ranges that expose and cover the intertidal zone.

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Port Townsend NAVD 88 DEM were originally referenced to a number of vertical datums including MLLW, MLW, MSL, and NAVD 88. All datasets except for the Canadian topographic data were transformed to NAVD 88 using the *VDatum* transformation tool (http://vdatum.noaa.gov/). The tidal relationships at the Port Townsend and Port Angeles tide stations (http://tidesandcurrents.noaa.gov/) are provided in Table 7 and 8 respectively. Locations of the tide stations are illustrated in Figure 26.

1) **Bathymetric data**

   The NOS hydrographic surveys and CHS multibeam were transformed from MLW, MLLW, and MSL to NAVD 88 using *VDatum*.

2) **Topographic data**

   The NED 1/3 arc-second DEM, NED 1/9 arc-second DEM, and PSLC lidar were originally referenced to NAVD 88 and required no vertical transformation. The CDED DEM is a Canadian dataset originally referenced to MSL. NGDC used the relationship between MSL and NAVD 88 at the Port Angeles, WA tide station (Table 8). Conversion to NAVD 88, using *FME* software, was accomplished by subtracting a constant offset value of 1.166 meters

Table 7. Relationships between vertical datums at the Port Townsend tide station (# 9444900).

Vertical datum	*Value (m)*
MHHW	2.596
MHW	2.389
MSL	1.522
MLW	0.760
MLLW	0.00

Table 8. Relationship between NAVD 88 and other vertical datums at the Port Angeles tide station (# 9444090).

Vertical datum	*Value (m)*	*Difference to NAVD 88 (m)*
MHHW	2.153	2.024
MHW	1.987	1.858
MSL	1.295	1.166
MLW	0.586	.457
NAVD 88	0.129	0.00
MLLW	0.00	-0.129

3.2.2 Horizontal datum transformations

Datasets used to compile the Port Townsend NAVD 88 DEM were originally referenced to WGS 84 geographic, NAD 83 geographic, NAD 27 geographic, NAD 83 UTM Zone 10 North, NAD 83 Washington State Plane North, and WGS 84 Washington State Plane North. The relationships and transformational equations between the geographic horizontal datums are well established. Transformations to NAD 83 geographic were accomplished using *FME* software.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting ESRI shapefiles were checked in ESRI *ArcMap* and *Quick Terrain Modeler* for inter-dataset consistency. 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:

- Inconsistent, overlapping topographic datasets. The lower resolution datasets were clipped to high resolution datasets.
- Data values over the ocean in the NED DEMs, CDED, and the PSLC lidar topographic datasets. These datasets required automated clipping to the combined coastline or were edited manually.
- Digital, measured bathymetric values from NOS surveys date back over 123 years. More recent data, differed from older NOS data by as much as 50 meters vertically. The older NOS survey data were excised where more recent bathymetric data exists.
- The breakwaters, jetties, and levees in the Port Townsend DEMs are not well-represented in available elevation data. Limited lidar data in the region and written descriptions of the features were used to estimate elevations.

3.3.2 Smoothing of bathymetric data

Older NOS hydrographic survey data are generally sparse at the resolution of the Port Townsend DEMs in both deep water and in some areas close to shore. In order to reduce the effect of artifacts in the form of lines or "pimples" in the DEM due to these low resolution datasets, and to provide effective interpolation into the coastal zone, a 1/3 arc-second-cell size 'pre-surface' bathymetric grid in NAVD 88 vertical datum was generated using *GMT*[7], an NSF-funded software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/).

The older NOS hydrographic point data, in xyz format, were clipped to remove overlap with the newer NOS surveys. All of the bathymetric data were combined with points extracted from the adjusted MHW coastline—to provide a buffer along the entire coastline. The coastline elevation values were assigned values congruent to the MHW-NAVD 88 conversion grid to prevent artificial flooding in the Port Townsend MHW DEM (see Sec. 3.4.4).

The point data were then median-averaged using the *GMT* tool 'blockmedian' to create a 1/3 arc-second grid 0.05 degrees (~5%) larger than the Port Townsend DEM 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. Figures 19 and 20 show histograms of the NOS and CHS multibeam compared to the 1/3 arc-second pre-surfaced bathymetric grid. Differences cluster around zero with the three datasets.

Some inconsistencies were identified while merging the bathymetric datasets due to the range in ages and resolutions of the NOS hydrographic surveys. In areas where more recent data were available, the older surveys were either edited or not used. The gridded bathymetric surface was then converted to an xyz file for use in building the NAVD 88 DEM.

8. GMT is an open source collection of ~60 tools for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing Encapsulated PostScript File (EPS) illustrations ranging from simple x-y plots via contour maps to artificially illuminated surfaces and 3-D perspective views. GMT supports ~30 map projections and transformations and comes with support data such as GSHHS coastlines, rivers, and political boundaries. GMT is developed and maintained by Paul Wessel and Walter H. F. Smith with help from a global set of volunteers, and is supported by the National Science Foundation. It is released under the GNU General Public License. URL: http://gmt.soest.hawaii.edu/ [Extracted from GMT web site.]

