NOAA Technical Memorandum NOS CS 22

VDATUM FOR THE COASTAL WATERS OF NORTH/CENTRAL CALIFORNIA, OREGON AND WESTERN WASHINGTON: TIDAL DATUMS AND SEA SURFACE TOPOGRAPHY

Silver Spring, Maryland
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noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Coast Survey Development Laboratory

Office of Coast Survey
National Ocean Service
National Oceanic and Atmospheric Administration
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VDATUM FOR THE COASTAL WATERS OF NORTH/CENTRAL CALIFORNIA, OREGON AND WESTERN WASHINGTON: TIDAL DATUMS AND SEA SURFACE TOPOGRAPHY

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ABSTRACT

VDatum, NOAA's vertical datum transformation software tool, allows users to transform vertical elevation/depth data between various tidal, orthometric, and ellipsoid-based 3D reference systems. An application of VDatum is developed for the coastal waters of north/central California, Oregon and western Washington. The region of interest extends from Pt. Buchon in California to Cape Flattery, Washington.

The tidal datums fields for this VDatum application were derived from tidal simulations using the 2D barotropic version of the finite element model ADCIRC. An unstructured triangular grid consisting of 293,009 nodes and 546,190 elements was created for these simulations. The model was forced with eight tidal constituents (M_2, S_2, N_2, K_2, K_1, P_1, O_1 and Q_1) and run for 67 days. Water level time series of the last 60 days were saved. Various tidal datum fields, including mean lower low water, mean low water, mean high water, and mean higher high water, were derived from these time series. Water level harmonic analysis was conducted on the model results for the NOAA/NOS standard 37 tidal constituents. Model results were validated by comparing with observations from 105 water level stations maintained by the NOAA's Center for Operational Oceanographic Products and Services (CO-OPS). Discrepancies between model results and observational datums were attributed to model errors and interpolated over the whole model domain using Tidal Constituent And Residual Interpolation, a spatial interpolation tool based on solution of Laplace's equation. These spatially varying error fields were added to the original model results to derive corrected tidal datum fields on the unstructured grid. These corrected tidal datum fields were then interpolated onto a regularly structured marine grid for use as input to the VDatum software.

The Topography of Sea Surface (TSS), defined as the elevation of NAVD88 relative to local mean sea level (LMSL), was developed based on interpolation of bench mark data maintained by CO-OPS and the National Geodetic Survey. The NAVD88-to-LMSL values were derived either by fitting tidal model results to tidal bench marks leveled in NAVD88 or by calculating orthometric-to-tidal datum relationships at NOAA tidal gauges. Results by both methodologies were coupled to create the final TSS grids by spatial interpolation.

Key Words: tides, tidal datums, California, Oregon, Washington, VDatum, west coast, ADCIRC, bathymetry, coastline, spatial interpolation, marine grid, North American Vertical Datum

1. Introduction

NOAA's NOS has developed a software tool called VDatum to transform elevation data among approximately 30 vertical datums (Milbert, 2002; Parker, 2002; Parker et al., 2003; Myers, 2005). Once VDatum has been established for a region, data sets referenced to different vertical datums can be integrated through transformations to a common vertical datum (Parker, 2002). VDatum allows bathymetric and topographic data to be integrated in this manner through its inherent geoidal, ellipsoidal, and tidal relationships.

Knowledge of the spatial distribution of tidal datums is necessary for developing accurate VDatum applications (Milbert and Hess, 2001). Tidal datum fields for VDatum are derived from water level observations at presently operating and historical NOAA tide stations and from numerical simulations by hydrodynamic models. The observations provide accurate tidal datums at the station locations, and the hydrodynamic models are an effective way to capture the spatially varying nature of the tidal datums between and away from stations. Differences between the model and the data are spatially interpolated to create a correction field used to produce a final set of tidal datum fields that match the observations.

This report describes the development of VDatum for an area extending from Cape Flattery, Washington to central California. Figure 1 displays a map of the area. In the figure, the black line represents the Mean High Water (MHW) coastline and the green line denotes the 25-nm offshore demarcation. Tidal datums for VDatum are generally developed for water areas between the coastline and the 25-nm offshore limit.

Creation of VDatum begins with tidal simulations using a hydrodynamic model. Tidal datums and harmonic constants of selected tidal constituents were computed from a 60-day simulated water level time series. Adjustments to model parameters were made based on comparisons between the modeled harmonic constituents and tidal datums with observational data. Final error corrections to the tidal datums were made using the Tidal Constituent and Residual Interpolation (TCARI) software to spatially interpolate model-data differences. Regularly structured marine grids were created and populated with these corrected tidal datums.

Finally, to be applicable over coastal waters, VDatum requires spatially-varying fields of the Topography of Sea Surface (TSS) as well, which refers to the elevation of the North American Vertical Datum of 1988 (NAVD88) relative to Local Mean Sea Level (LMSL). The NAVD88-to-LMSL field was derived by either fitting tidal model results to tidal bench marks leveled in NAVD88 or calculating orthometric-to-tidal datum relationships at NOAA tide stations.

This technical report is organized as follows: After an introduction in Section 1, Section 2 discusses data needed for driving and validating the hydrodynamic model. Section 3 and 4 describe the set-up and sensitivity studies of the tide model, respectively. Section 5 discusses creation of regularly structured marine grid required for the VDatum software tool and its population with error-corrected model datums. In Section 6, creation of TSS for the area is described. The efforts of establishing a relationship between Columbia River Datum (CRD) and NAVD 88 are described in Section 7. Finally, a summary is given in Section 8.

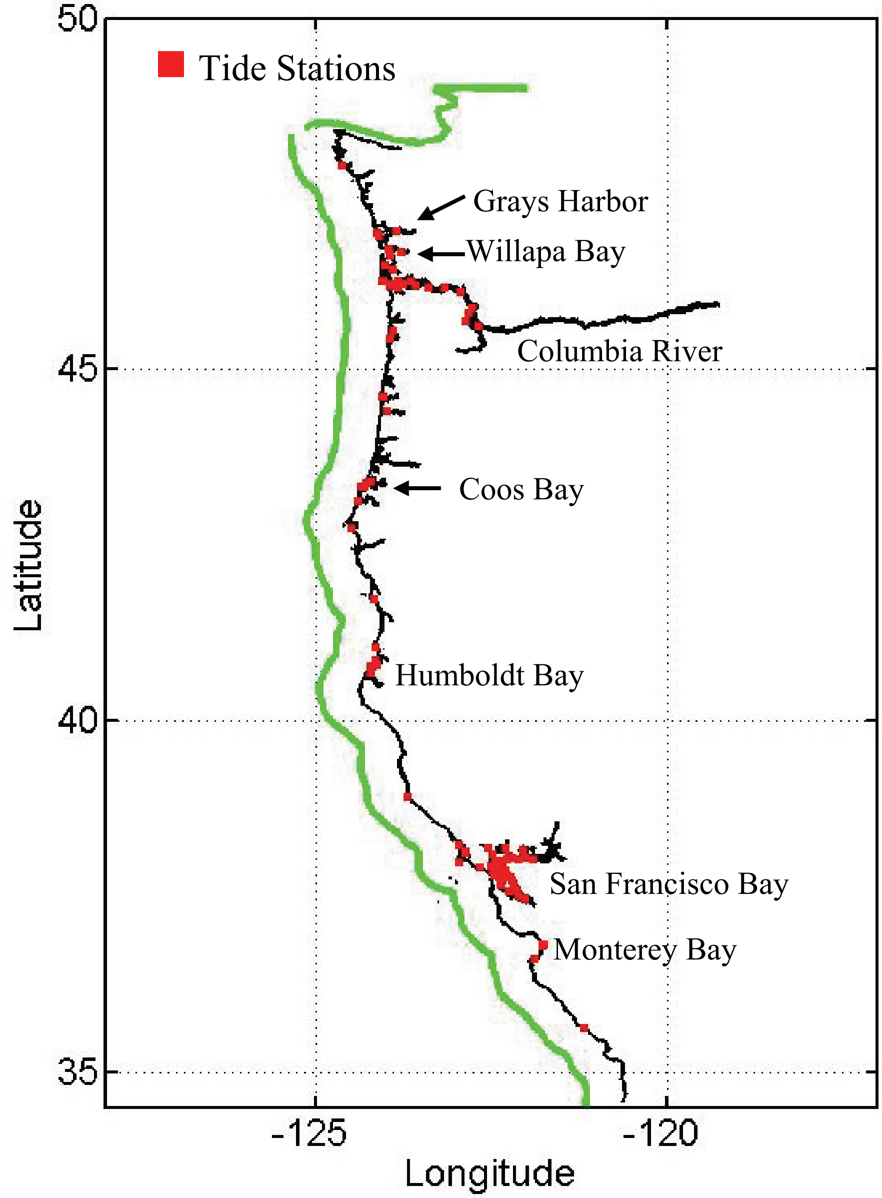

Figure 1. Map of the coastal waters for the VDatum region of interest. The black line illustrates the MHW coastline. The green line marks a distance of 25-nautical miles offshore. Red squares show the locations of the NOAA tide stations.

2. Data Description

To derive spatially varying tidal datum fields for VDatum, a hydrodynamic model was used to simulate the tidal dynamics in this region. Coastline and bathymetric data were required to build the model grid for the tidal simulation. Observational tidal datums were used to verify the model results and to make corrections in the final tidal datum fields.

2.1. Digital Coastline

The MHW coastline was used to delineate the land-water boundaries and to guide the building of the unstructured grid used in the tide model. High resolution digital shoreline was produced from current NOAA Electronic Navigational Chart (ENC) and Raster Navigational Chart data. The Coastline (COALNE) and Shoreline Construction (SLCONS) ENC object classes were obtained for both the Harbor and Approach scalebands and converted from their native S57 format to ESRI shapefiles for use in ArcGIS 9.3. The ENC data were merged and edited against NOAA charts to produce a continuous shoreline product representing the most detailed and most current information available. The Charts used typically ranged in scale from 1:5,000 to 1:80,000. A commercial software package called Surface-Water Modeling System (SMS) was used to read in the shapefile and manually connect the shoreline segments together and to correct errors in the original digital coastlines. In Figure 1, the black line illustrates this final coastline.

2.2. Bathymetric Data

Bathymetric data used in this study were from several sources: NOS soundings, the NOAA ENCs, NOAA nautical charts and U.S. Army Corps of Engineers (USACE) navigational channel surveys.

The NOS soundings were from the NOS/OCS hydrographic database maintained at the National Geophysical Data Center (NGDC) and include surveys conducted between 1851 and 2004. The USACE is responsible for maintaining and dredging the navigational channels. Where available, this dataset is usually the most dense and most recent. However, USACE's bathymetry surveys are only conducted for the major ports and harbors. In the studied area, this dataset only covers the navigational channels in the Columbia River, Grays Harbor and San Francisco Bay. The survey coverage in Columbia River is shown in Figure 2a. Figures 2b and 2c depict the data coverage of NOS soundings and the ENC's bathymetry.

It is noted that even with the combined datasets from above three sources, there are certain nearshore areas and some bays/rivers uncovered. NOAA nautical chart bathymetry, wherever they are available, was then manually digitized to compensate for the missing coverage. All sources of bathymetric data were used for the best regional coverage. However, they were prioritized based on the data quality as follows: USACE dredging/survey data, NOS sounding, ENCs and manually digitized nautical charts.

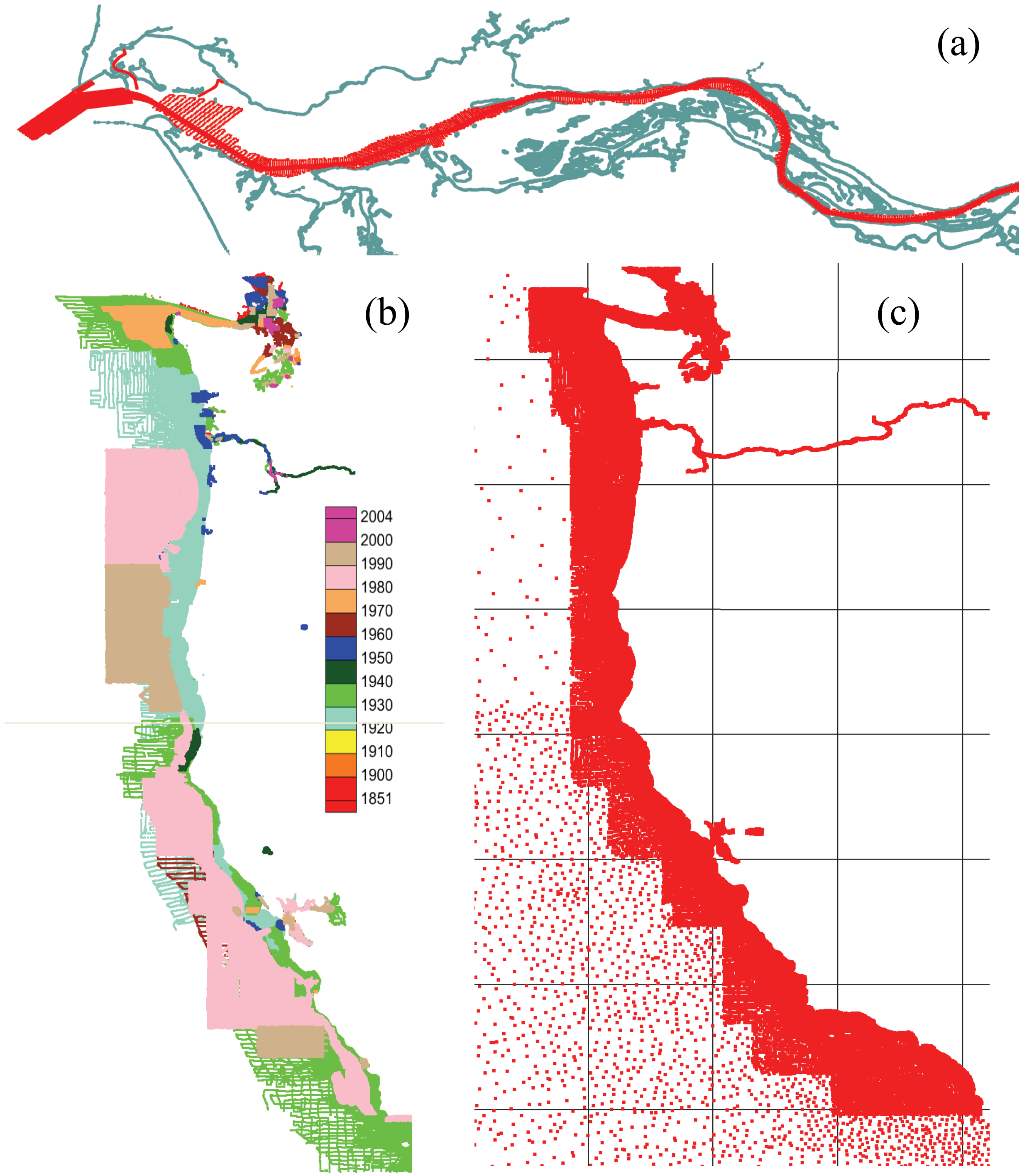

Figure 2. (a) ACE bathymetry survey in Columbia River; (b) Dates and locations of NOS sounding surveys and (c) distribution of ENC bathymetric data.

2.3. Water level station data

Tidal datums derived from NOAA tide station water level observations were used to verify and correct model results. There are a total of 159 stations in the region from central California to

Washington. However, some stations are located within either small embayments or upper reaches of rivers that are not represented in the present model grid (Section 3.2) and some stations have no observationally derived tidal datums. These stations were therefore excluded, leaving 105 stations used for model validation in this study. The station locations are shown as red squares in Figure 1. All tidal datums are relative to the present National Tidal Datum Epoch (1983-2001). Table A1 in Appendix A lists the station and tidal datum information used here.

3. Tidal Datum Simulation

3.1. Hydrodynamic model

The ADvanced CIRCulation (ADCIRC) model (Luettich et al., 1992; Westerink et al., 1994) is a finite element hydrodynamic model. It was developed to simulate water level and hydrodynamic circulation along shelves, coastal ocean and within estuaries and has been applied to model tides (Westerink et al., 1993; Luettich et al., 1999; Mukai et al., 2002; Spargo et al., 2004), storm surge (Blain et al,, 1998; Westerink et al., 2008; Demirbilek et al., 2008), inundation, and other applications.

The ADCIRC model can be run in either two- or three- dimensional mode. To simulate tides for computing tidal datums, the model was run in the two-dimensional barotropic mode with wetting and drying. Tidal potential body force of eight major diurnal and semidiurnal constituents (K_1, O_1, P_1, Q_1, M_2, S_2, N_2 and K_2) was included in the model. Water elevations constructed from the same eight constituents were also applied at open ocean boundary and were extracted from a regional northeast Pacific Ocean tide model (Foreman et al., 2000). No atmospheric forcing was used. River flows were not included in the initial model setup and were imposed for Columbia River and Sacramento River later due to their significant effects on tides in the corresponding systems to improve the model results. Lateral viscosity was set as a constant, 5.0 m s^{-2}, throughout the model domain. A 1s time step was used to ensure computational stability. The model was run for 67 days with a 7-day ramping using a hyperbolic tangent function. The 6-minute water level time series were stored for the last 60 days for computing tidal datums and harmonic analysis. Sensitivity studies of some parameters and river effects will be discussed in sections 4.1 and 4.2. The final model set-up including all model input files are archived along with modeled tidal datums output, correction and quality control tests under the VDatum project archive.

3.2. Model grid

ADCIRC model runs utilize unstructured triangular grids. The unstructured mesh with variable horizontal resolution allows more accurate representation of complex shoreline and bathymetry. The model domain extends from central California to north of the Juan de Fuca Strait and adjacent coastal waters, as well as many embayments along the California, Oregon and Washington coasts (Figure 1). The SMS software (http://www.aquaveo.com/sms) was used to generate the high resolution unstructured model grid (Figure 3), which extends from the MHW shoreline to beyond the continental shelf break offshore. Due to the large coverage, the domain was divided into six smaller pieces for mesh generation and connected together afterwards. Generally speaking, the grid resolution increases from the open ocean to coasts and embayments to better represent the complexity in the shorelines and shallow water tidal dynamics. The grid sizes range from around 50 m in some riverine systems and embayments to about 32 km along the open ocean boundary. The grid resolves major islands/rocks, various rivers and small tributaries, as well as embayments and inlets along the coasts. Figures 3(b) and (c) show close-up views of the grid in Willapa Bay and lower Columbia River and San Francisco Bay, respectively.

3.3. Bathymetry on model grid

The bathymetric datasets described in Section 2.2 were used to specify the model grid bathymetry. Bathymetry at each node is specified by the arithmetic mean of data points within the node's surrounding elements. Since element size changes throughout the model domain, the searching ranges for bathymetric data points vary from node to node. As the element size is smaller in coastal waters and increases towards deep oceans, bathymetry for nodes near the coastline were from more locally distributed data points compared to those in deep waters and thus were better resolved.

The bathymetric data were all referenced to Mean Lower Low Water (MLLW) except in the Columbia River where a local datum called the Columbia River Datum (CRD) was used. Because of the interaction between tides and river flow, the tidal dynamics in a riverine system is largely influenced by the river discharge (Parker, 1991). The discharge rate of the Columbia River varies greatly seasonally and interannually. Therefore, the tidal range and tidal datum fields change accordingly. Generally speaking, CRD is derived from MLLW computed from tidal observations during low river-discharge period. Station data from CO-OPS with CRD to MLLW survey bench mark ties were used to derive a transformation relationship from CRD to MLLW in the Columbia River. The stations are marked in Figure 4. To simplify the problem, the stations were divided into two groups based on the river orientation: stations from Astoria to Longview (1 to 4) are put in a first group and stations from Longview to Vancouver (4 to 9) in a second group. For group one, a second-order polynomial regression model was built using longitude as the independent variable; while for group two, latitude was used as the independent variable. The two relationships obtained by fitting MLLW relative to CRD data to either longitude or latitude are:

$$MLLW - CRD = 0.701926 * Lon^2 + 174.123538 * Lon + 10798.4474 \quad (group\ 1)$$
$$MLLW - CRD = 0.63046 * Lat^2 - 57.368414 * Lon + 1305.57 \quad (group\ 2) \qquad (1)$$

The regression model and data are contrasted in Figure 5 for each group and all stations in the River. Equation (1) was used to convert bathymetric data in Columbia River east of Harrington Point (123.6667º W, marked in Figure 4) from CRD to MLLW.

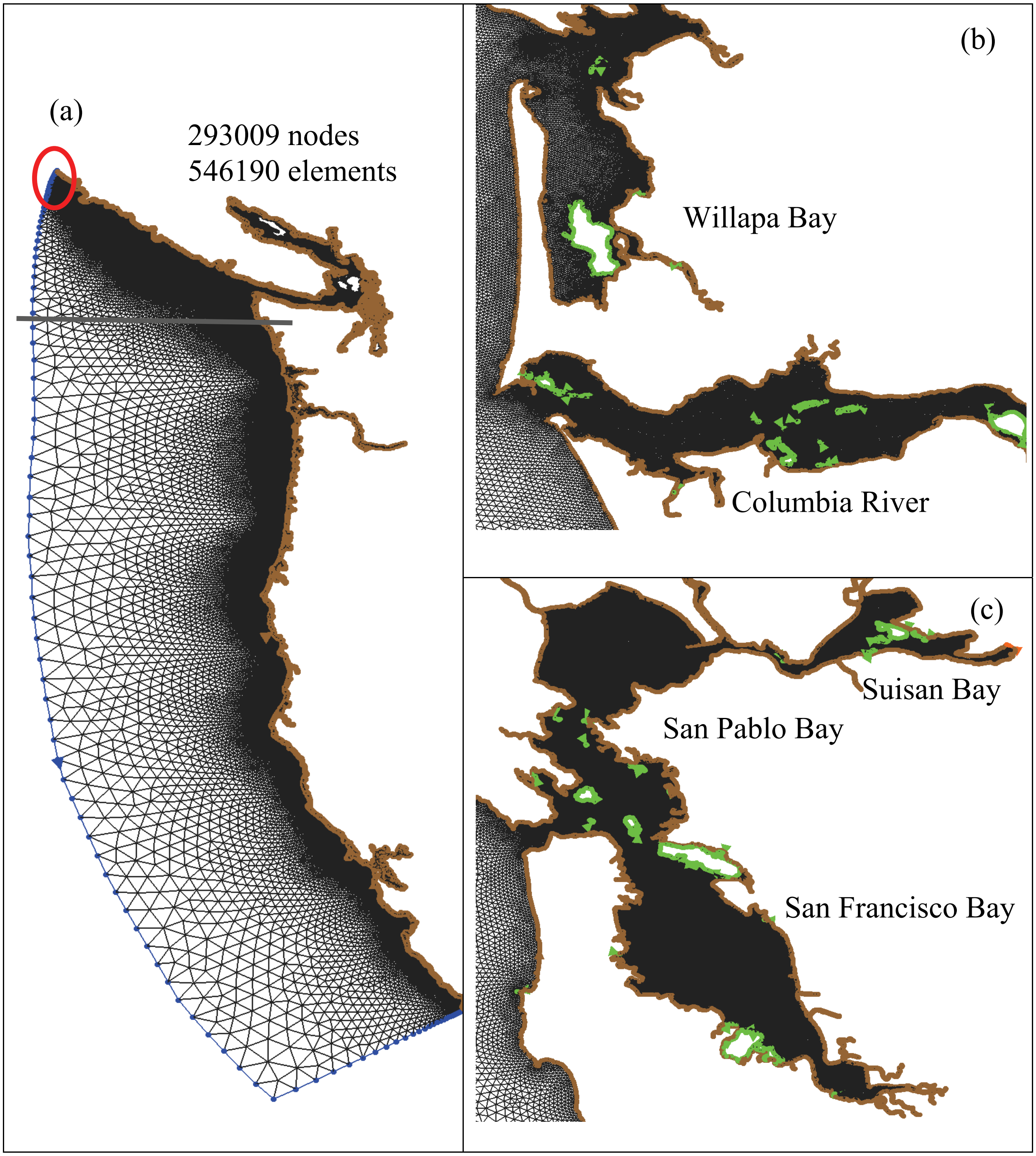

Figure 3. Unstructured grid for (a) the entire model domain and an enlargement of (b) Willapa Bay and the lower Columbia River and (c) San Francisco Bay. The blue line represents the model open ocean boundary; the green lines represent islands and the brown line is the mainland boundary.

After all bathymetric data are referred to a common vertical datum (MLLW), they were furthered transformed to the model datum – the model zero (MZ), a geopotential surface. An initial guess of 1m difference between MZ and MLLW was made based on the average MSL relative to MLLW at stations within the model domain. After a stable model run was achieved, the model bathymetry was furthered adjusted based on the modeled tidal datum fields. This process was repeated iteratively until the tidal datums converged. The final model bathymetry is shown in Figure 6. Please note that the contour intervals are not of equal values so that the shallow regions along the coast and the continental shelf break can be better resolved.

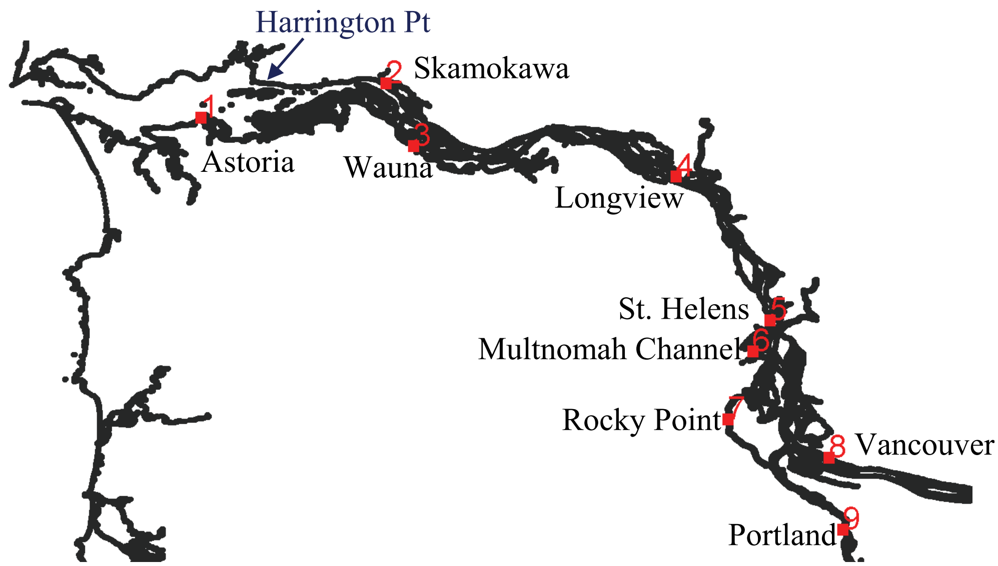

Figure 4. The location of stations in Columbia River with CRD to MLLW data from CO-OPS.

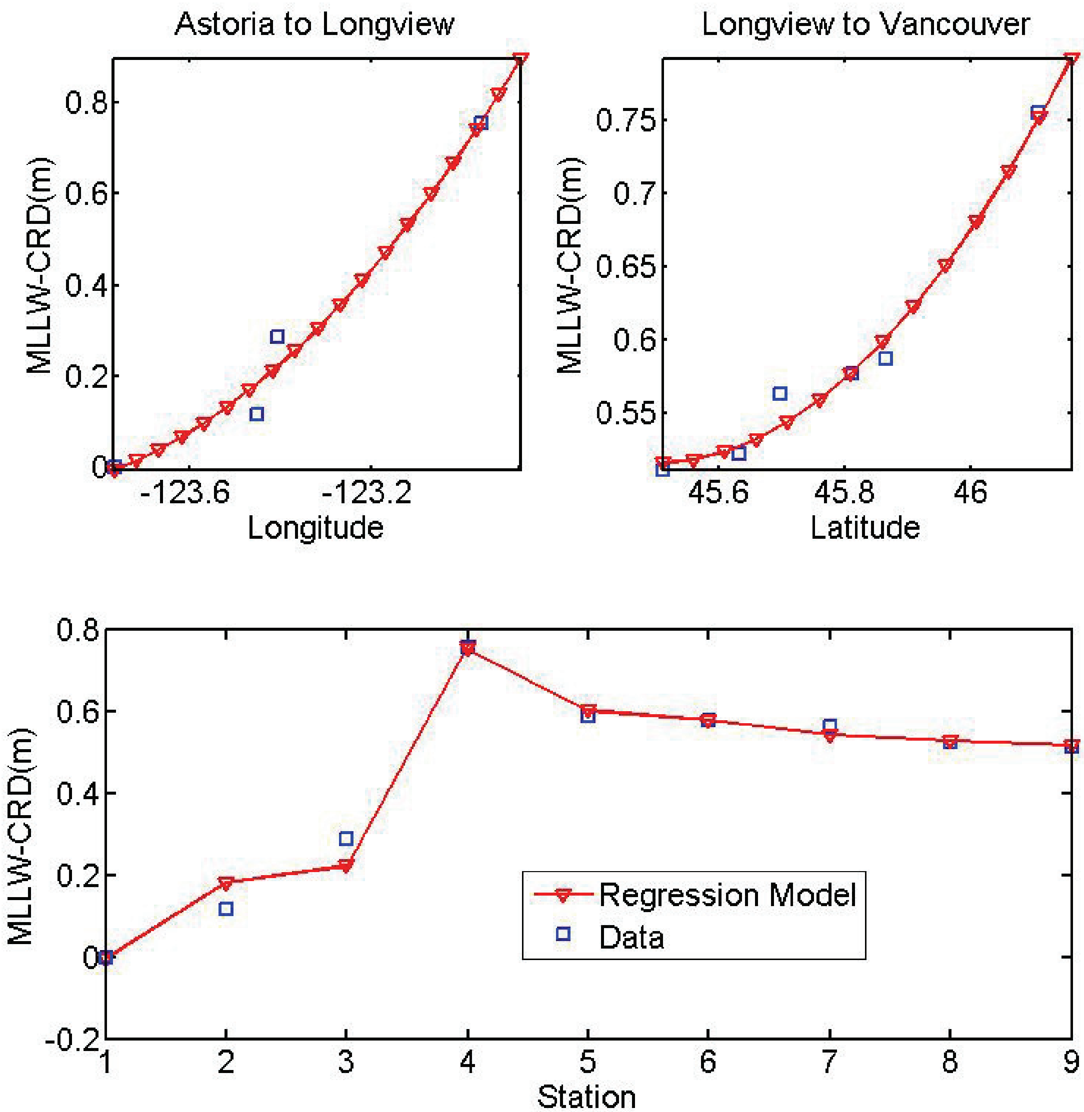

Figure 5. The regression model of CRD to MLLW in Columbia River (a) from Astoria to Longview, (b) from Longview to Vancouver and (c) for the whole river as a combination of (a) and (b).

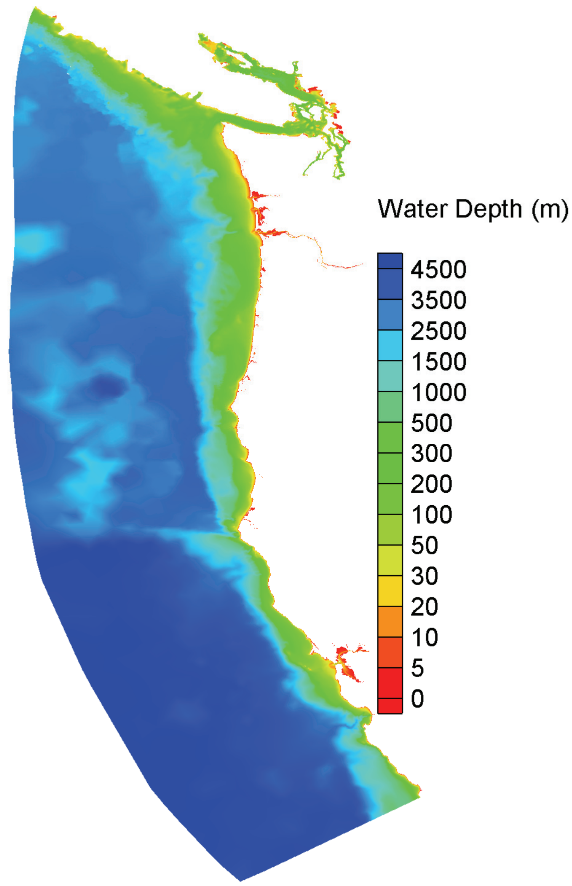

Figure 6. Final model bathymetry relative to Model Zero (MZ).

4. Model Results Analysis and Sensitivity Tests

To verify the model results, the simulated water level time series at each grid node and CO-OPS water level station were recorded at 6-minute intervals to compute tidal datum fields for MSL, MHHW, MHW, MLW, MLLW, Mean Tidal Level (MTL) and Diurnal Tidal Level (DTL). MHHW, MHW, MLW and MLLW are then adjusted to be relative to the MSL field. The four tidal datum fields are compared against those from the 105 NOAA tide stations. Because MTL and DTL were defined as the algebraic averages of MHW/MLW, and MHHW/MLLW, respectively, these two fields are only computed using the corrected datum fields (Section 4.4).

4.1 Sensitivity study

The initial model setup resulted in consistent instabilities along the Northern boundary (shown as a thick grey line in Figure 3). To resolve the problem, uniformly increased horizontal diffusion was tested and spatially varying numerical horizontal diffusion was implemented in the model. However, the model only ran slightly longer before it blew up. We extended the model domain northward to its current coverage shown in Figure 3 in an effort to avoid the problem. However the region of the instability now moved to the northeast corner of the open boundary marked by the red circle in Figure 3. Runs with significantly increased horizontal diffusivity, increased grid resolution in that area, as well as radiation boundary conditions for that portion of the open boundary all failed to stabilize the model simulations. Bottom friction coefficients in that area were increased to 0.1 so that it acted as a sponge layer to achieve a stable model run. This implementation appeared to work well and did not significantly change the interior model results of the region of interest.

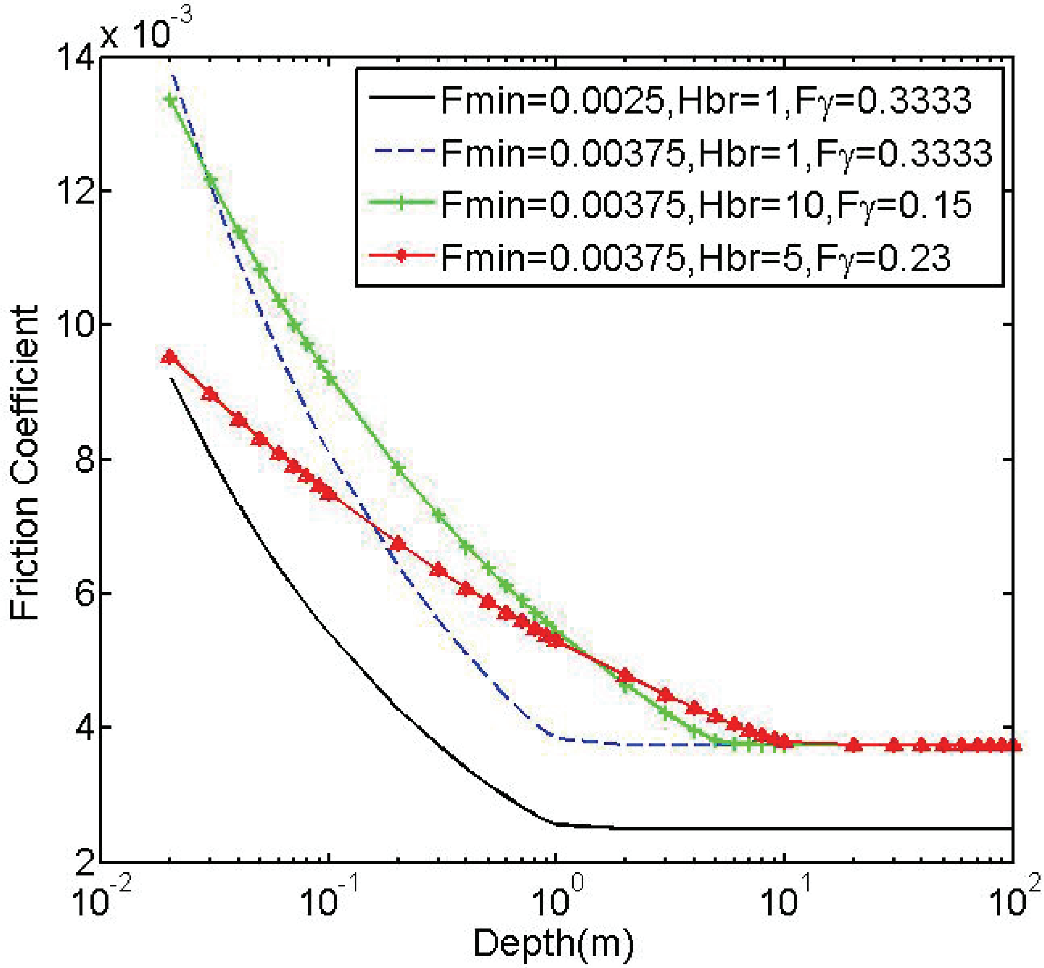

Figure 7. The bottom friction coefficient calculated by different values for the parameters in Equation (2).