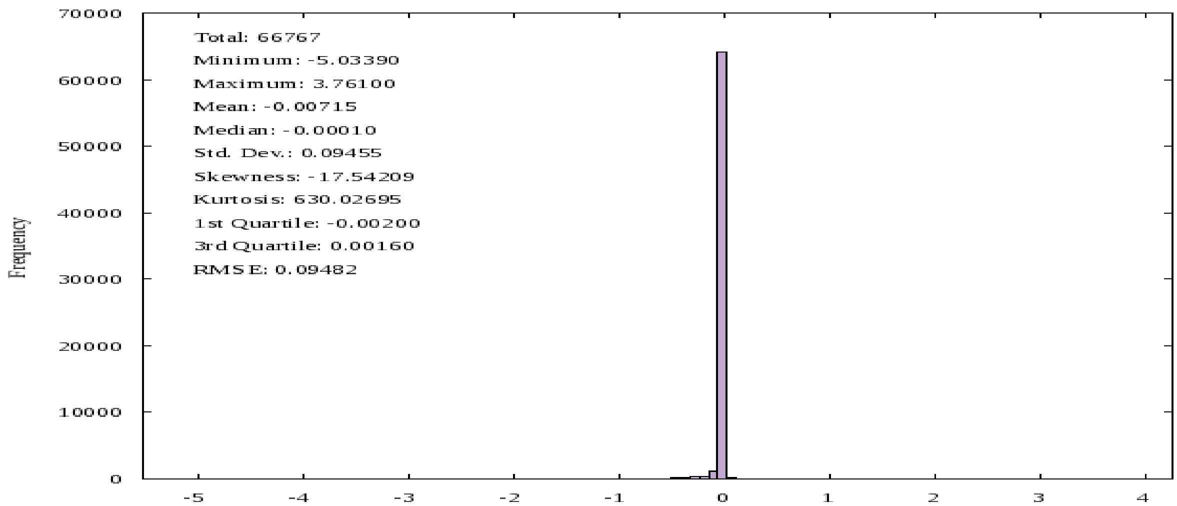

Figure 19. Histogram of the differences between NOS hydrographic survey H11317 and the 1/3 arc-second pre-surfaced bathymetric grid.

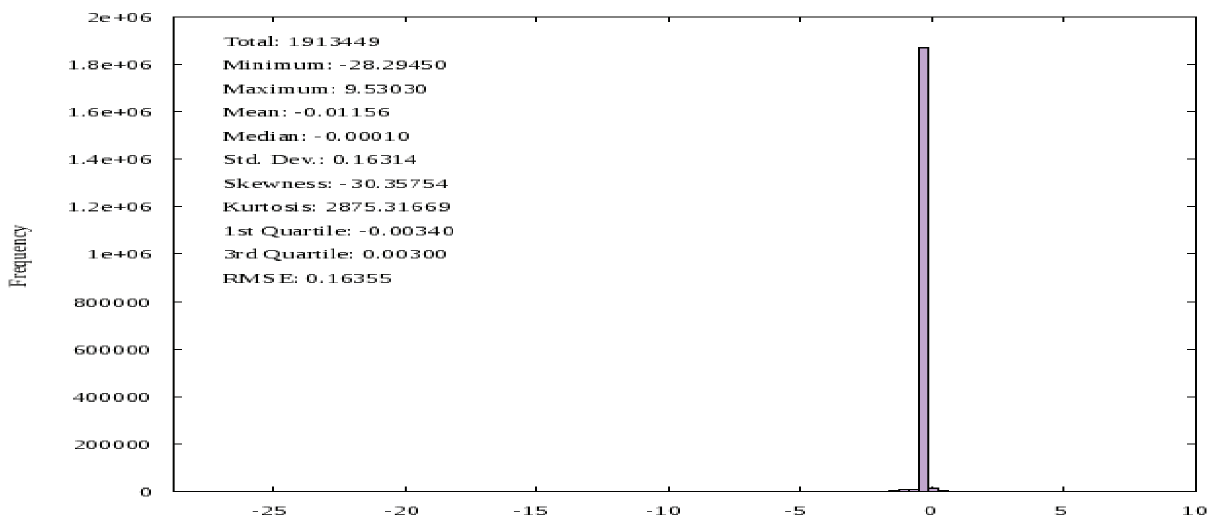

Figure 20. Histogram of the differences between the CHS multibeam swath sonar bathymetry and the 1/3 arc-second pre-surfaced bathymetric grid.

3.3.3 Building the NAVD 88 DEM

MB-System was used to create the 1/3 arc-second Port Townsend NAVD 88 DEM. 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 9. Greatest weight was given to the NED 1/9 arc-second DEM, CHS multibeam, JALBTCX bathymetric-topographic lidar, PSLC bathymetric-topographic lidar, and PSLC topographic lidar. Least weight was given to the pre-surfaced bathymetric grid.

Table 9.....Data hierarchy used to assign gridding weight in *MB-System*

Dataset	*Relative Gridding Weight*
NGDC Bathymetric Surface	0.01
NGDC digitized elevations	1
NOS hydrographic surveys	10
USGS NED 1/3 Topographic DEM	10
CDED topographic DEM	10
PSLC topographic lidar	100
PSLC bathymetric-topographic lidar	100
JALBTCX	100
CHS Multibeam	100
USGS NED 1/9 Topographic DEM	100

3.3.4 Building the MHW DEM

The MHW DEM was created by adding an NAVD 88-to-MHW conversion grid to the NAVD 88 DEM.

1) Developing the conversion grid

Using extents slightly larger (~ 5 percent) than the DEM, an initial xyz file was created that contained the coordinates of the four bounding vertices and midpoint of the larger extents. The elevation value at each of the points was set to zero. The *GMT* tool 'surface' applied a tension spline to interpolate cell values making a zero-value 3 arc-second grid. This zero-value grid was then converted to an intermediate xyz file using the *GMT* tool 'grd2xyz'.

Conversion values from NAVD 88 to MHW at each xyz point were generated using *VDatum*. Null values were removed and a converted xyz file was created by clipping the data to the combined shoreline using *FME*. The converted xyz file was then interpolated with the *GMT* tool 'surface' to create the 1/3 arc-second 'NAVD 88 to MHW' conversion grid with the extents slightly larger (~ 5 percent) than the NAVD 88 DEM (Fig. 21).

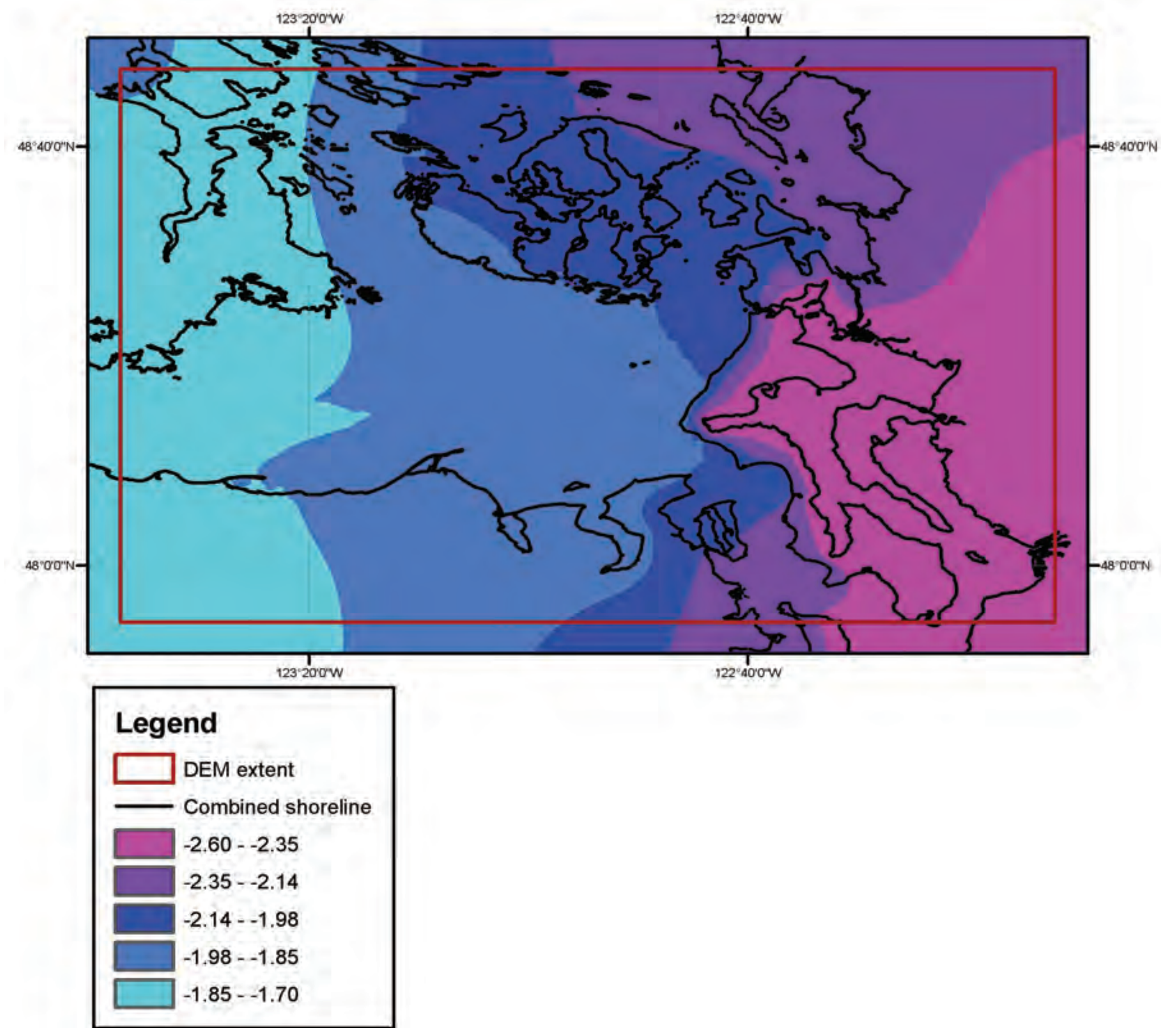

Figure 21. Image of the NAVD 88 to MHW conversion grid used to generate the MHW DEM. Coastline in black. Brown box denotes DEM boundary. Values in meters.

2) Assessing the accuracy of the conversion grid

The NAVD 88-to-MHW conversion grid was assessed using the NOS survey data. For testing of this methodology, the NOS hydrographic survey data were transformed from MLLW to NAVD 88 using *VDatum*. Shapefiles of the resultant xyz files were created and null values removed using *FME*. The shapefiles were then merged to create a single shapefile of all NOS surveys with a vertical datum of NAVD 88. A second shapefile of NOS data were created with a vertical datum of MHW using the same method. Elevation differences between the MHW and NAVD 88 shapefiles were computed after performing a spatial join in *ArcGIS*.

To verify the conversion grid methodology, the difference shapefile created using *ArcGIS* was converted to xyz format using *FME*. The 'NAVD 88-to-MHW' grid was then compared to the difference xyz file. Figure 22 indicates an agreement to approximately +/- 0.00640 meters with a mean difference of 0.00008 meters. Errors in the source datasets require rebuilding only the NAVD 88 DEM.