Further tests were carried out using different bottom friction coefficients. Hybrid nonlinear bottom friction was used in the model so that in deep water, the friction coefficient is constant and in shallow water the friction coefficient increases as the depths decreases. The friction coefficients are calculated by the following formula:

$$\text{FFACTOR} = \text{FFACTORMIN} * (1 + (\text{HBREAK}/\text{H})^{\text{FTHETA}})^{(\text{FGAMMA}/\text{FTHETA})} \qquad (2)$$

Where FFACTORMIN is the minimum friction coefficient which is equivalent to the coefficient in deep water (when H>HBREAK), HBREAK is the break depth separating the bottom friction schemes, and FGAMMA and FTHETA are two parameters to determine how fast the friction coefficient increases in shallow waters. Because the formulation is not very sensitive to the choices of FTHETA, it was set to be the recommended value of 10. Figure 7 shows an example of the effect of different choices of FFACTORMIN (F_{min}), HBREAK (H_{br}) and FGAMMA ($F\gamma$) on the bottom friction coefficient where the black line represent the base line by setting all values as recommended in ADCIRC user's manual. The effect of FFACTORMIN on model results is quite straightforward with higher values giving rise to overall higher bottom friction, which tends to damp tidal amplitudes and slow water currents. However, the effects of different values of other parameters are more complicated and often lead to compromising model results in different regions. Based on the model-data comparison, the parameters represented by the blue dashed line in Figure 7 were used in the final model setup.

4.2 Effect of river flow

The initial model setup with no river flows showed sizeable errors in the modeled tidal datums for the Columbia River and northeastern San Francisco Bay (i.e. Suisan Bay, see Figure 3c) when compared with values from the CO-OPS' tidal datum database.

River flows interact with tides both linearly and nonlinearly. As a result, tides in the river with considerable discharge are often damped and distorted. To examine the river effect on simulated tidal datum fields we conducted three experiments: one with high flow discharge from Columbia River, one with low river discharge and one with extremely low river discharge. Firstly, we observed that the water level time series have a mean elevation that is much higher with high flow than with low flow (Figures 8a and 8b). The initial model run with no river flow failed to simulate the natural setup of the mean water surface going up the river. With high flow, the water surface in the upper reach of the river is further raised up. Figure 8a illustrates modeled water level time series at Vancouver, Washington (marked in Figure 4) while Figure 8b shows the observed water level during two eight-day periods with contrasting flow conditions: one with high flow and one with low flow. Secondly, the tidal ranges in the upper reaches of river are heavily damped (Figures 8c and d) due to more energy loss by friction during ebb tides. Thirdly, the derived tidal datum fields vary considerably depending on flow condition. As shown in Figure 8e, the MLLW difference (green line) from the two low river flow runs differ by up to 70cm at the stations in the upper reaches of the river and will be even larger closer to the Bonneville Dam. Also shown in the plot is the MLLW relative to CRD at those stations from the CO-OPS' database. As mentioned, CRD is a representation of MLLW under low river discharge.

A similar problem exists in Suisan Bay, California. However, including river flow from the Sacramento River alone did not improve the simulated tidal datums significantly. As contrasted to the Columbia River where tidal propagation is restricted by the Dam, the tides are still strong in Suisan Bay and progress in and out of the delta region beyond the tide model domain. Therefore, a radiation boundary condition along with river flow had to be imposed for better results.

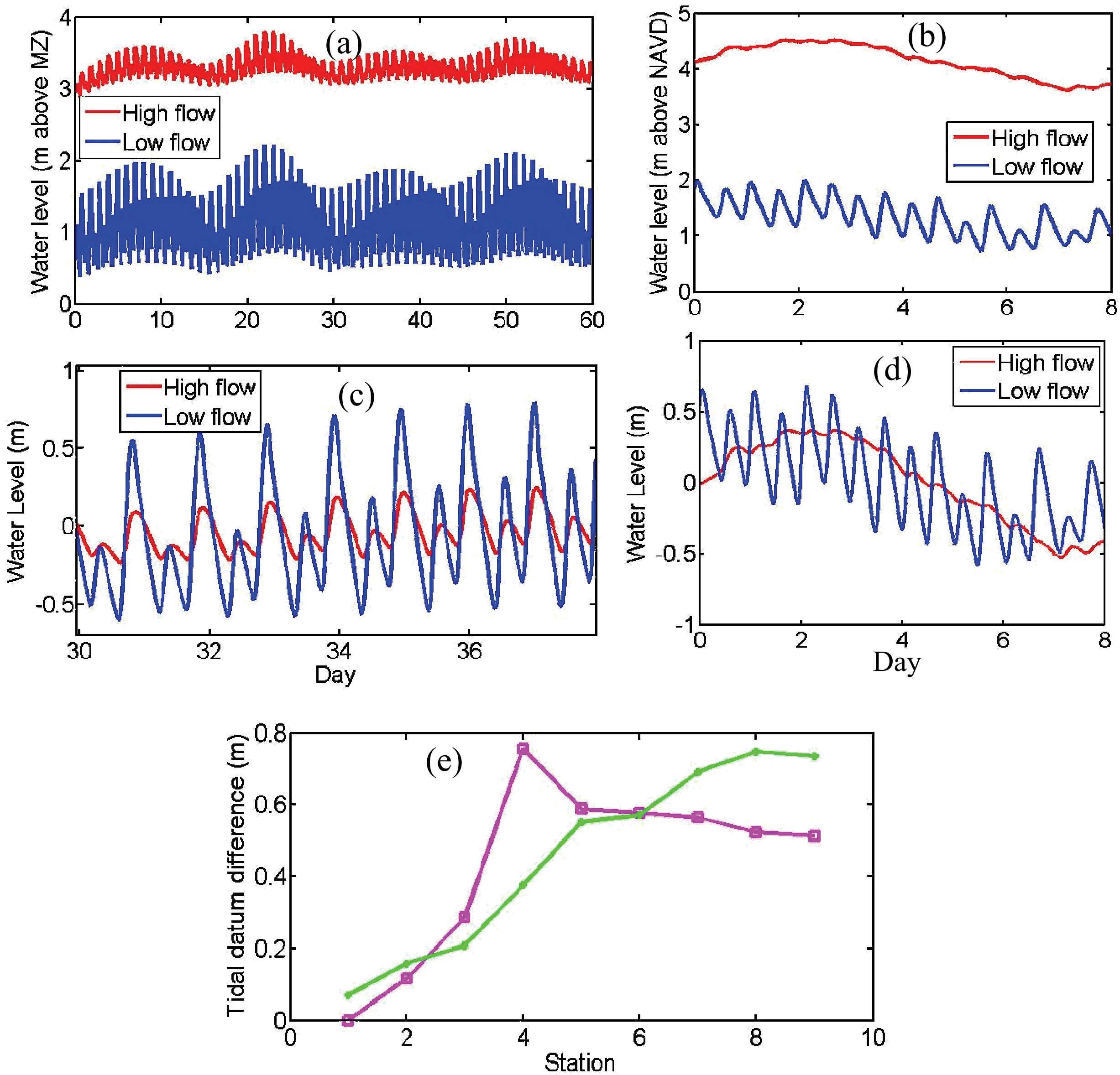

Figure 8. Modeled water levels at Vancouver, WA during high- and low- flow (a) relative to Model Zero (MZ) (c) relative to mean water level. Observed water levels during high- (May, 2008) and low- (Feb., 2008) flows (b) relative to NAVD88 and (d) relative to mean water level. (e) MLLW differences between simulations of a relatively low river flow and a very low river flow in Columbia River (in green) and MLLW relative to Columbia River Datum (in magenta) from the CO-OPS.

4.3. Verification of modeled tidal datums

Figures 9a-d display the model derived tidal datum fields for MHHW, MHW, MLW, and MLLW, respectively. The four fields exhibit a similar spatial pattern. In the open ocean and coastal region, tides are amplified approaching the shallow water from the open ocean and from south to north, which is manifested by the increased magnitudes of tidal datums close to the shorelines and towards the north. The tidal ranges (defined as MHW – MLW) increase from less than 1 m in the south to over 2m in the north. Tides in the riverine and estuarine systems along the shore become more complicated due to the interaction with shoreline, bathymetry and river flow. Therefore, no uniform trend can be derived and each system needs to be examined individually. For example, in Willapa Bay, tides generally get stronger propagating inwards and southwards. The MHW increases from about 1m at the entrance to over 1.3m at the south end of the Bay (Figure 10a). In San Francisco Bay, tides are amplified traveling south. In the north of San Francisco Bay, tides are amplified in San Pablo Bay but are damped in Suisan Bay (Figure 10b).

Figure 11 illustrates model-data comparisons for MHHW, MHW, MLW, and MLLW relative to MSL. The black line shows the one-to-one correlation. In general, the comparisons exhibit good model-data agreement. Over the 105 stations, magnitudes of the absolute model-data differences on average are 7.3 cm, 4.5 cm, 6.1 cm, and 8.1 cm for MHHW, MHW, MLW, and MLLW, respectively. The root mean squared error for all four tidal datums is 6.8 cm. The 95 percentile of errors in the tidal datums is 15.7 cm in absolute error or 16.5% in relative error. Of the four tidal datums, the largest discrepancy shows up in MLLW, which probably is related to the difficulty in calculating low waters when ponding and drying happen over very shallow waters. The model-data differences of each tidal datum at individual stations are listed for all stations in Table B1 Appendix B.

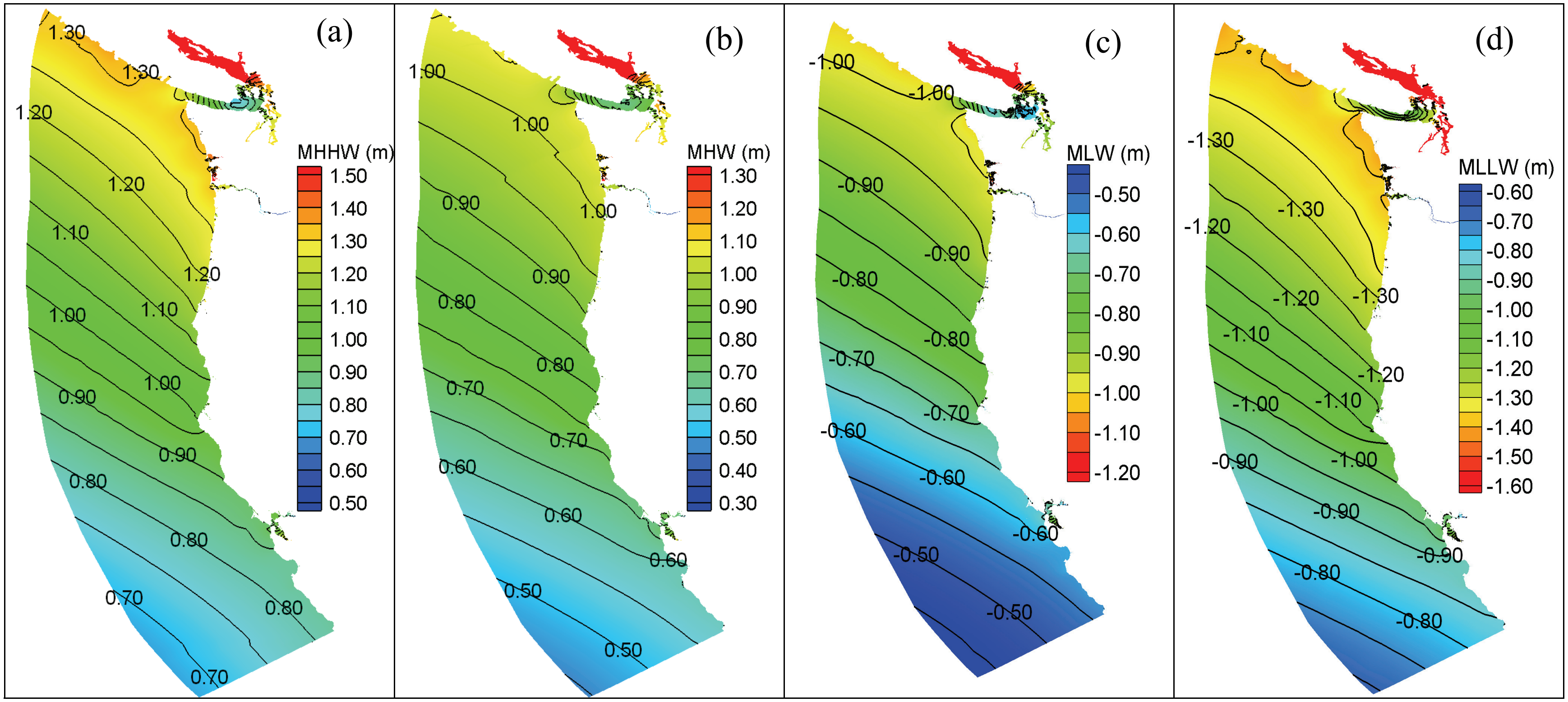

Figure 9: Model derived tidal datums relative to MSL: (a) MHHW, (b) MHW, (c) MLW and (d) MLLW.

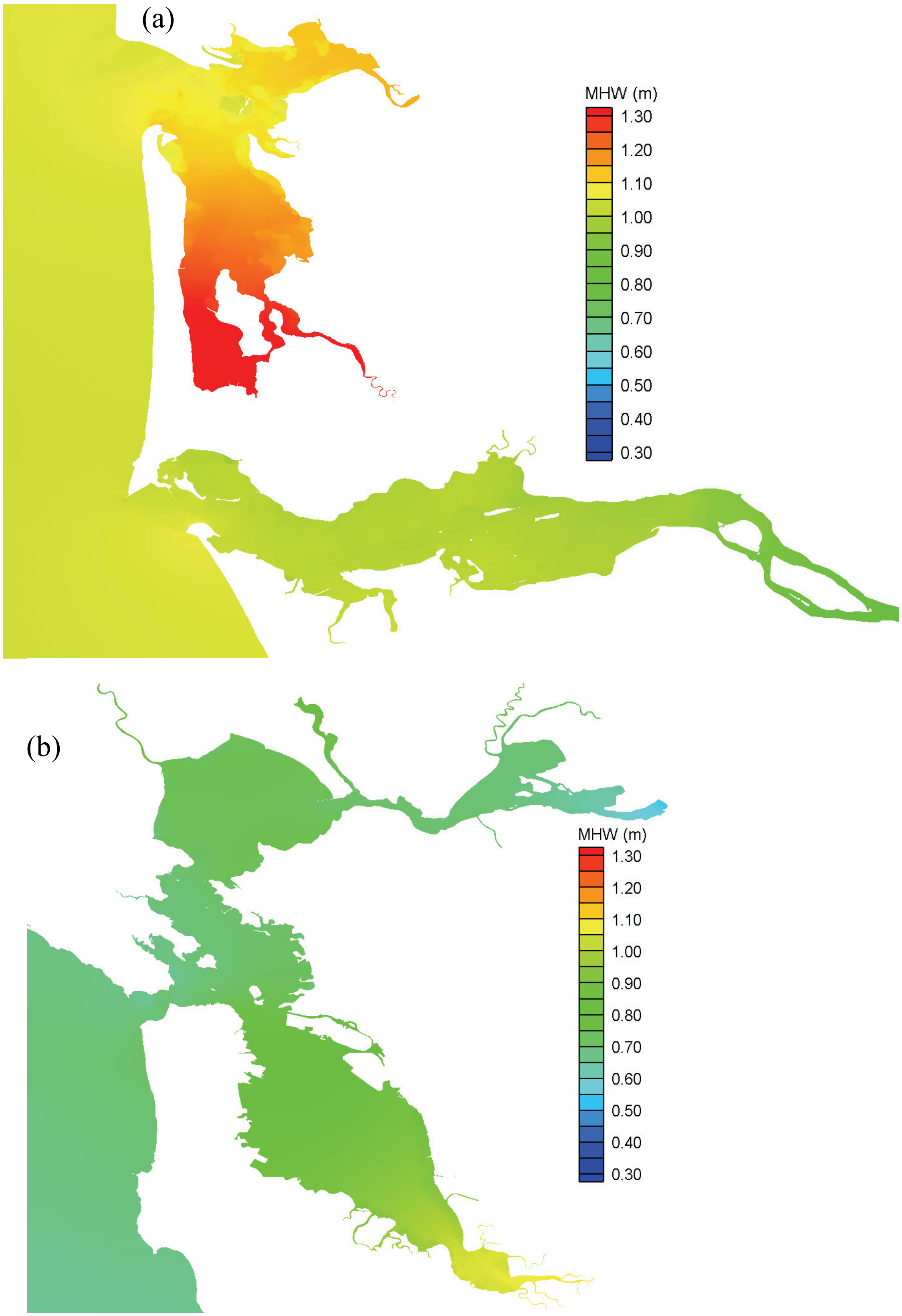

Figure 10. A close-up view of modeled MHW relative to MSL in (a) Willapa Bay and lower Columbia River and (b) San Francisco Bay.

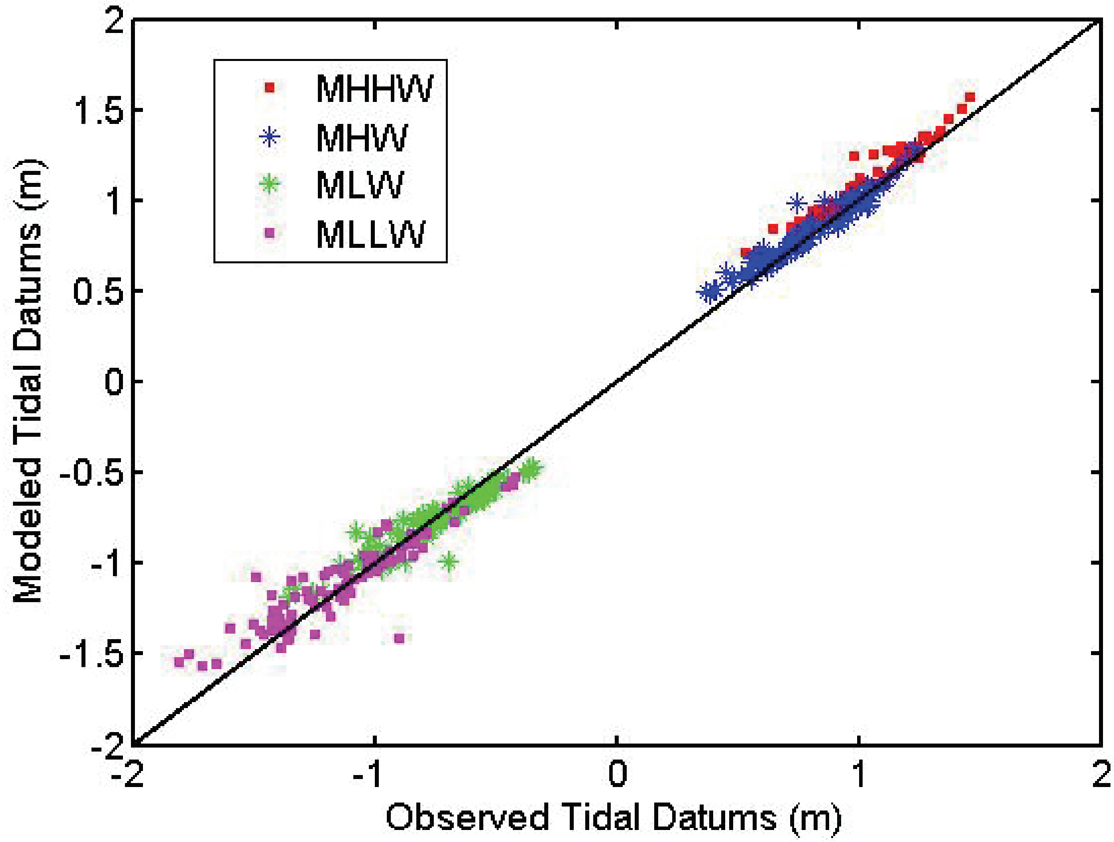

Figure 11. Modeled versus observed MHHW (red squares), MHW (blue stars), MLW (green stars), and MLLW (magenta squares) (all relative to MSL).

4.4. Corrections of modeled tidal datum errors

The tidal datum results from the model generally agree well with the CO-OPS water level station data at most locations. However, they are not expected to match exactly, and at certain stations the discrepancy is fairly large. The results presented above are accepted with the understanding that i) the model simulates the astronomical tides only, while the station data includes non-tidal river flow, ocean circulation and meteorological effects, ii) the bathymetric data coverage around some stations are sparse (if any) and/or outdated, and iii) the grid resolution may not be enough in some small rivers/embayments.

To eliminate the model-data difference at the stations and to match existing VDatum project across the project boundary, the TCARI program (Hess et al., 1999; Hess, 2002; Hess, 2003) was applied to spatially interpolate the error fields. TCARI may be run using either structured or unstructured grids. A version of TCARI written in the Python computer language and based on use of an unstructured grid (Barry Gallagher, personal comm.) was used in this application.

To run TCARI, both the observational stations and locations along the domain boundary (see section below) are treated equally as control stations. For each tidal datum, both model-data differences at the tidal stations and across-boundary discrepancies between current model results and existing VDatum results (Southern California VDatum at the south and the Juan de Fuca Strait VDatum at the north) were computed and input to TCARI. Artificial stations were added along the offshore open ocean boundary with zero model-data difference so that the interpolated error fields would taper down towards zero when approaching the open boundaries offshore instead of some averaged error value by default. This is more appropriate in this application because the model results were validated in the open ocean against some National Data Buoy Center bottom pressure DART buoy data (not shown). Figure 12 shows the interpolated error field for MHW over the whole domain with default boundary conditions and added control stations along the open-ocean boundary. The two fields agree with each other along the shoreline where tide station data are available but differ in the open ocean. A choice of different open-ocean boundary conditions in the TCARI program may be implemented later for similar occasions in future applications.

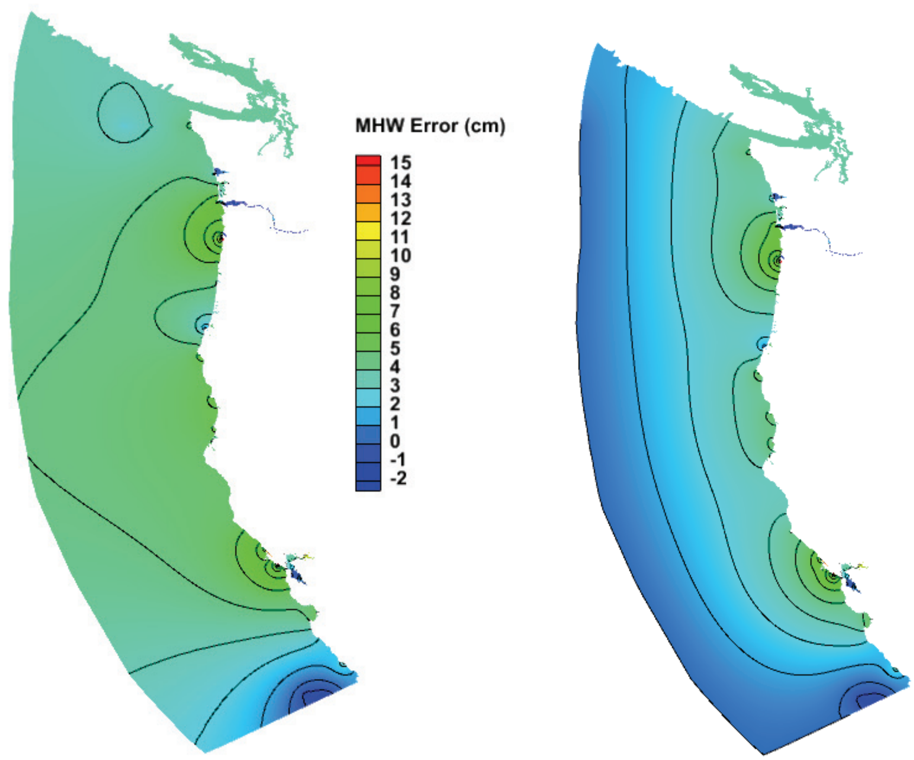

Figure 12. TCARI interpolated model MHW error with (a) default boundary conditions and (b) added control stations along the outer boundary so that the errors approach zero at the outer boundary.

The error fields for MHHW, MHW, MLW, and MLLW derived from TCARI were then added to the model results to get the final tidal datum elevations for VDatum. These TCARI-corrected results match the tide station data at the included stations and seamlessly connect to existing adjacent VDatum regions.

Note that the other two tidal datum fields, the MTL and DTL, were produced in a different way. They were derived from the four corrected datums by taking the averages between MHW and

MLW and between MHHW and MLLW, respectively. This is the accepted procedure for determining these datum elevations (Gill and Schultz, 2001).

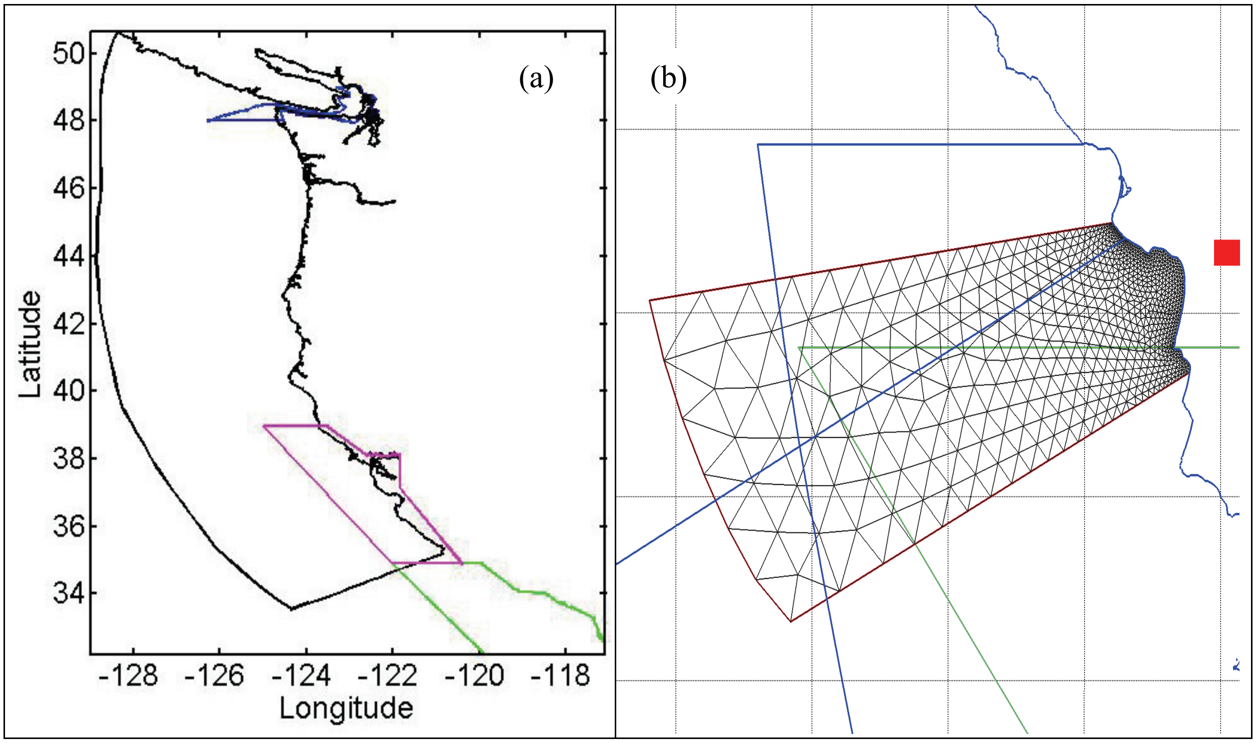

Figure 13. (a) Map of Pacific Northwest model domain (black line) and bounding polygons of the Juan de Fuca Strait (blue line), Central California (magenta line) and Southern California (green line) VDatum areas. (b) A close-up view of the overlapping area between PNW and SCA and the construction of triangular grid for transitional area. Model domain outlined in blue. Bounding polygon for SCA is in green.

4.5. Connecting with adjacent VDatum areas

The present Pacific Northwest (PNW) model domain overlaps with the previously developed central California (CCA) (Myers and Hess, 2006), southern California (SCA) (Yang et al., 2009) and Juan de Fuca Strait (JFS) VDatum areas (Spargo et al., 2006). Figure 13(a) illustrates the coverage of the current model domain with respect to existing VDatum areas. In terms of coverage, there is no problem for the current model to connect with JFS in the north. However, there is a small triangular area to be filled out in order for the current project to replace the existing CCA VDatum and connect directly with SCA Vdatum area. Figure 13(b) shows a close-up view of the problem. Even though the current model domain overlaps with SCA model domain, its south boundary is not fully connected with the northern boundary of the bounding polygon for SCA. Therefore, a small triangular grid was constructed for the transitional area to avoid rebuilding the marine grid for SCA or to extend the current model domain further south. The tidal datum fields on this extension grid were populated using TCARI. In the input file for TCARI, tidal datums at/close to the northern boundary taken from the PNW model and the southern part which falls in the SCA bounding polygon taken from SCA model, as well as the values from a water level station (marked by red square in Figure 13b) were used.

In reality, tidal datums fields should be matched seamlessly across the boundaries. However, this is not necessarily engendered when the three tidal datum products were developed separately through different model approaches. Therefore, discrepancies across the boundaries were examined and existing VDatum values at the boundaries were treated the same way as observations at tidal stations in the TCARI input files (See section 4.4) to have continuous tidal datum fields which match exactly at the overlapping boundaries.

5. Creation and Population of the Marine Grid

5.1. Creation of VDatum marine grid

Tidal datums in the VDatum software are defined on regularly structured grid called the VDatum marine grid. Each node in the marine grid is designated as either a water node or a land node based on the high resolution coastline and the bounding polygon. The water nodes are populated with valid tidal datum values and the land nodes are assigned null values. The bounding polygon helps to constrain model extrapolation within a certain distance to the modeled domain without going to rivers/embayment completely outside of the model domain.

The FORTRAN programs vgrid.f and vpop.f were used to generate and populate the marine grid, respectively. Due to the large size of the domain, a set of five similarly sized marine grids were generated to cover the whole region (Figure 14). Cautions were taken in making the division so that no rivers or embayments were divided into two regions.

Marine grid points are equally spaced within each region. The resolution of each marine grid is set to be 0.001 degree in both zonal and meridional directions, which is the same resolution as the Southern California VDatum marine grid. Details of each marine grid boundary limits and grid size information are listed in Table 1.

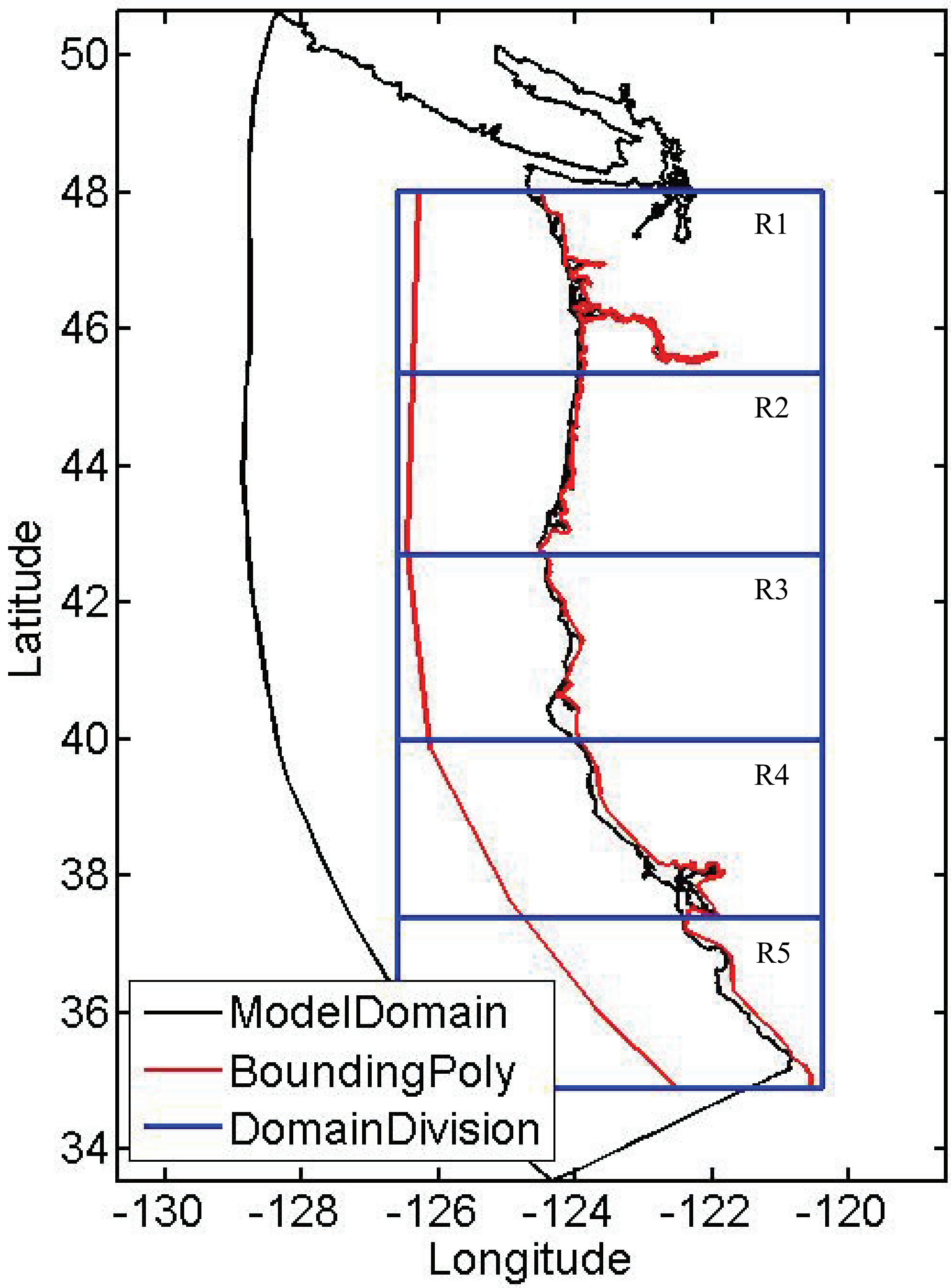

Figure 14. An illustration of the domain division.

Table 1. VDatum marine grid information for the five regions.

VDatum Region	*Lat. Lon. Window*	*Horiz. Spacing (deg)*	*Vertical Spacing (deg)*	*No. of Horiz. Nodes*	*No. of Vertical Nodes*
R1	[-126.40 -121.94 45.35 48.02]	0.001	0.001	4461	2671
R2	[-126.47 -123.88 42.69 45.37]	0.001	0.001	2591	2681
R3	[-126.47 -123.88 39.99 42.71]	0.001	0.001	2591	2721
R4	[-126.20 -121.82 37.39 40.01]	0.001	0.001	4381	2621
R5	[-124.81 -120.565 34.89 37.41]	0.001	0.001	4246	2521

5.2. Population of VDatum grid with tidal datums

Tidal datums on the VDatum marine grid were populated by interpolating TCARI-corrected tidal datums (Section 4.4) according to the algorithm of Hess and White (2004). Datums at each VDatum marine grid point were computed by averaging or linearly interpolating those values within a user-specified searching radius or the closest user-specified number of points. In the present case, the interpolation was accomplished using the FORTRAN program vpop12.f. It populates marine points differently depending on whether the point is inside/outside of the ADCIRC model grid elements. If the point was inside an element, datums were calculated using an interpolation of the three nodes of the element; if the point was outside any elements, datums were computed using the inverse distance weighting of the closest two node values. For region R5, modifications in the code were made to take results from both the PNW grid and the small grid for the transitional area.

Two types of verifications were conducted for the tidal datums populated on the marine grids: comparing with observations from the CO-OPS tidal stations and examining the match across its boundaries with the existing JFS and SCA VDatum regimes. For each of the four datums (MHHW, MHW, MLW, and MLLW), the model-data error is less than 0.1 cm and the differences between current and previous VDatum projects are less than 0.5 cm for both boundaries.

The consistency between datum fields across the boundaries of different regions of this VDatum project was also evaluated. Because the datum fields on these regions were extracted and interpolated from the same model results, they were practically identical across all boundaries. For each of MHHW, MHW, MLW, and MLLW, maximum differences are less than 0.01 cm. The final tidal datums fields on the marine grids (Figure B1) are shown in Appendix B.