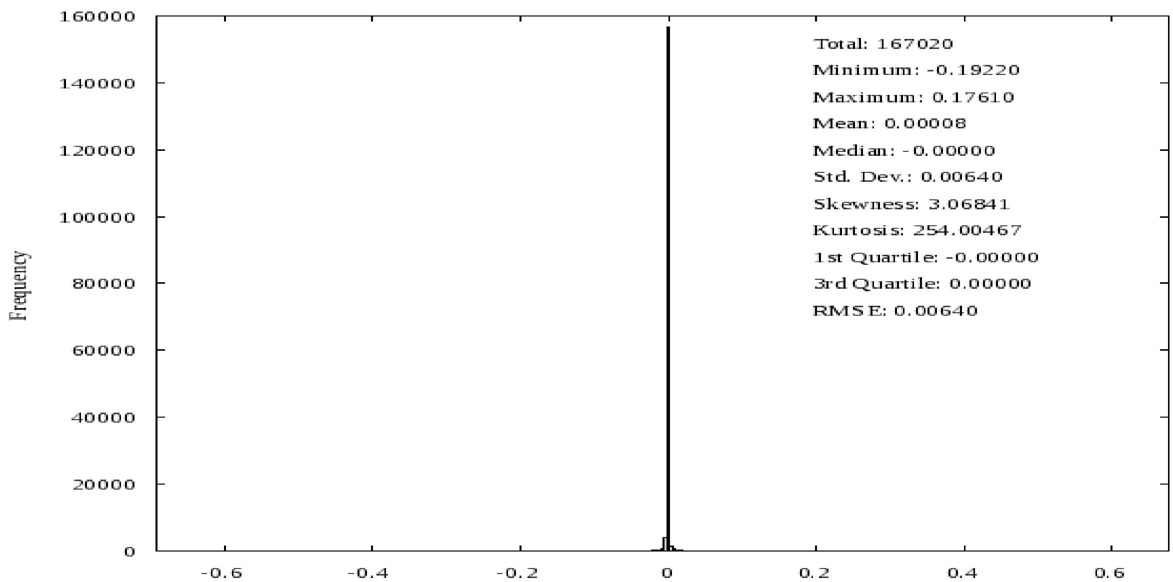

Figure 22. Histogram of the differences between the conversion grid and xyz difference files using NOS hydrographic survey data.

3) Creating the MHW DEM

Once the NAVD 88 DEM was complete and assessed for errors, the NAVD 88 to MHW conversion grid was added to it using *ArcCatalog*. The resulting MHW DEM was reviewed and assessed using RNCs, USGS topographic maps, and ESRI *World 2D* imagery. Problems encountered were determined to reside in source datasets, which were corrected before building a new NAVD 88 DEM.

3.4 Quality Assessment of the DEMs

3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Port Townsend DEMs is dependent upon DEM cell size and source datasets. Topographic features in the DEM have an estimated horizontal accuracy of 10 meters: gridded PSLC lidar data have an accuracy of approximately 1 meter, NED 1/3 topographic DEM is accurate to approximately 10 meters, NED 1/9 topographic DEM is accurate to approximately 3 meters, and the CDED topographic DEM is accurate to approximately 8 meters. Bathymetric-topographic features obtained from PSLC and JALBTCX have an estimated horizontal accuracy of approximately 1 meter. 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 and potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values in the Port Townsend DEMs is also dependent upon the source datasets contributing to DEM cell values. Topographic data have an estimated vertical accuracy of approximately 0.1 meters for PSLC lidar data, approximately 1 meter for the NED 1/9 arc-second DEM, and 7-15 meters for the NED 1/3 arc-second DEM. Bathymetric values have an estimated accuracy between 0.1 meters and 5% of water depth. Those values were derived from the wide range of sounding measurements from the early 20th century to recent, GPS-navigated multibeam swath sonar survey. Gridding interpolation to determine bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations in deep water.

3.4.3 Slope map and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the Port Townsend NAVD 88 DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 23). The DEM was transformed to NAD 83 UTM Zone 10 North 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 using *QT Modeler* and *Fledermaus* revealed suspect data points, which were corrected before recompiling the DEM. Figure 1 shows a color image of the 1/3 arc-second Port Townsend NAVD 88 DEM in its final version. Figure 24 shows a perspective rendering of the final NAVD 88 DEM. Figure 25 shows a data contribution plot of the Port Townsend DEMs.

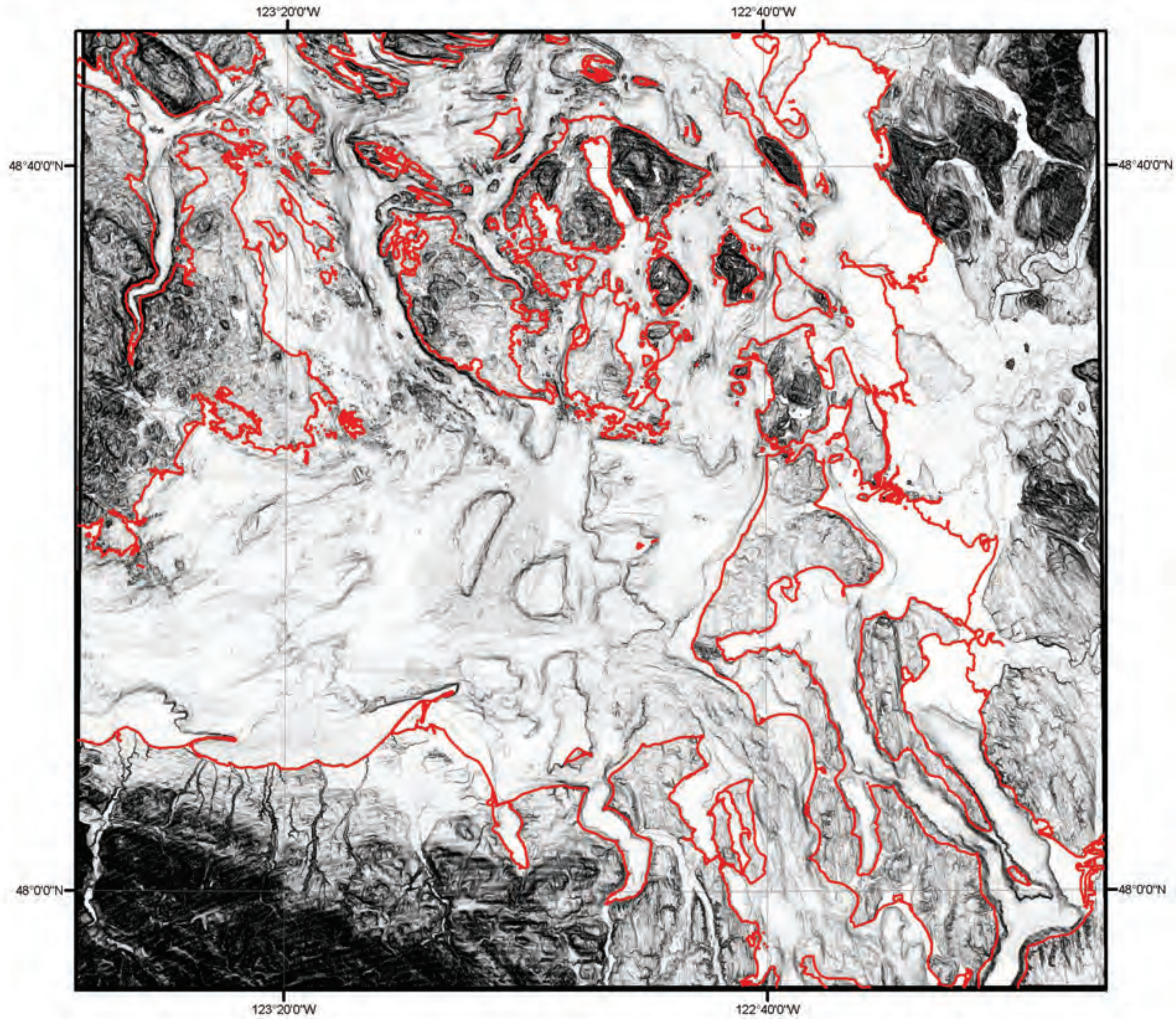

Figure 23. Slope map of the Port Townsend NAVD 88 DEM. Flat-lying slopes are shown in white; dark shading denotes steep slopes; combined shoreline indicated in red.

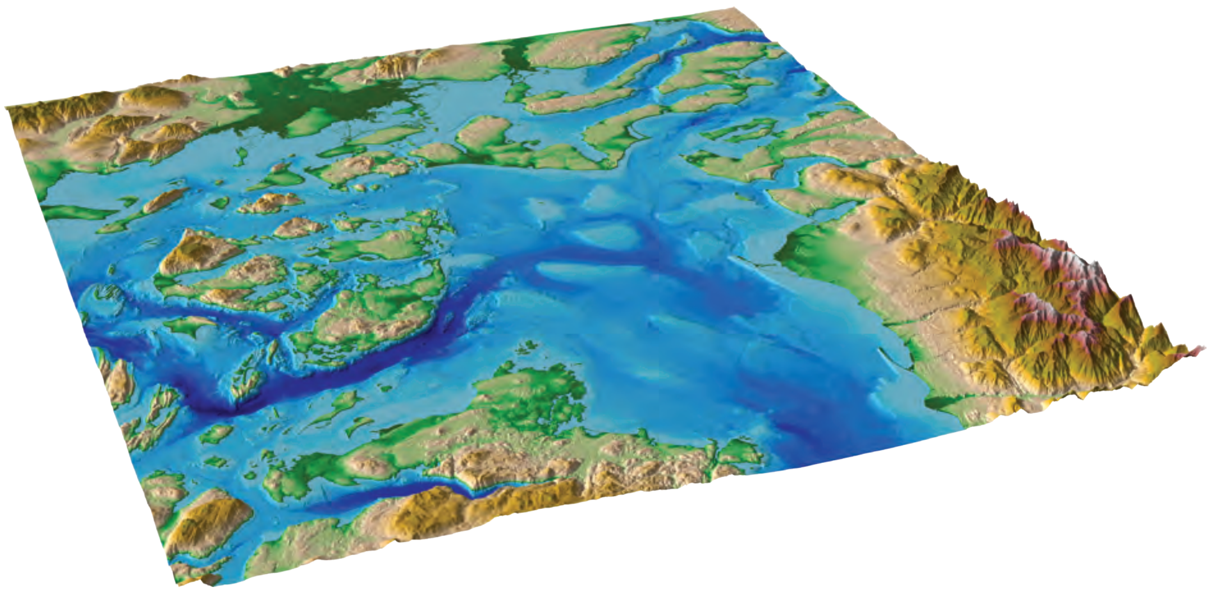

Figure 24. Perspective view from the west of the 1/3 arc-second Port Townsend NAVD 88 DEM. Vertical exaggeration–times 2.