6. Topography of the Sea Surface

The Topography of the Sea Surface (TSS) is defined as the elevation of the North American Vertical Datum of 1988 (NAVD88) relative to local mean sea level (LMSL). Two methodologies were utilized for computing NAVD88-to-LMSL values, and the results were coupled for creation of the final TSS grid. This grid represents the local variations between a LMSL surface and the NAVD88 geopotential surface over the Pacific Northwest VDatum region. A positive value specifies that the NAVD88 reference value is further from the center of the Earth than the local mean sea level surface. All data are based on the most recent National Tidal Datum Epoch (1983-2001). The location of NOAA tide stations and tidal bench marks used are illustrated in Figure 155.

The two methodologies used for creating the NAVD88-to-MSL values are called the indirect method and the direct method. The indirect method consists of deriving a value calibrated by fitting tide model results to tidal benchmarks leveled in NAVD88. This process used the four tidal datum (MHHW, MHW, MLW, and MLLW) values on the marine grids. At each NGS benchmark location, we have TBMnavd88, that is the NAVD88 elevation of the tidal benchmark relative to MLLW, and a set of TBMdatum values, which is the tidal datum elevation relative to MLLW (i.e., Datum – MLLW) at the tidal benchmark. Also, from the four tidal datum grids, we have a set of VDdatum values, which is the difference between the tidal datum and MSL (i.e., Datum – MSL).

For the first step, we compute four residuals. The residual, R, for each datum is defined as:

Rdatum = TBMnavd88 – TBMdatum + VDdatum

Note that the VD values are interpolated to the location of the benchmark. The four residuals at the benchmark are averaged to produce the mean. Note that this mean is an estimate of the quantity NAVD88 – MSL. These NAVD88 – MSL derived estimates for the West Coast of the Continental United States region can be found in Table C1 in Appendix C.

The direct method of obtaining NAVD 88-to-LMSL values includes calculating orthometric-to-tidal datum relationships at NOAA tide stations where elevation information has been compiled as part of the CO-OPS procedures for computing accepted tidal datums and orthometric datum relationships at tide stations. This process averages elevation relationships of two or more bench marks at each station that have published NAVD88 heights. The tide stations and associated elevation information used in the computation of the TSS are presented in Table C2. Data for the direct method were supplied by CO-OPS and NGS.

Next, a continuous surface for the West Coast of the Continental United States was generated representing inverse sea-surface topography (Figure 16). The mean residuals at all benchmarks are merged with values of the quantity NAVD88 – MSL at NOAA tide stations to produce input data for gridding. A mesh covering the entire area of benchmarks and water level stations with a spatial resolution similar to that of the tidal marine grids is created. Breaklines are inserted to represent the influence of land. A sea surface topography field is generated using the Surfer© software's minimum curvature algorithm to create a surface that honors the data as closely as possible. The maximum allowed departure value used was 0.001 meters. To control the amount of bowing on the interior and at the edges of the grid, an internal tension of 0.3 and boundary tension of 0.5 was utilized. Once the gridded topography field has been generated, null values are obtained from the marine tidal grids and are inserted to denote the presence of land.

Quality control was facilitated through several different pathways. After the initial TSS was created through interpolation of data compiled through both methodologies, a set of 'Delta' values are computed. Delta represents the difference between the observed tidal datum and the datum as computed by the gridded fields. If S represents the value of the quantity NAVD88 – MSL obtained from the sea surface topography grid, Delta (D) for each tidal datum is computed as:

$$D_{datum} = TBM_{navd88} - TBM_{datum} - VD_{datum} - S$$

The averaged Deltas tabulated for the West Coast of the Continental United States TSS's are consistent and small. This provides confidence that grids are in agreement. If they are not, the input data and grids are examined, appropriate changes are made, and a new TSS grid is computed from the first step. In response to the limited amount of data available, the data used to compile the TSS grids for both the direct and indirect methods were utilized in comparing against the TSS grid to generalize internal consistency. The mean delta between NAVD88 (realized through GEOID03) to MSL relationships for the West Coast of the Continental United States region was 0.000009 meters with a standard deviation of 0.001882 meters.

Data derived from both the indirect and direct methodology are initially relative to NAVD88 realized through GEIOD03. This data derived from both methods is transformed back through GEIOD03 to an ellipsoidal reference and then transformed back utilizing GEIOD99 (Figure 17). The mean delta between NAVD88 (realized through GEOID99) to MSL relationships for this region was -0.000059 meters with a standard deviation of 0.00188 meters.

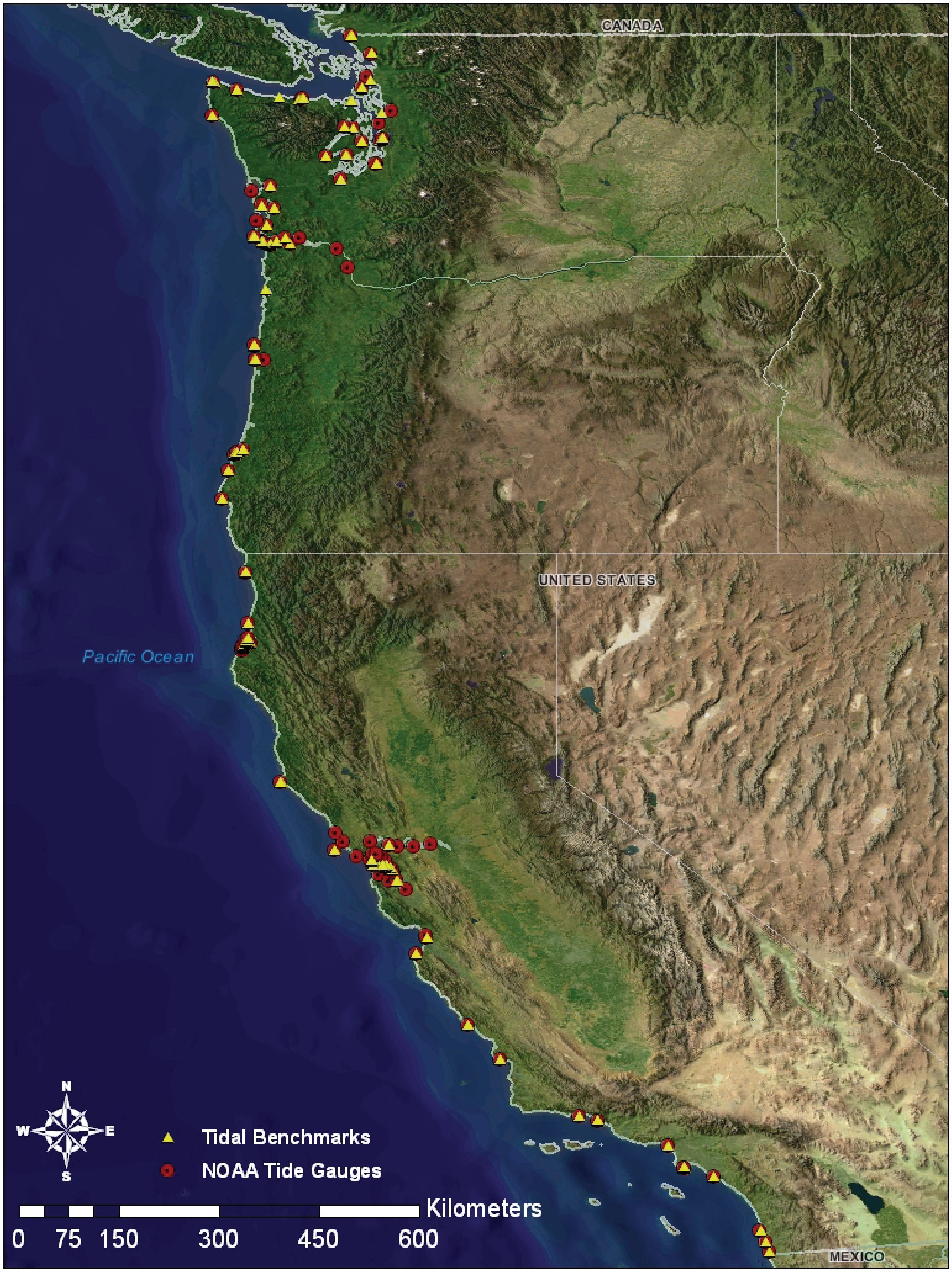

Figure 15. Location of tidal benchmarks and tide stations used to compute the West Coast of the Continental United States VDatum TSS grids.

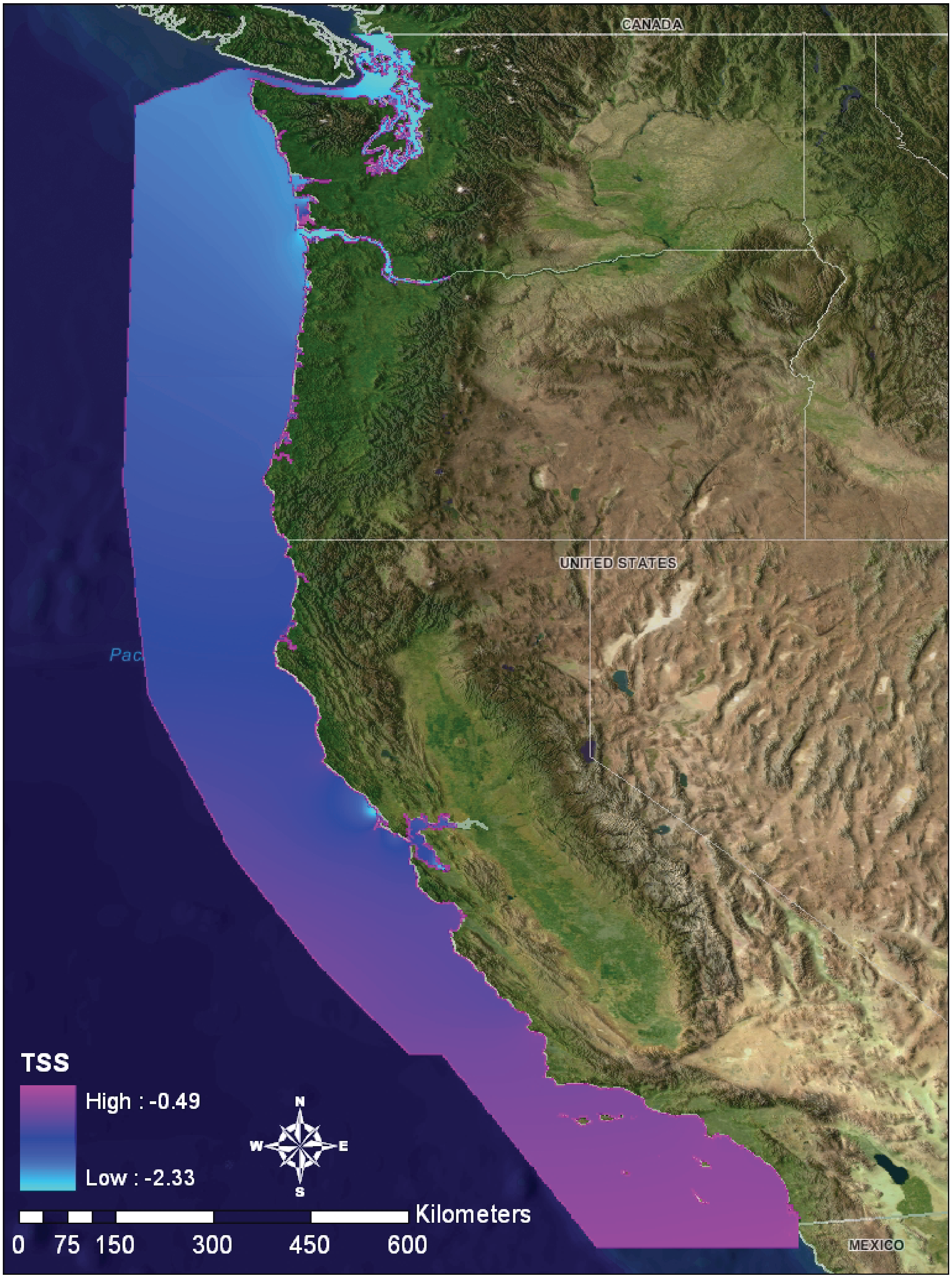

Figure 16. The West Coast of the Continental United States TSS Grid (NAVD88 realized through GEOID03).

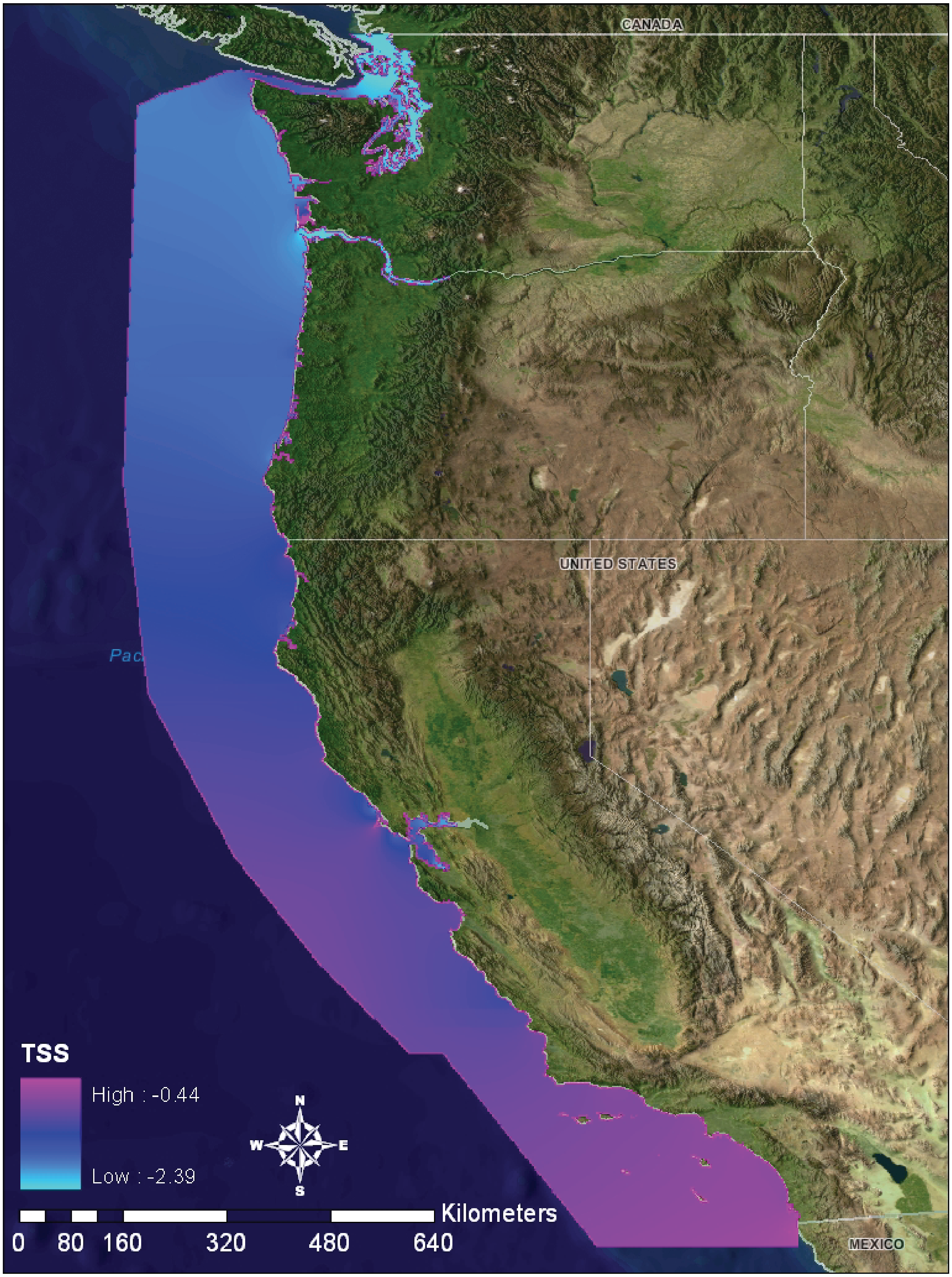

Figure 17. The West Coast of the Continental United States TSS Grid (NAVD88 realized through GEOID99).

7. Columbia River Datum Ties to the Ellipsoid

In the Columbia River that is upstream of the entrance estuary, a fixed low water datum called the Columbia River Datum was established by the USACE in 1911. Because of the interaction between river discharge and tides and the great seasonal and interannual variation in the discharge rate, the low water elevation in the Columbia River can change considerably. Therefore, the river datum zero was set at a point below the average low water, but not as low as the lowest record for a long period which resulted from a combination of circumstances that seldom occur. The relationships between tidal datums are derived from the tide model. This section focuses on establishing the spatial relationship between CRD and NAVD88.

The CRD relative to NAVD88 data are available from the USACE and are referenced to river miles along the river channel and in state plane coordinates (Table D1 in Appendix D). We first converted the state plane coordinates to NAD83 to be consistent with the horizontal datum frame used throughout this study. Figure 18(a) shows the data coverage in longitude/ latitude, and Figures 18(b) and 18(c) illustrate the relationship between CRD and NAVD88 along the river channel in the Columbia River and Willamette River, respectively.

To build the spatial coverage of this relationship, we first extended the data at the centerline of the channel along transects perpendicular to the channel (Figure 19). The relationship is assumed to remain the same along the transect within the channel but unknown outside. Therefore, the transects are not extended all the way to intersect with the shoreline. Instead, the transect only extends 0.002 degree (about 150m at this latitude) away from the center line on each side and is further sampled at equal spacing of about 30m, which resulted in 5 points on each side. This also eliminates the problem of intersecting transects at the river bends which would result in multiple values at the same location. The TCARI program was used to interpolate and extrapolate the data shown in Figure 19 to the Columbia River portion of the tidal model grid (Figure 20). The points along the transects that lie outside the coastline or on an island were not used in the TCARI program. As shown in Figures 18 (b) and (c), the CRD to NAVD88 difference increase towards the upper reaches of the river. However, the relationship is not a linear one even along the river channel, as indicated by the density of the contours (Figure 20).

USACE contracted a private company, David Evans and Associates, Inc., to work on a model for the relationship between CRD and the GRS80 ellipsoid over the survey area. Comparison of the results from both approaches will be conducted. The final results and the integration within the VDatum transformation tool are subject to further consultation with USACE.