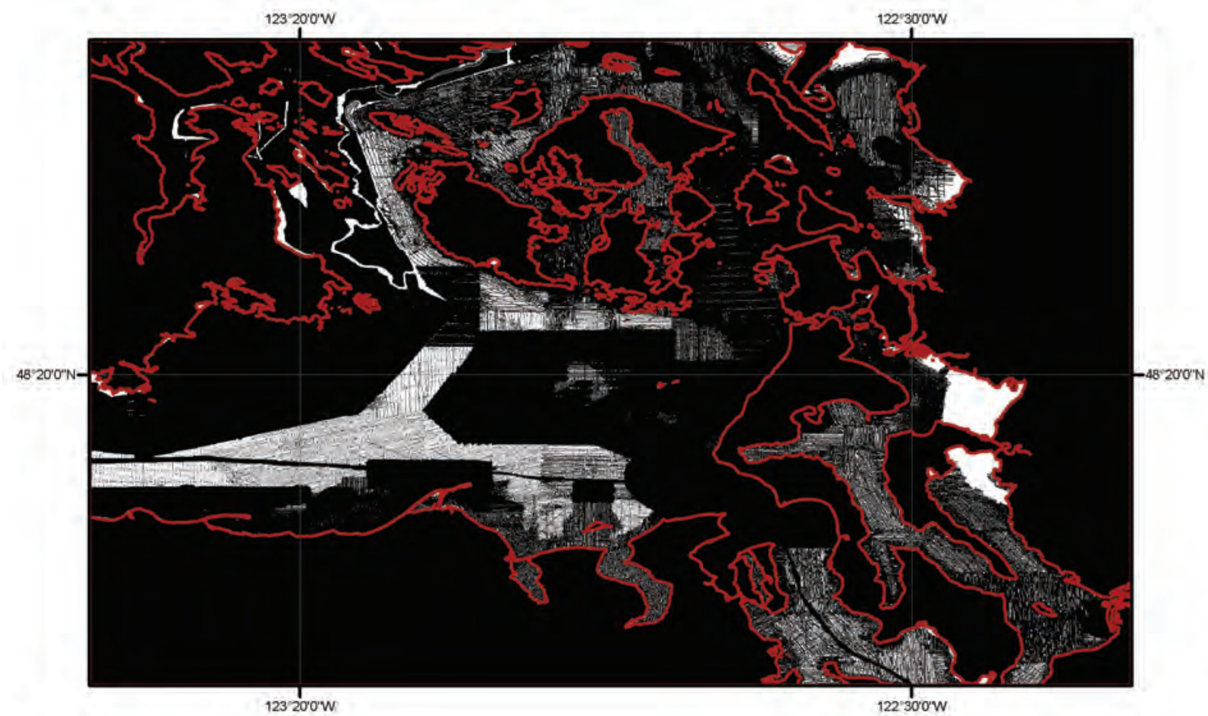

Figure 25. Data contribution plot of the Port Townsend NAVD 88 DEM. Black depicts DEM cells constrained by source data; white depicts cells with elevation values derived from interpolation. Due to the scale of the image, sparse soundings may not be visible in the graphic. Shoreline is shown in red.

3.4.4 Comparison with National Geodetic Survey geodetic monuments

The elevations of 1856 U.S. geodetic monuments were extracted from the NOAA NGS web site (http://www.ngs.noaa.gov/) in shapefile format (see Fig. 26 for monument locations). Shapefile attributes give positions in NAD 83 geographic (typically sub-mm accuracy) and elevations in NAVD 88 (in meters). Elevations were compared to the Port Townsend NAVD 88 DEM (Fig. 27). Differences between the DEM and the monument elevations range from -109.94 to 345.48 meters. The majority are within several meters. Large differences in elevations occurred where monuments are located on road cuts, on the top of buildings, or have conversion errors evident on the NGS data sheet (e.g., feet instead of meters).

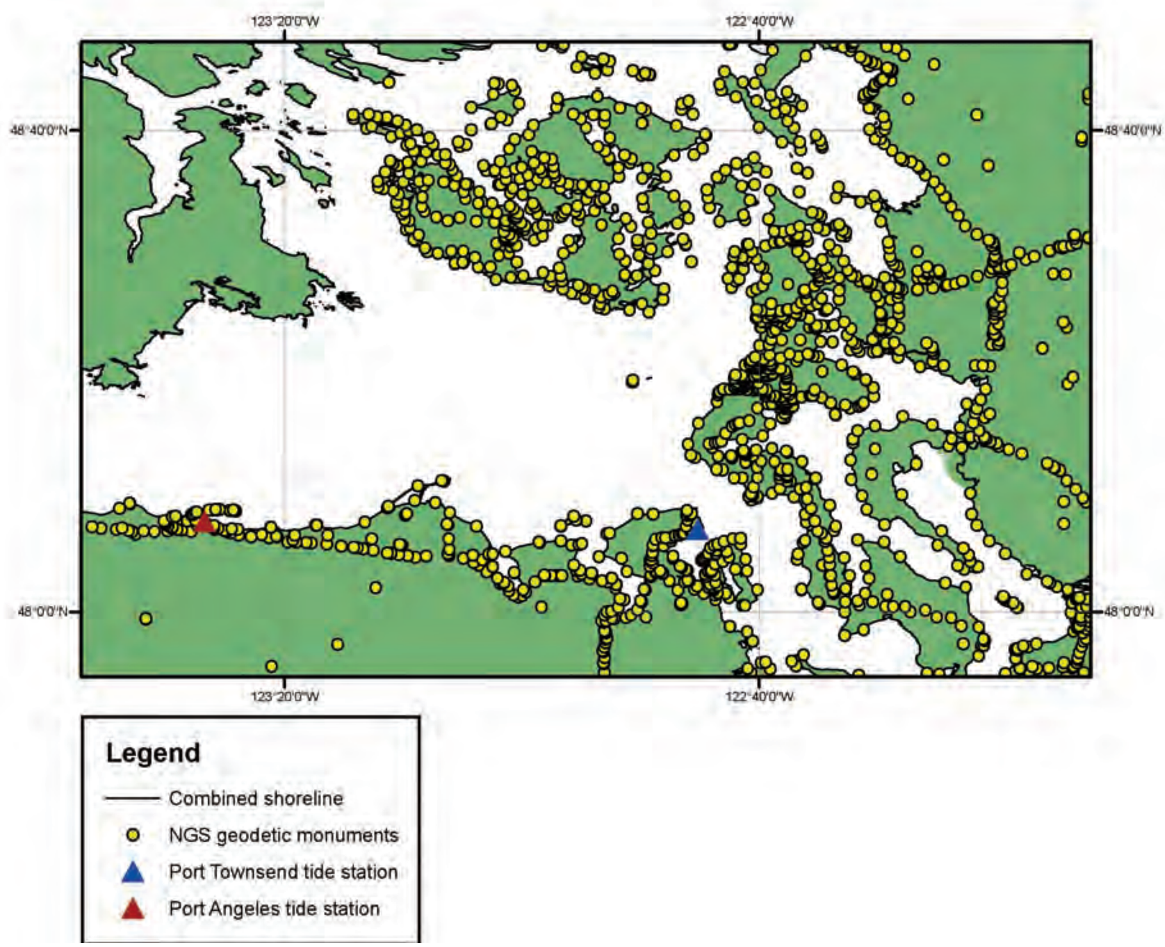

Figure 26. Location of NGS geodetic monuments, shown as yellow circles, in the Port Townsend region. Triangles represent NOAA tide stations mentioned in the report.

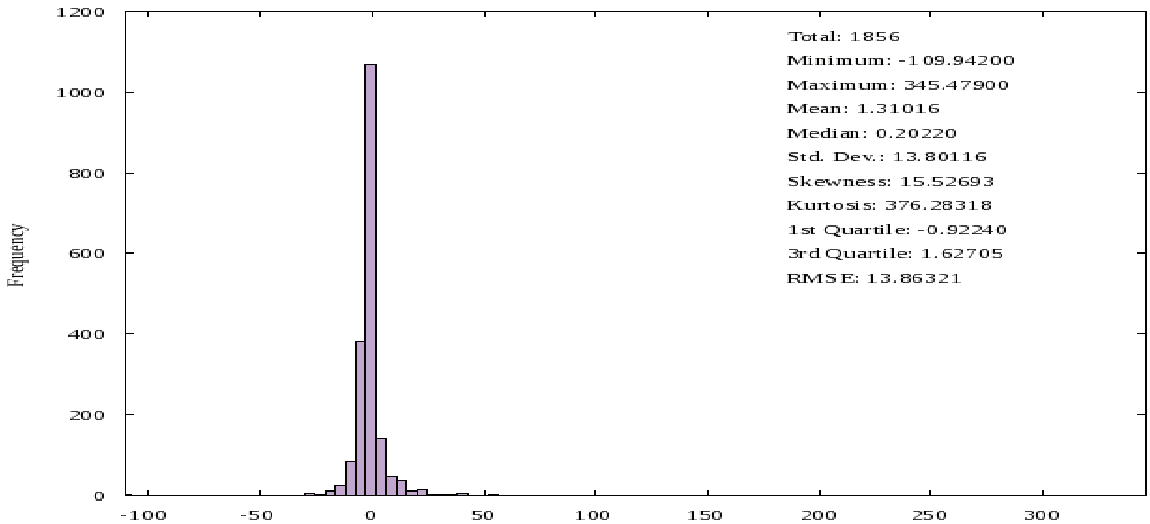

Figure 27. Histogram of the differences between NGS geodetic monument elevations and the Port Townsend NAVD 88 DEM.

3.4.5 NAVD 88 DEM comparison with source data files

To ensure grid accuracy, select bathymetric and topographic source data files were compared to the Port Townsend NAVD 88 DEM using *Fledermaus*, *FME* and *ArcMap*.

A histogram of the differences between data points from the PSLC topographic lidar data DEM and the Port Townsend NAVD 88 DEM is shown in Figure 28. Differences cluster around zero with the majority are within ± 0.5 meters.

A random selection of NED 1/9 topographic points were compared to the Port Townsend NAVD 88 DEM (Fig. 29; a random selection was used to represent the overall survey as there were too many points to statistically compare with current processing methods). The histogram shows the differences in elevations are clustered around zero and the majority are within ± 1 meter.

Comparison of all the CDED topographic points and the Port Townsend NAVD 88 DEM are shown in Figure 30. The histogram shows the differences in elevations are clustered around zero with the elevation differences ranging from -0.0064 to +25.27. The largest differences occur along the edge of steep slopes.

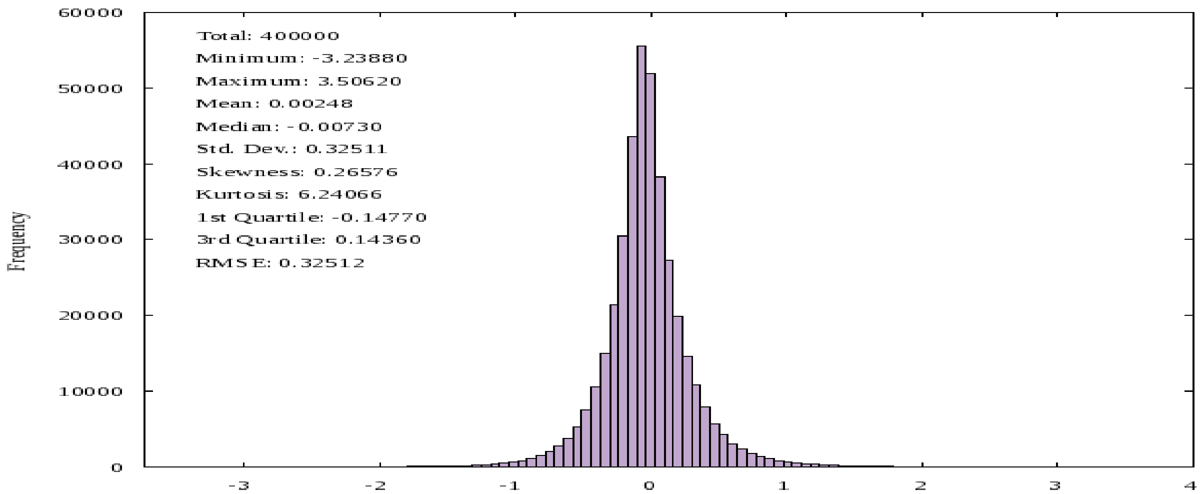

Figure 28. Histogram of the differences between select PSLC topographic data points and the Port Townsend NAVD 88 DEM.