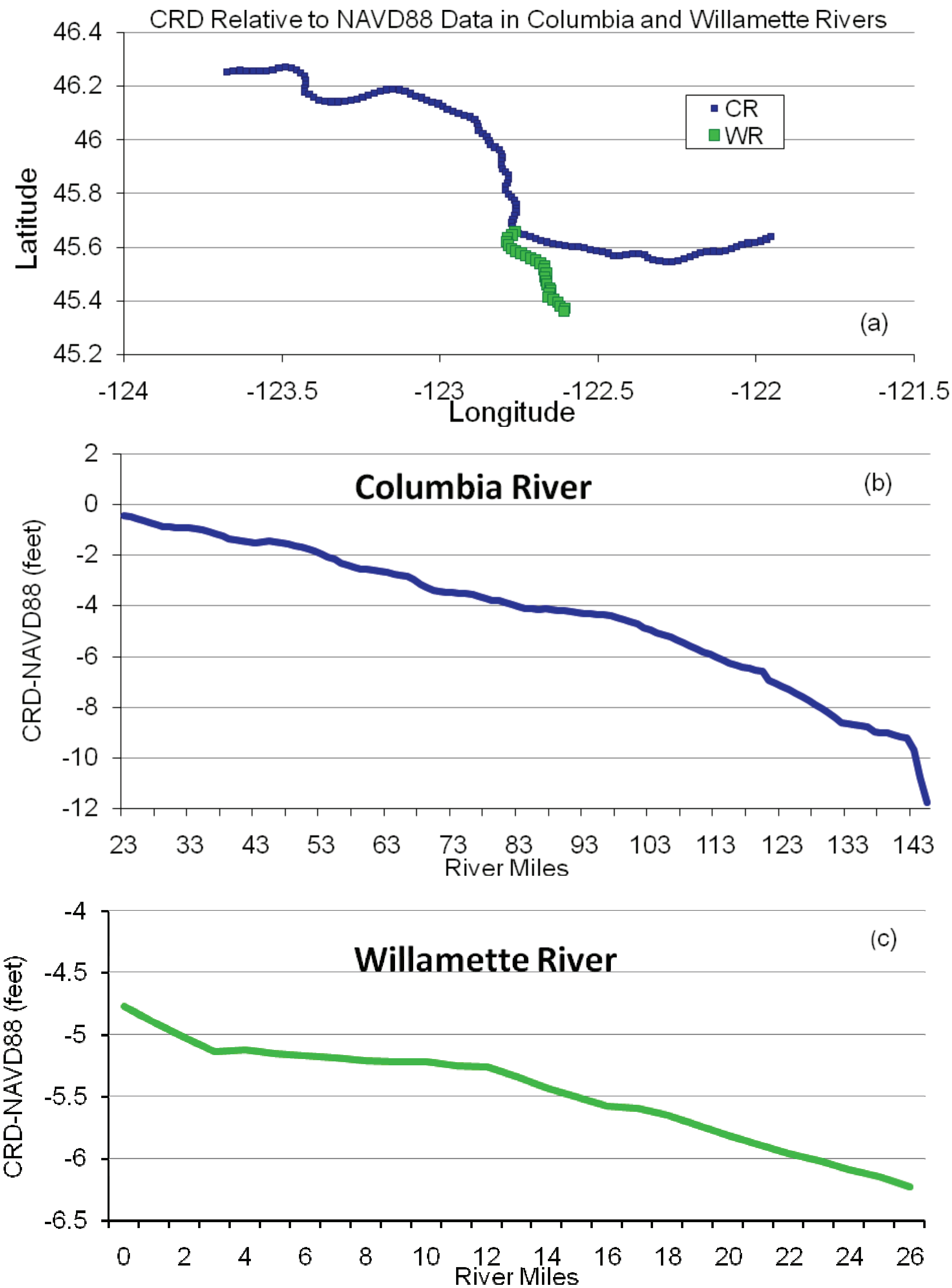

Figure 18. (a) Data availability along the river channel and CRD relative to NAVD88 in (b) Columbia River and (c) Willamette River.

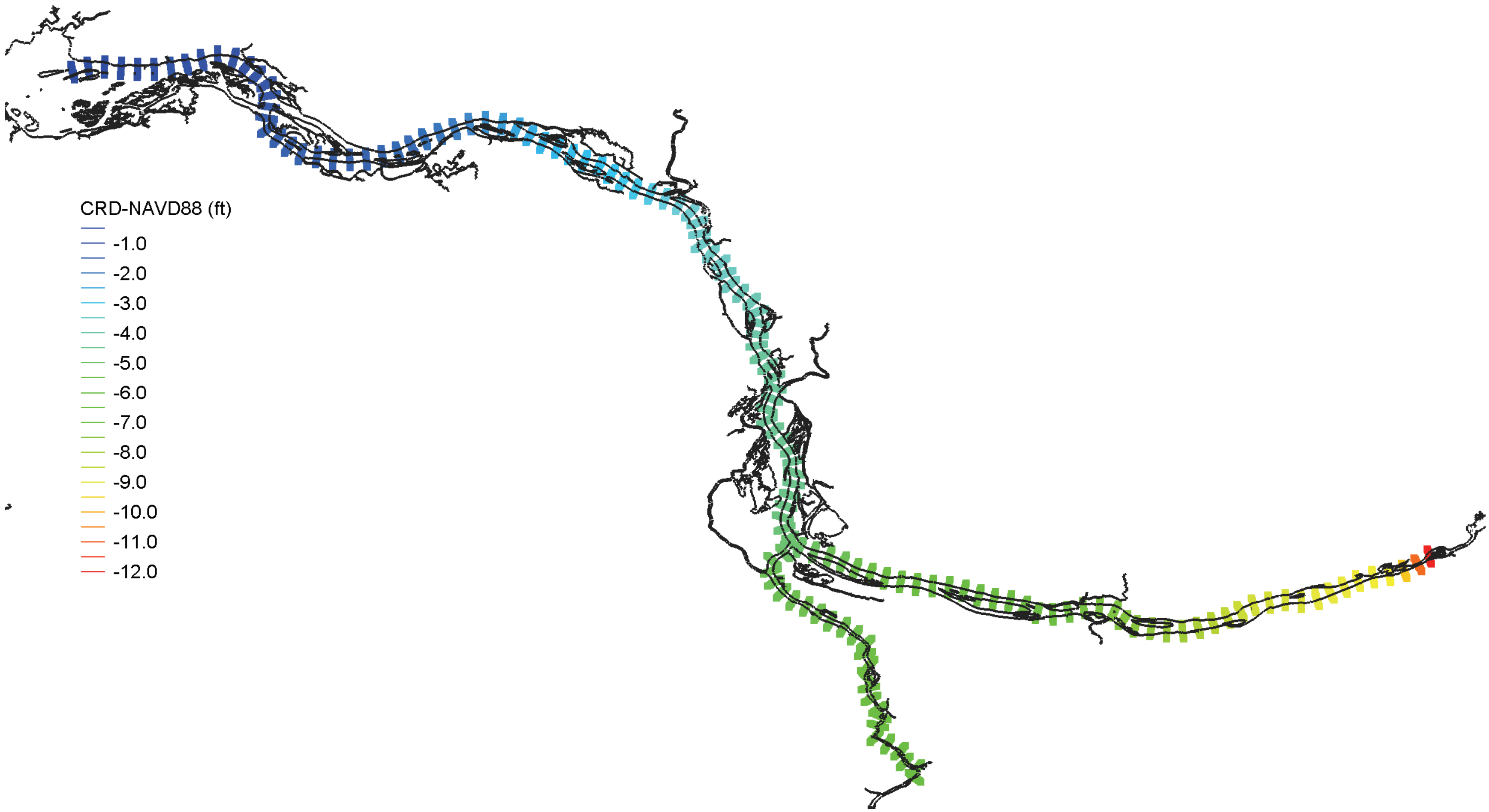

Figure 19. The perpendicular transects of the river channel and the color-coded data values in feet. The black line shows the shoreline.

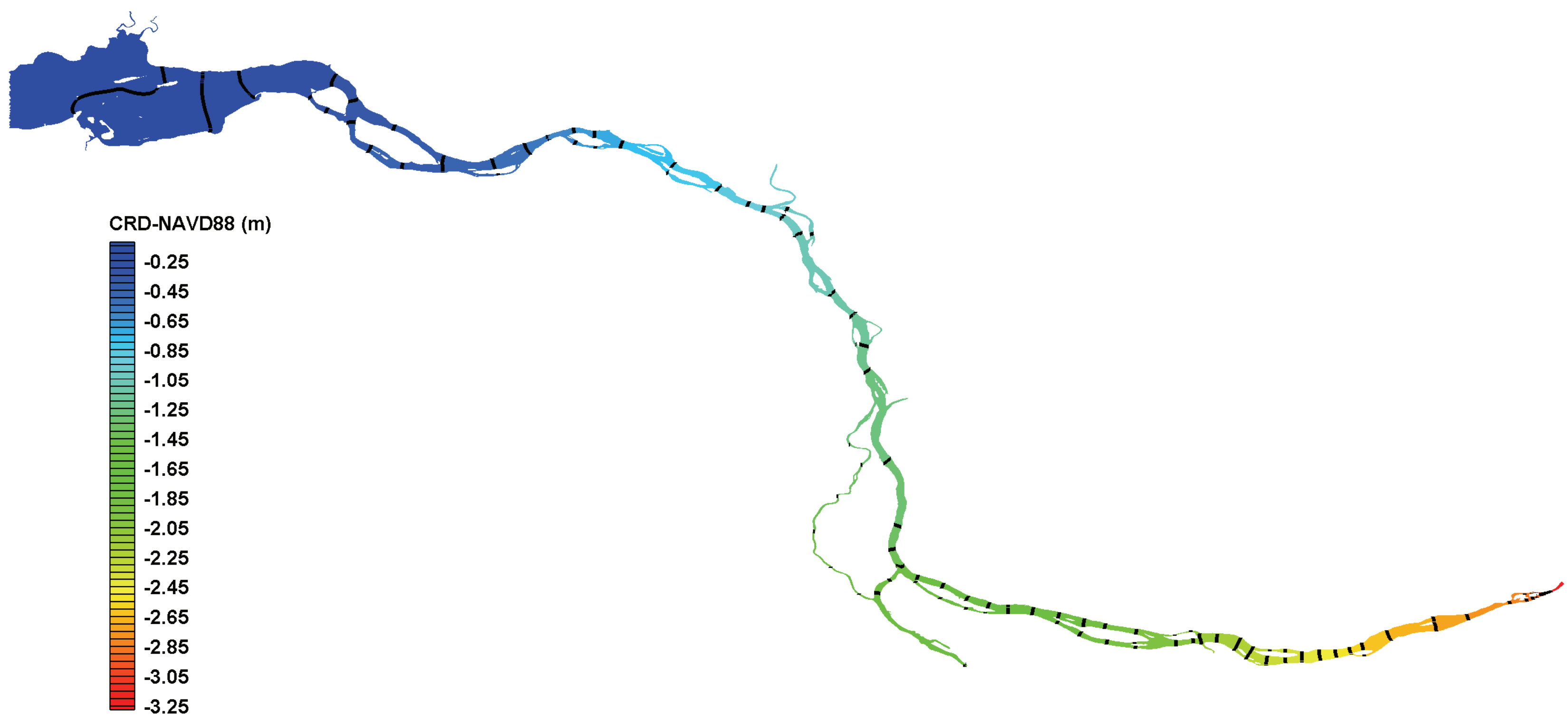

Figure 20. Columbia River Datum relative to NAVD88 in meters. Contour interval is 0.05 m.

8. Summary

VDatum tidal datum and TSS fields for the coastal waters extending from central California to north of Juan de Fuca Strait were developed in this study. Numerous embayments and rivers, such as San Francisco Bay and the Columbia River, were also included in the high resolution model grid. Tidal dynamics in the study area were simulated using the two-dimensional mode of ADCIRC. Tidal datum fields, including mean lower low water (MLLW), mean low water (MLW), mean high water (MHW), and mean higher high water (MHHW), were calculated from modeled water level time series. The TCARI program was used to generate the interpolated error fields from the model-data discrepancies at the water level stations. The errors in the modeled tidal datums were compensated for by subtracting the interpolated error fields, and the resulting VDatum values match the CO-OPS database closely at the stations.

VDatum software requires that tidal datum fields be defined on regular grids. Due to the large size of the studied area, five VDatum marine grids were built to cover the whole domain. Tidal datums defined on the unstructured grid were interpolated onto the regular grids to be used as input to the VDatum software tool.

The TSS field was derived using two methodologies: fitting tidal model results to tidal bench marks leveled in NAVD88 or calculating orthometric-to-tidal datum relationships at NOAA tide stations. Results from two methods were coupled to create the final TSS grids and were incorporated into the VDatum tool.

A simple approach to establish the relationship between CRD and NAVD88 was developed. The results can be incorporated in the VDatum software for data conversion between CRD and other vertical datums in the Columbia River.

ACKNOWLEDGMENTS

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APPENDIX A. WATER LEVEL STATIONS

Table A1. NOS Water Level Stations in the Pacific Northwest VDatum region.

No.	Station ID	Latitude	Longitude	Station Name
1	9412553	35.641700	-121.188000	SAN SIMEON
2	9413450	36.605000	-121.888000	MONTEREY, MONTEREY HARBOR
3	9413616	36.801700	-121.790000	MOSS LANDING,OCEAN PIER
4	9413623	36.810000	-121.785000	ELKHORN SLOUGH, ENTRANCE BRIDGE
5	9413631	36.818300	-121.747000	ELKHORN SLOUGH AT ELKHORN
6	9414290	37.806700	-122.465000	SAN FRANCISCO, SAN FRANCISCO BAY
7	9414317	37.790000	-122.387000	PIER 22 1/2, SAN FRANCISCO
8	9414358	37.730000	-122.357000	HUNTERS POINT, S.F. BAY
9	9414392	37.665000	-122.377000	OYSTER POINT MARINA, SAN FRANCISCO BAY
10	9414458	37.580000	-122.253000	SAN MATEO BRIDGE, WEST SIDE
11	9414509	37.506700	-122.115000	DUMBARTON BRIDGE, SAN FRANCISCO BAY
12	9414519	37.493300	-122.042000	MOWRY SLOUGH, SAN FRANCISCO BAY
13	9414523	37.506700	-122.210000	REDWOOD CITY, WHARF 5, S. F. BAY
14	9414575	37.465000	-122.023000	COYOTE CREEK, ALVISO SLOUGH
15	9414632	37.595000	-122.145000	ALAMEDA CREEK, SAN FRANCISCO BAY
16	9414688	37.695000	-122.192000	SAN LEANDRO MARINA, SAN FRANCISCO BAY
17	9414711	37.731700	-122.208000	OAKLAND AIRPORT, SAN FRANCISCO BAY
18	9414746	37.771700	-122.235000	OAKLAND/ALAMEDA PARK ST. BRIDGE
19	9414750	37.771667	-122.298333	ALAMEDA, SAN FRANCISCO BAY
20	9414764	37.795000	-122.282000	OAKLAND INNER HARBOR, SAN FRANCISCO BAY
21	9414767	37.793300	-122.315000	ALAMEDA NAS, NAVY FUEL PIER
22	9414777	37.805000	-122.338000	OAKLAND MIDDLE HARBOR, PIER 40
23	9414782	37.810000	-122.360000	YERBA BUENA ISLAND, SAN FRANCISCO BAY
24	9414806	37.846700	-122.477000	SAUSALITO, SAN FRANCISCO BAY
25	9414816	37.865000	-122.307000	BERKELEY,S.F.BAY
26	9414818	37.863300	-122.420000	ANGEL ISLAND, EAST GARRISON, S.F. BAY
27	9414819	37.865000	-122.493000	SAUSALITO, COE DOCK, S.F. BAY
28	9414837	37.891700	-122.443000	POINT CHAUNCEY, RICHARDSON BAY
29	9414849	37.910000	-122.358000	RICHMOND INNER HARBOR, SAN FRANCISCO BAY
30	9414863	37.928300	-122.400000	RICHMOND, CHEVRON OIL PIER
31	9414873	37.945000	-122.475000	POINT SAN QUENTIN, SAN FRANCISCO BAY
32	9414874	37.943300	-122.513000	CORTE MADERA CREEK
33	9414881	37.958300	-122.425000	POINT ORIENT
34	9414958	37.910000	-122.682000	BOLINAS, BOLINAS LAGOON
35	9415009	37.993300	-122.447000	POINT SAN PEDRO, SAN FRANCISCO BAY
36	9415020	37.996100	-122.976700	POINT REYES, DRAKES BAY
37	9415052	38.015000	-122.503000	GALLINAS, GALLINAS CREEK
38	9415056	38.015000	-122.363000	POINT PINOLE, SAN PABLO BAY

39	9415074	38.023300	-122.292000	HERCULES WHARF
40	9415096	38.036700	-121.880000	PITTSBURG, NEW YORK SLOUGH, SUISUN BAY
41	9415111	38.043300	-122.130000	BENICIA, CARQUINEZ STRAIT
42	9415112	38.043300	-121.918000	MALLARD ISLAND, SUISUN BAY
43	9415144	38.056700	-122.038000	PORT CHICAGO, SUISUN BAY
44	9415218	38.070000	-122.250000	MARE IS.NAVAL SHIPYARD,CARQUINEZ STRAIT
45	9415228	38.113300	-122.868000	INVERNESS, TOMALES BAY
46	9415252	38.111700	-122.498000	PETALUMA RIVER ENTRANCE
47	9415265	38.128300	-122.073000	SUISUN SLOUGH ENTRANCE
48	9415320	38.146700	-122.883000	REYNOLDS, TOMALES BAY
49	9415379	38.180000	-122.045000	JOICE ISLAND, SUISUN SLOUGH
50	9415415	38.191700	-122.312000	EDGERLEY ISLAND, NAPA RIVER
51	9415423	38.198300	-122.547000	LAKEVILLE, PETALUMA RIVER
52	9415477	38.231700	-122.968000	SAND POINT, TOMALES BAY
53	9416841	38.913300	-123.708000	ARENA COVE, PACIFIC OCEAN
54	9418686	40.686700	-124.222000	HOOKTON SLOUGH,HUMBOLDT BAY
55	9418723	40.723300	-124.222000	FIELDS LANDING, HUMBOLDT BAY
56	9418739	40.739000	-124.213200	RED BLUFF, HUMBOLDT BAY
57	9418767	40.766700	-124.217000	NORTH SPIT, HUMBOLDT BAY
58	9418778	40.778300	-124.197000	BUCKSPORT, HUMBOLDT BAY
59	9418799	40.798300	-124.120000	FRESHWATER SLOUGH, HUMBOLDT BAY
60	9418801	40.806700	-124.167000	EUREKA, HUMBOLDT BAY
61	9418802	40.806700	-124.142000	EUREKA SLOUGH, HUMBOLDT BAY
62	9418817	40.818000	-124.180000	SAMOA, HUMBOLDT BAY
63	9418865	40.865000	-124.148000	MAD RIVER SLOUGH, ARCATA BAY
64	9419059	41.056700	-124.147000	TRINIDAD HARBOR
65	9419750	41.745000	-124.183000	CRESCENT CITY, PACIFIC OCEAN
66	9431647	42.738970	-124.498278	PORT ORFORD, PACIFIC OCEAN
67	9432373	43.120000	-124.413000	BANDON, COQUILLE RIVER
68	9432771	43.341700	-124.367000	CAPE ARAGO LIGHTHOUSE
69	9432780	43.345000	-124.322000	CHARLESTON, COOS BAY
70	9432796	43.351700	-124.192000	ISTHMUS SLOUGH, COOS BAY
71	9432879	43.376700	-124.297000	SITKA DOCK, COOS BAY
72	9432895	43.410000	-124.218000	NORTH BEND, COOS BAY
73	9434938	44.413300	-123.990000	DRIFT CREEK, ALSEA RIVER
74	9435308	44.593300	-124.008000	WEISER POINT, YAQUINA RIVER
75	9435380	44.625000	-124.043000	SOUTH BEACH, YAQUINA RIVER
76	9435385	44.626700	-124.055000	YAQUINA USCG STA, NEWPORT
77	9435827	44.810000	-124.058000	DEPOE BAY
78	9437262	45.430000	-123.945000	NETARTS, NETARTS BAY
79	9437540	45.554530	-123.918944	GARIBALDI
80	9438125	45.811700	-122.827000	MULTNOMAH CHANNEL, COLUMBIA RIVER
81	9439008	46.206700	-123.950000	FORT STEVENS