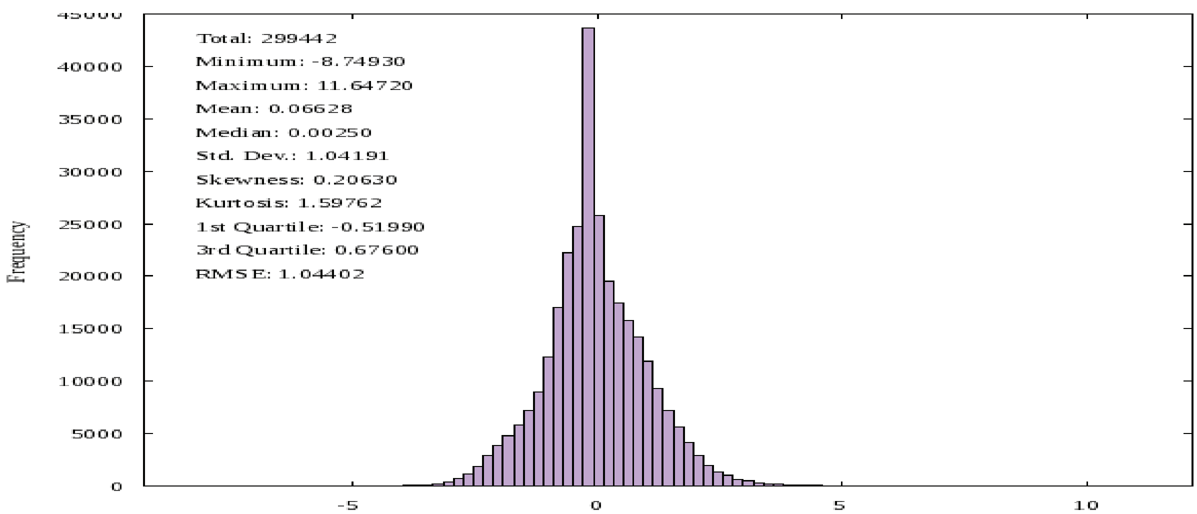

Figure 29. Histogram of the differences between select NED 1/9 data points and the Port Townsend NAVD 88 DEM.

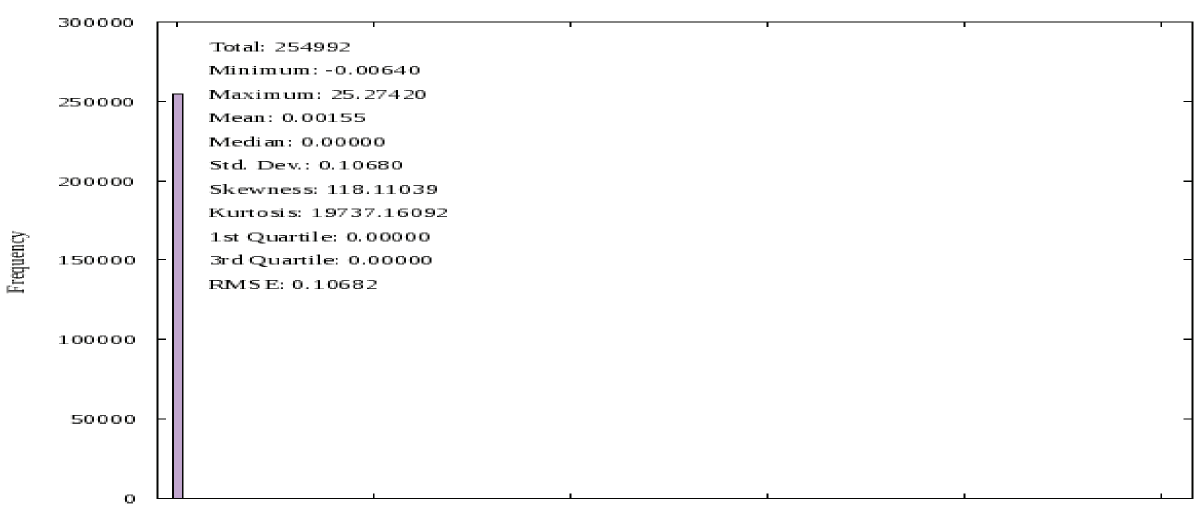

Figure 30. Histogram of the differences between CDED topographic data points and the Port Townsend NAVD 88 DEM.

4. Summary and Conclusions

Two integrated bathymetric–topographic digital elevation models of the Port Townsend, Washington region with cell sizes of 1/3 arc-second, were developed for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research. The best available digital data from U.S. federal, state, local, and academic 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*, ESRI *ArcGIS World Imagery 2-D*, *FME*, *Fledermaus*, *GMT*, *MB-System*, *QT Modeler*, and *VDatum* software.

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

- Conduct high-resolution bathymetric surveys along the Canada/United States border.
- Conduct bathymetric-topographic lidar surveys in lowland areas along estuaries.
- Extend VDatum coverage into Canada.

5. Acknowledgments

The creation of the Port Townsend DEM was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Nazila Merati, Marie Eble, and Vasily Titov (PMEL). Special thanks to Rob Hare (CHS) who provided Canadian multibeam bathymetry.

6. References

Nautical Chart #18400, 48th Edition, 2008. Strait of Georgia and Strait of Juan De Fuca. Scale 1:200,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18421, 49th Edition, 2008. Strait of Georgia and Strait of Juan De Fuca. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing Software

ArcGIS v. 9.3.1 – developed and licensed by ESRI, Redlands, Washington, http://www.esri.com/.

ESRI World Imagery (ESRI_Imagery_World_2D) – ESRI ArcGIS Resource Centers http://resources.esri.com/arcgisonlineservices/.

FME 2010 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/.

Fledermaus v. 7.0.0 – developed and licensed by Interactive Visualization Systems (IVS 3D), Fredericton, New Brunswick, Canada, http://www.ivs3d.com/products/fledermaus/.

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

GMT v. 4.3.4 – Generic Mapping Tools, freeware 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 – software developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System/.

Quick Terrain Modeler v. 7.0.0 – LiDAR processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/.

VDatum Transformation Tool, Washington - Washington Juan De Fuca, v. 01 – developed and maintained by NOAA's National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS), http://vdatum.noaa.gov/.

VDatum Transformation Tool, Washington - Washington Puget Sound, v. 01 – developed and maintained by NOAA's National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS), http://vdatum.noaa.gov/.