82	9439011	46.201700	-123.945000	HAMMOND NMFS PIER
83	9439026	46.171700	-123.842000	ASTORIA, YOUNGS BAY
84	9439040	46.207310	-123.768306	ASTORIA, TONGUE POINT, COLUMBIA RIVER
85	9439069	46.186700	-123.588000	KNAPPA
86	9439099	46.160000	-123.405000	WAUNA, COLUMBIA RIVER
87	9439135	46.181700	-123.180000	BEAVER
88	9439189	45.696700	-122.868000	ROCKY POINT, MULTNOMAH CHANNEL
89	9439201	45.865000	-122.797000	ST. HELENS, COLUMBIA RIVER
90	9440083	45.631700	-122.697000	VANCOUVER, COLUMBIA RIVER
91	9440422	46.108300	-122.957000	LONGVIEW, COLUMBIA RIVER
92	9440569	46.266700	-123.452000	SKAMOKAWA, COLUMBIA RIVER
93	9440571	46.265000	-123.653000	ALTOONA, COLUMBIA RIVER
94	9440572	46.268300	-124.037000	JETTY A, COLUMBIA RIVER
95	9440574	46.273300	-124.072000	NORTH JETTY
96	9440575	46.268300	-123.827000	KNAPPTON
97	9440691	46.430000	-123.903000	NASELLE RIVER SWING BRIDGE
98	9440747	46.501700	-124.023000	NAHCOTTA, WILLAPA BAY
99	9440846	46.623300	-123.945000	BAY CENTER, PALIX RIVER, WILLAPA BAY
100	9440875	46.663300	-123.798000	SOUTH BEND
101	9440910	46.707470	-123.966917	TOKE POINT, WILLAPA BAY
102	9441102	46.904310	-124.105083	WESTPORT
103	9441156	46.950000	-124.128000	POINT BROWN
104	9441187	46.968300	-123.853000	ABERDEEN, GRAYS HARBOR
105	9442396	47.913300	-124.637000	LA PUSH, QUILLAYUTE RIVER

APPENDIX B. Modeled Tidal Datum Errors and Corrected TIDAL DATUMS ON MARINE GRID

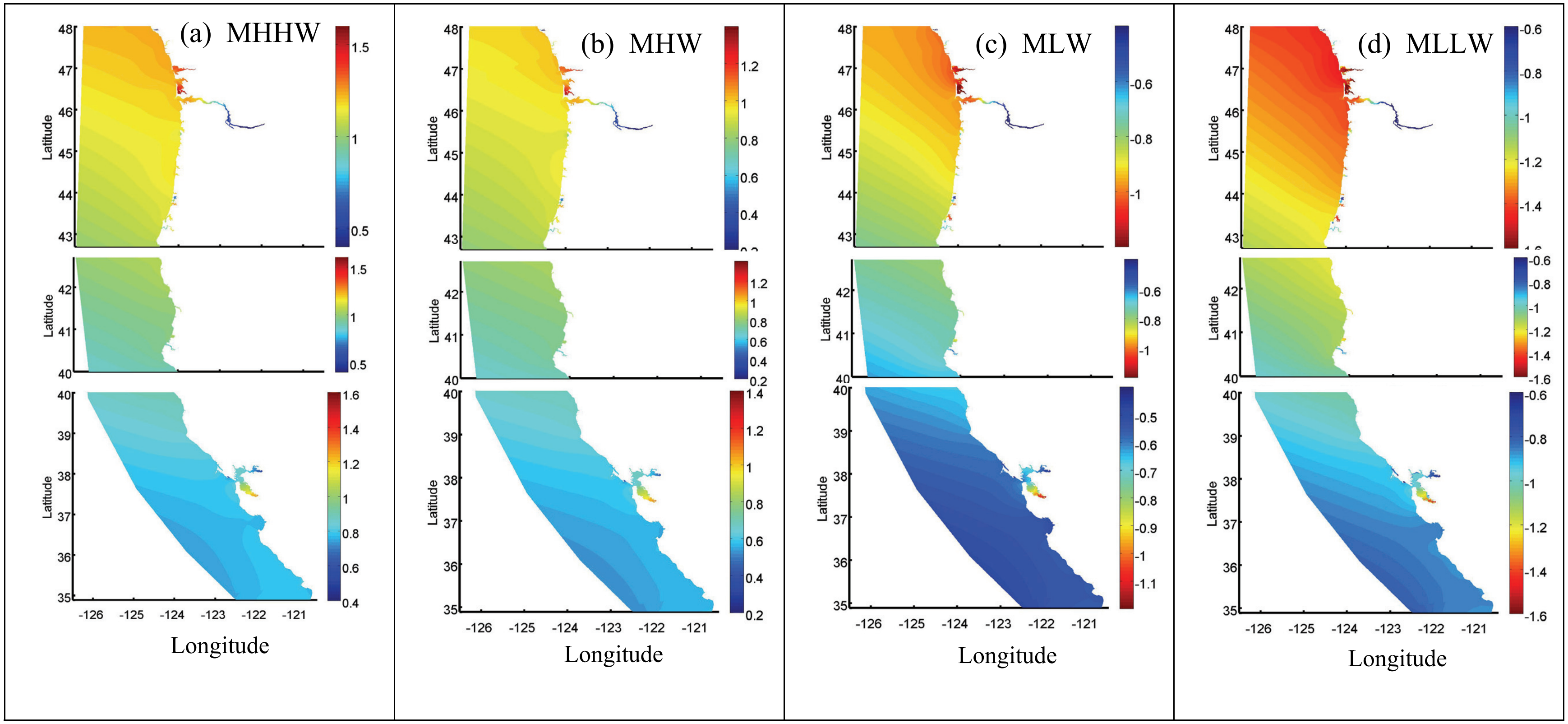

Figure B1. Tidal datums on Pacific Northwest VDatum marine grids. (a) MHHW, (b) MHW, (c) MLW, (d) MLLW. Color bars are in the unit of meters.

Table B1. Tidal datum errors (modeled minus observed in meters and the absolute relative error) at the 105 CO-OPS water level stations.

No.	Station ID	MHHW	MHW	MLW	MLLW
1	9412553	0.065 8.52%	0.043 7.95%	-0.050 9.63%	-0.014 1.64%
2	9413450	0.065 8.44%	0.050 9.05%	-0.050 9.51%	-0.024 2.74%
3	9413616	0.071 9.43%	0.056 10.28%	-0.062 12.07%	-0.053 6.31%
4	9413623	0.057 7.44%	0.039 6.91%	-0.069 13.42%	-0.050 6.00%
5	9413631	0.078 10.36%	0.062 11.53%	-0.051 9.59%	-0.031 3.55%
6	9414290	0.060 7.18%	0.021 3.29%	-0.048 7.97%	-0.038 4.01%
7	9414317	0.059 6.47%	0.022 3.02%	-0.045 6.93%	-0.037 3.67%
8	9414358	0.037 3.73%	-0.010 1.21%	-0.016 2.22%	0.003 0.27%
9	9414392	0.024 2.33%	-0.020 2.39%	-0.007 0.85%	0.013 1.11%
10	9414458	0.031 2.85%	-0.015 1.65%	0.017 1.93%	0.045 3.61%
11	9414509	0.040 3.33%	-0.004 0.36%	0.040 3.93%	0.057 4.09%
12	9414519	0.050 4.11%	0.007 0.67%	0.094 8.83%	0.165 11.61%
13	9414523	0.026 2.27%	-0.020 2.08%	0.039 3.98%	0.064 4.74%
14	9414575	0.042 3.39%	-0.008 0.79%	0.097 8.64%	0.168 11.19%
15	9414632	0.127 12.70%	0.076 9.39%	0.027 3.33%	-0.053 5.90%
16	9414688	0.030 2.76%	-0.016 1.79%	0.000 0.04%	0.027 2.27%
17	9414711	0.036 3.72%	-0.008 0.96%	-0.012 1.62%	0.008 0.71%
18	9414746	0.022 2.25%	-0.021 2.72%	-0.039 5.69%	-0.027 2.66%
19	9414750	0.040 4.19%	-0.006 0.74%	-0.035 5.01%	-0.018 1.68%
20	9414764	0.040 4.27%	-0.007 0.91%	-0.031 4.53%	-0.016 1.54%
21	9414767	0.037 4.06%	-0.006 0.82%	-0.034 4.96%	-0.016 1.55%

22	9414777	0.054	0.004	-0.045	-0.038
		6.05%	0.50%	6.82%	3.85%
23	9414782	0.054	0.011	-0.034	-0.025
		6.07%	1.53%	5.03%	2.52%
24	9414806	0.064	0.023	-0.058	-0.040
		7.95%	3.67%	9.84%	4.26%
25	9414816	0.066	0.026	-0.047	-0.032
		7.65%	3.88%	7.18%	3.19%
26	9414818	0.065	0.023	-0.043	-0.027
		7.88%	3.59%	6.88%	2.81%
27	9414819	0.074	0.031	-0.060	-0.046
		9.17%	5.05%	9.94%	4.92%
28	9414837	0.070	0.028	-0.060	-0.054
		8.56%	4.43%	10.05%	5.84%
29	9414849	0.059	0.021	-0.038	-0.023
		6.91%	3.19%	5.86%	2.35%
30	9414863	0.055	0.014	-0.035	-0.020
		6.43%	2.04%	5.42%	2.01%
31	9414873	0.068	0.028	-0.048	-0.042
		8.29%	4.36%	7.82%	4.51%
32	9414874	0.047	0.003	0.044	0.160
		5.67%	0.55%	7.07%	16.89%
33	9414881	0.060	0.020	-0.034	-0.019
		7.06%	3.05%	5.33%	1.97%
34	9414958	0.207	0.159	-0.080	-0.103
		32.12%	35.00%	17.56%	15.40%
35	9415009	0.067	0.028	-0.051	-0.043
		7.88%	4.25%	8.28%	4.56%
36	9415020	0.064	0.043	-0.042	-0.011
		7.87%	7.05%	7.26%	1.12%
37	9415052	0.069	0.033	-0.022	-0.004
		8.18%	5.03%	3.42%	0.44%
38	9415056	0.084	0.050	-0.039	-0.027
		9.80%	7.45%	5.98%	2.78%
39	9415074	0.055	0.019	-0.013	-0.001
		6.31%	2.79%	1.90%	0.15%
40	9415096	0.061	0.082	-0.040	0.019
		9.63%	17.31%	8.34%	2.79%
41	9415111	0.100	0.078	-0.050	-0.018
		13.21%	13.12%	8.32%	2.10%
42	9415112	0.077	0.090	-0.047	0.008
		12.11%	18.59%	9.45%	1.20%
43	9415144	0.115	0.098	-0.071	-0.043
		16.05%	17.46%	12.80%	5.49%
44	9415218	0.072	0.040	-0.019	0.008
		8.80%	6.09%	2.94%	0.84%

45	9415228	0.125 15.05%	0.126 20.83%	-0.081 14.04%	-0.069 7.76%
46	9415252	0.072 8.32%	0.029 4.13%	0.004 0.60%	0.045 4.45%
47	9415265	0.129 17.88%	0.110 19.42%	-0.064 11.10%	-0.035 4.42%
48	9415320	0.134 16.54%	0.131 22.28%	-0.104 19.00%	-0.118 14.03%
49	9415379	0.134 17.71%	0.114 18.78%	-0.061 10.13%	-0.027 3.26%
50	9415415	0.063 7.17%	0.037 5.26%	-0.025 3.45%	-0.030 3.02%
51	9415423	0.093 10.51%	0.051 7.11%	0.014 1.83%	0.022 2.14%
52	9415477	0.121 15.75%	0.112 20.33%	-0.094 18.65%	-0.106 13.22%
53	9416841	0.060 7.19%	0.044 7.05%	-0.038 6.25%	-0.031 3.26%
54	9418686	0.065 6.76%	0.048 6.50%	-0.000 0.04%	0.011 0.93%
55	9418723	0.090 9.54%	0.063 8.63%	-0.033 4.59%	-0.001 0.08%
56	9418739	0.084 8.89%	0.061 8.39%	-0.020 2.69%	-0.008 0.74%
57	9418767	0.055 5.70%	0.029 3.87%	0.031 4.16%	0.074 6.51%
58	9418778	0.046 4.65%	0.025 3.28%	0.054 7.15%	0.110 9.59%
59	9418799	0.047 4.44%	0.017 2.09%	0.052 6.73%	0.099 8.87%
60	9418801	0.104 10.62%	0.058 7.47%	0.074 9.23%	0.152 12.78%
61	9418802	0.051 4.94%	0.026 3.14%	0.075 9.17%	0.153 12.64%
62	9418817	0.055 5.38%	0.028 3.54%	0.092 11.15%	0.177 14.49%
63	9418865	0.069 6.67%	0.040 5.00%	0.127 14.37%	0.220 17.01%
64	9419059	0.082 8.58%	0.055 7.40%	-0.040 5.46%	-0.058 5.26%
65	9419750	0.103 10.65%	0.062 8.06%	-0.051 6.79%	-0.072 6.37%
66	9431647	0.089 8.71%	0.063 7.82%	-0.054 6.94%	-0.036 2.99%
67	9432373	0.087 8.59%	0.055 6.91%	-0.034 4.35%	-0.034 2.96%

68	9432771	0.027 2.33%	-0.015 1.60%	-0.046 5.44%	-0.106 8.99%
69	9432780	0.084 7.74%	0.016 1.77%	0.003 0.35%	0.011 0.92%
70	9432796	0.123 10.52%	0.051 5.25%	0.252 23.33%	0.421 28.25%
71	9432879	0.080 7.44%	0.009 1.03%	0.046 5.26%	0.083 6.52%
72	9432895	0.126 11.03%	0.047 4.97%	0.162 15.90%	0.256 18.00%
73	9434938	0.013 1.24%	0.007 0.88%	-0.133 19.07%	-0.253 28.08%
74	9435308	0.091 7.63%	0.036 3.62%	-0.058 5.92%	-0.081 5.86%
75	9435380	0.098 8.31%	0.050 5.16%	-0.060 6.45%	-0.061 4.52%
76	9435385	0.132 11.57%	0.056 5.84%	-0.055 5.91%	-0.054 3.97%
77	9435827	0.083 7.15%	0.037 3.87%	-0.029 3.15%	-0.022 1.61%
78	9437262	0.268 27.41%	0.241 32.31%	-0.070 8.85%	-0.036 3.27%
79	9437540	0.021 1.84%	-0.050 5.50%	0.141 14.98%	0.248 18.45%
80	9438125	0.078 14.71%	0.028 7.48%	-0.042 11.73%	-0.024 5.49%
81	9439008	0.034 2.77%	-0.021 2.09%	0.031 3.15%	0.060 4.30%
82	9439011	0.075 6.30%	0.014 1.46%	0.001 0.14%	0.028 2.10%
83	9439026	0.011 0.88%	-0.045 4.30%	0.075 7.16%	0.119 8.39%
84	9439040	-0.007 0.53%	-0.065 6.21%	0.094 9.19%	0.156 11.37%
85	9439069	0.011 0.89%	-0.042 4.17%	0.100 9.76%	0.157 11.80%
86	9439099	-0.016 1.48%	-0.075 8.18%	0.069 8.27%	0.110 10.54%
87	9439135	0.038 4.08%	-0.025 3.26%	-0.012 1.80%	-0.003 0.35%
88	9439189	-0.022 3.77%	-0.050 12.17%	-0.003 0.73%	0.030 6.89%
89	9439201	0.065 11.97%	0.011 2.72%	-0.026 6.79%	-0.005 1.10%
90	9440083	-0.028 4.77%	-0.053 13.11%	0.006 1.72%	0.043 10.22%

91	9440422	0.055 7.12%	-0.017 2.78%	-0.031 5.94%	-0.016 2.53%
92	9440569	-0.011 0.93%	-0.068 7.09%	0.079 8.66%	0.130 11.23%
93	9440571	0.015 1.25%	-0.041 4.19%	0.087 8.87%	0.144 11.23%
94	9440572	0.090 7.57%	0.046 4.76%	-0.017 1.80%	0.017 1.22%
95	9440574	0.162 14.55%	0.093 10.25%	-0.109 12.52%	-0.138 11.11%
96	9440575	-0.017 1.33%	-0.070 6.70%	0.094 9.18%	0.142 10.17%
97	9440691	0.114 7.77%	0.055 4.51%	0.171 12.60%	0.270 14.97%
98	9440747	0.084 5.86%	0.025 2.07%	0.194 14.59%	0.274 15.45%
99	9440846	0.076 5.97%	0.023 2.19%	0.035 3.15%	0.087 5.72%
100	9440875	0.052 3.90%	0.002 0.21%	0.061 5.02%	0.105 6.34%
101	9440910	0.098 7.74%	0.053 5.12%	0.013 1.30%	0.071 4.88%
102	9441102	0.048 3.71%	-0.004 0.41%	0.062 5.91%	0.102 6.95%
103	9441156	0.025 1.90%	-0.025 2.29%	0.140 12.25%	0.228 14.26%
104	9441187	0.077 5.57%	0.014 1.19%	0.098 7.82%	0.150 8.76%
105	9442396	0.074 6.06%	0.034 3.37%	-0.005 0.46%	0.057 3.98%

APPENDIX C. TSS at NGS Bench Marks and CO-OPS Water Level Stations

Table C1. Derived NAVD 88-to-LMSL values for each tidal datum at NGS benchmarks from the West Coast of the Continental United States Tidal Grids. NAVD88 values realized through GEOID03.

Bench-mark	Latitude	Longitude	From MLLW (m)	From MLW (m)	From MHW (m)	From MHHW (m)	Average (m)	Std. Dev. (m)
FV0898	35.17083	-120.75500	-0.829	-0.829	-0.829	-0.828	-0.829	0.001
FV1994	35.17111	-120.75583	-0.829	-0.829	-0.829	-0.828	-0.829	0.001
FV1077	35.17194	-120.75527	-0.832	-0.832	-0.832	-0.831	-0.832	0.001
FV1993	35.17194	-120.75583	-0.832	-0.832	-0.832	-0.831	-0.832	0.001
FV1078	35.17222	-120.75527	-0.832	-0.832	-0.832	-0.831	-0.832	0.001
FV1992	35.17222	-120.75583	-0.829	-0.829	-0.829	-0.828	-0.829	0.001
FV1991	35.17333	-120.75500	-0.832	-0.832	-0.832	-0.831	-0.832	0.001
FV1079	35.17500	-120.75444	-0.829	-0.829	-0.829	-0.828	-0.829	0.001
FV1124	35.64277	-121.19027	-0.909	-0.910	-0.905	-0.904	-0.907	0.003
FV1125	35.64277	-121.19138	-0.910	-0.912	-0.904	-0.903	-0.907	0.005
FV1121	35.64305	-121.18666	-0.910	-0.911	-0.910	-0.909	-0.910	0.001
FV1123	35.64305	-121.19000	-0.909	-0.910	-0.905	-0.904	-0.907	0.003
FV0986	35.64416	-121.18777	-0.911	-0.912	-0.910	-0.908	-0.910	0.002
FV1119	35.64416	-121.18555	-0.907	-0.908	-0.907	-0.906	-0.907	0.001
FV1120	35.64444	-121.18583	-0.907	-0.908	-0.907	-0.906	-0.907	0.001
GU3221	36.59777	-121.89000	-0.908	-0.907	-0.907	-0.907	-0.907	0.001
GU3220	36.60027	-121.88916	-0.905	-0.904	-0.904	-0.904	-0.904	0.001
GU4116	36.60138	-121.89166	-0.908	-0.908	-0.906	-0.906	-0.907	0.001
GU3229	36.60166	-121.88861	-0.905	-0.904	-0.904	-0.904	-0.904	0.001
GU4117	36.60194	-121.88861	-0.905	-0.904	-0.904	-0.904	-0.904	0.001
GU2088	36.60305	-121.89166	-0.902	-0.902	-0.900	-0.900	-0.901	0.001
GU2090	36.60361	-121.89194	-0.902	-0.902	-0.900	-0.900	-0.901	0.001
GU3218	36.60361	-121.89250	-0.905	-0.905	-0.903	-0.903	-0.904	0.001
GU3219	36.60638	-121.89277	-0.911	-0.911	-0.909	-0.909	-0.910	0.001
GU3224	36.60750	-121.89333	-0.905	-0.905	-0.903	-0.903	-0.904	0.001
GU3204	36.81416	-121.74388	-0.867	-0.868	-0.866	-0.866	-0.867	0.001
GU3203	36.81472	-121.74305	-0.846	-0.847	-0.845	-0.845	-0.846	0.001
HT2357	37.59305	-122.13944	-1.135	-1.134	-1.134	-1.134	-1.134	0.001
HT2358	37.59305	-122.14027	-1.137	-1.135	-1.134	-1.134	-1.135	0.002
HT2360	37.59333	-122.14222	-1.137	-1.135	-1.135	-1.135	-1.135	0.001
HT2361	37.59333	-122.14305	-1.134	-1.132	-1.132	-1.132	-1.132	0.001
HT2362	37.59361	-122.14500	-1.137	-1.133	-1.132	-1.132	-1.133	0.002
HT0279	37.72916	-122.20777	-1.014	-1.013	-1.015	-1.014	-1.014	0.001
HT0277	37.73055	-122.20888	-1.017	-1.016	-1.018	-1.017	-1.017	0.001
HT0027	37.77055	-122.23638	-0.980	-0.981	-0.979	-0.979	-0.980	0.001
HT0025	37.77111	-122.23583	-0.980	-0.981	-0.979	-0.979	-0.980	0.001

Bench-mark	Latitude	Longitude	From MLLW (m)	From MLW (m)	From MHW (m)	From MHHW (m)	Average (m)	Std. Dev. (m)
HT3551	37.77194	-122.29750	-0.981	-0.980	-0.978	-0.981	-0.980	0.001
HT0024	37.77277	-122.23444	-0.980	-0.981	-0.979	-0.979	-0.980	0.001
HT3550	37.77416	-122.29944	-1.010	-1.010	-1.014	-1.018	-1.013	0.004
HT0890	37.77527	-122.29833	-0.986	-0.986	-0.990	-0.994	-0.989	0.004
HT0888	37.77833	-122.29694	-0.998	-0.998	-1.002	-1.006	-1.001	0.004
HT0882	37.78000	-122.29722	-0.986	-0.986	-0.990	-0.994	-0.989	0.004
HT3554	37.78361	-122.29611	-0.983	-0.983	-0.987	-0.991	-0.986	0.004
HT0884	37.78444	-122.29611	-0.980	-0.980	-0.984	-0.988	-0.983	0.004
HT0758	37.78805	-122.38916	-0.994	-0.994	-0.988	-0.990	-0.991	0.003
HT0787	37.78805	-122.38722	-0.990	-0.989	-0.980	-0.982	-0.985	0.005
HT0788	37.78805	-122.38722	-0.993	-0.992	-0.983	-0.985	-0.988	0.005
HT0759	37.79027	-122.38750	-0.984	-0.984	-0.984	-0.985	-0.984	0.001
HT0654	37.79555	-122.27861	-0.984	-0.984	-0.983	-0.982	-0.983	0.001
HT0655	37.79666	-122.27888	-0.984	-0.984	-0.983	-0.982	-0.983	0.001
HT3538	37.80333	-122.46555	-0.979	-0.980	-0.977	-0.977	-0.979	0.002
HT0705	37.80361	-122.46611	-0.973	-0.974	-0.971	-0.971	-0.972	0.001
HT0701	37.80472	-122.46583	-0.973	-0.974	-0.971	-0.971	-0.972	0.001
HT0702	37.80500	-122.46611	-0.976	-0.977	-0.974	-0.974	-0.975	0.001
AE5209	37.80555	-122.46555	-0.976	-0.977	-0.974	-0.974	-0.975	0.001
AH7158	37.80666	-122.33111	-0.993	-0.990	-0.986	-0.987	-0.989	0.003
HT0697	37.80833	-122.46972	-0.960	-0.961	-0.975	-0.975	-0.968	0.009
HT0700	37.80861	-122.46972	-0.959	-0.960	-0.976	-0.976	-0.968	0.009
HT2255	37.80861	-122.47000	-0.959	-0.960	-0.976	-0.977	-0.968	0.010
HT0698	37.80861	-122.46972	-0.959	-0.960	-0.976	-0.976	-0.968	0.009
AH7160	37.80888	-122.32944	-0.993	-0.991	-0.986	-0.987	-0.989	0.003
AH7161	37.80888	-122.32722	-0.993	-0.988	-1.000	-0.999	-0.995	0.006
AH7162	37.80888	-122.32833	-0.993	-0.991	-0.986	-0.987	-0.989	0.003
AH7163	37.80888	-122.32833	-0.993	-0.991	-0.986	-0.987	-0.989	0.003
HT0696	37.80888	-122.47027	-0.957	-0.959	-0.977	-0.978	-0.968	0.011
HT2253	37.80888	-122.47055	-0.957	-0.958	-0.978	-0.978	-0.968	0.012
HT3537	37.84888	-122.47722	-0.992	-0.991	-0.987	-0.987	-0.989	0.003
HT1073	37.85250	-122.47777	-0.990	-0.991	-0.982	-0.982	-0.986	0.005
HT1074	37.85611	-122.47861	-0.992	-0.993	-0.980	-0.979	-0.986	0.008
HT1070	37.85916	-122.48416	-0.999	-0.998	-0.996	-0.996	-0.997	0.001
HT3536	37.86055	-122.48638	-0.993	-0.992	-0.991	-0.990	-0.992	0.001
HT3535	37.86138	-122.48833	-1.000	-0.999	-0.997	-0.997	-0.998	0.001
HT1066	37.86277	-122.49166	-0.990	-0.990	-0.990	-0.990	-0.990	0.000
HT1067	37.86333	-122.49222	-0.999	-0.999	-1.000	-1.000	-0.999	0.000
HT3508	37.99472	-122.97583	-0.929	-0.933	-0.937	-0.938	-0.934	0.004
HT3510	37.99472	-122.97500	-0.931	-0.936	-0.940	-0.942	-0.937	0.005
HT3509	37.99527	-122.97611	-0.937	-0.936	-0.937	-0.938	-0.937	0.001
HT1838	37.99555	-122.97638	-0.937	-0.936	-0.937	-0.938	-0.937	0.001

Bench-mark	Latitude	Longitude	From MLLW (m)	From MLW (m)	From MHW (m)	From MHHW (m)	Average (m)	Std. Dev. (m)
HT1839	37.99555	-122.97638	-0.940	-0.939	-0.940	-0.941	-0.940	0.001
HT3507	37.99583	-122.97666	-0.934	-0.933	-0.934	-0.935	-0.934	0.001
HT3503	37.99611	-122.97805	-0.937	-0.936	-0.937	-0.938	-0.937	0.001
HT3505	37.99611	-122.97777	-0.937	-0.936	-0.937	-0.938	-0.937	0.001
HT3506	37.99611	-122.97722	-0.937	-0.936	-0.937	-0.938	-0.937	0.001
HT3504	37.99638	-122.97861	-0.937	-0.936	-0.937	-0.938	-0.937	0.001
JT9538	38.07416	-122.25277	-1.072	-1.075	-1.098	-1.097	-1.085	0.014
JT0318	38.07611	-122.24805	-1.071	-1.075	-1.095	-1.093	-1.083	0.012
JT9537	38.07611	-122.24833	-1.074	-1.078	-1.098	-1.096	-1.086	0.012
JT9387	38.91055	-123.70083	-0.927	-0.927	-0.926	-0.925	-0.926	0.001
JT9388	38.91194	-123.70305	-0.924	-0.924	-0.923	-0.922	-0.923	0.001
JT9393	38.91277	-123.70944	-0.920	-0.920	-0.921	-0.920	-0.920	0.001
JT9392	38.91305	-123.70944	-0.923	-0.923	-0.924	-0.923	-0.923	0.001
JT9390	38.91472	-123.70722	-0.926	-0.926	-0.927	-0.926	-0.926	0.001
JT9391	38.91500	-123.70861	-0.923	-0.923	-0.924	-0.923	-0.923	0.001
LV0656	40.72583	-124.21944	-0.938	-0.942	-0.938	-0.936	-0.939	0.002
LV0264	40.73666	-124.20777	-0.930	-0.950	-0.942	-0.937	-0.940	0.008
LV0264	40.73666	-124.20777	-0.948	-0.947	-0.948	-0.946	-0.947	0.001
LV0652	40.73722	-124.21027	-0.952	-0.951	-0.952	-0.950	-0.951	0.001
LV0653	40.73861	-124.21166	-0.955	-0.951	-0.946	-0.944	-0.949	0.005
LV0266	40.74472	-124.19555	-1.001	-0.977	-0.938	-0.937	-0.963	0.031
LV0636	40.76638	-124.21750	-1.025	-1.025	-1.027	-1.027	-1.026	0.001
LV0360	40.76666	-124.21666	-1.028	-1.028	-1.029	-1.029	-1.028	0.001
LV0361	40.76666	-124.21694	-1.028	-1.028	-1.029	-1.029	-1.028	0.001
LV0637	40.76666	-124.21694	-1.025	-1.025	-1.026	-1.026	-1.025	0.001
LV0359	40.76694	-124.21638	-1.031	-1.031	-1.032	-1.031	-1.031	0.000
LV0634	40.76694	-124.21750	-1.025	-1.025	-1.027	-1.027	-1.026	0.001
LV0630	40.76805	-124.21750	-1.022	-1.021	-1.021	-1.021	-1.021	0.000
LV0632	40.76833	-124.21638	-1.020	-1.020	-1.020	-1.019	-1.020	0.001
LV0631	40.76861	-124.21694	-1.020	-1.020	-1.020	-1.019	-1.020	0.001
LV0647	40.77722	-124.19250	-0.963	-0.962	-0.968	-0.970	-0.966	0.004
LV0642	40.79500	-124.12500	-0.978	-0.978	-0.976	-0.976	-0.977	0.001
LV0643	40.79527	-124.12000	-0.972	-0.972	-0.970	-0.969	-0.971	0.001
LV0289	40.80444	-124.12500	-0.953	-0.970	-0.977	-0.979	-0.970	0.012
LV0287	40.80500	-124.14055	-0.971	-0.972	-0.973	-0.971	-0.972	0.001
LV0639	40.80694	-124.14222	-0.973	-0.972	-0.974	-0.973	-0.973	0.001
LV0640	40.80694	-124.14166	-0.976	-0.975	-0.977	-0.975	-0.976	0.001
LV0352	40.81805	-124.17972	-1.050	-1.051	-1.050	-1.049	-1.050	0.001
LV0351	40.82222	-124.17527	-1.058	-1.060	-1.054	-1.055	-1.056	0.003
LV0350	40.82861	-124.17138	-1.071	-1.072	-1.048	-1.050	-1.060	0.013
LV0344	40.86444	-124.15194	-0.990	-0.991	-0.991	-0.990	-0.990	0.001
LV0346	40.86527	-124.14888	-0.990	-0.991	-0.991	-0.990	-0.991	0.001

Bench-mark	Latitude	Longitude	From MLLW (m)	From MLW (m)	From MHW (m)	From MHHW (m)	Average (m)	Std. Dev. (m)
LV0599	41.05611	-124.14861	-1.022	-1.023	-1.020	-1.020	-1.021	0.002
LV0598	41.05638	-124.14861	-1.022	-1.023	-1.020	-1.020	-1.021	0.001
LV0600	41.05638	-124.14805	-1.022	-1.022	-1.021	-1.020	-1.021	0.001
LV0601	41.05638	-124.14777	-1.022	-1.022	-1.021	-1.021	-1.021	0.001
LV0602	41.05638	-124.14750	-1.019	-1.019	-1.018	-1.018	-1.018	0.001
LV0603	41.05694	-124.14694	-1.021	-1.022	-1.021	-1.021	-1.021	0.001
LV0604	41.05722	-124.14638	-1.021	-1.022	-1.021	-1.021	-1.021	0.001
LV0597	41.05833	-124.14750	-1.021	-1.022	-1.021	-1.021	-1.021	0.001
LV0110	41.74611	-124.18250	-1.014	-1.015	-1.013	-1.013	-1.014	0.001
LV0565	41.74638	-124.18055	-1.017	-1.015	-1.007	-1.004	-1.011	0.006
LV0566	41.74638	-124.18000	-1.026	-1.022	-1.005	-1.000	-1.013	0.013
LV0101	41.74777	-124.18333	-1.016	-1.016	-1.012	-1.011	-1.014	0.003
LV0563	41.74805	-124.18027	-1.014	-1.015	-1.013	-1.013	-1.014	0.001
LV0562	41.75027	-124.18055	-1.018	-1.017	-1.010	-1.008	-1.014	0.005
LV0561	41.75138	-124.18250	-1.024	-1.022	-1.012	-1.009	-1.017	0.007
OA0789	42.73888	-124.49861	-1.047	-1.047	-1.046	-1.048	-1.047	0.001
OA0787	42.73916	-124.49888	-1.050	-1.050	-1.049	-1.051	-1.050	0.001
OA0788	42.73916	-124.49861	-1.050	-1.050	-1.049	-1.051	-1.050	0.001
OA0790	42.73916	-124.49805	-1.047	-1.047	-1.046	-1.048	-1.047	0.001
OA0786	42.73944	-124.49916	-1.047	-1.047	-1.046	-1.048	-1.047	0.001
OA0785	42.74000	-124.49944	-1.047	-1.048	-1.045	-1.047	-1.047	0.001
OA0075	42.74111	-124.49722	-1.050	-1.050	-1.049	-1.051	-1.050	0.001
OA0783	42.74194	-124.49777	-1.047	-1.047	-1.046	-1.048	-1.047	0.001
OA0427	43.11805	-124.41388	-1.117	-1.117	-1.116	-1.116	-1.117	0.001
OA0428	43.11916	-124.41055	-1.107	-1.108	-1.105	-1.105	-1.106	0.001
OA0426	43.12055	-124.41638	-1.119	-1.117	-1.109	-1.108	-1.113	0.006
OA0644	43.34361	-124.32416	-1.091	-1.092	-1.093	-1.092	-1.092	0.001
OA0645	43.34388	-124.32305	-1.089	-1.089	-1.088	-1.086	-1.088	0.001
OA0651	43.34444	-124.32638	-1.095	-1.097	-1.098	-1.096	-1.097	0.001
OA0649	43.34472	-124.32305	-1.101	-1.101	-1.101	-1.100	-1.101	0.001
OA0650	43.34472	-124.32444	-1.096	-1.096	-1.097	-1.095	-1.096	0.001
OA0652	43.34666	-124.32777	-1.095	-1.095	-1.095	-1.094	-1.095	0.001
OA0653	43.34750	-124.32805	-1.088	-1.089	-1.089	-1.087	-1.088	0.001
OA0635	43.37277	-124.29027	-1.099	-1.098	-1.092	-1.093	-1.095	0.004
OA0639	43.37277	-124.29305	-1.097	-1.095	-1.094	-1.095	-1.095	0.001
OA0636	43.37305	-124.29166	-1.100	-1.098	-1.095	-1.096	-1.097	0.002
OA0638	43.37305	-124.29333	-1.091	-1.089	-1.087	-1.088	-1.089	0.001
OA0637	43.37333	-124.29250	-1.098	-1.096	-1.094	-1.094	-1.095	0.002
OA0499	43.40527	-124.22055	-1.126	-1.132	-1.131	-1.131	-1.130	0.003
OA0626	43.40527	-124.22083	-1.126	-1.132	-1.131	-1.131	-1.130	0.003
OA0654	43.40777	-124.22000	-1.123	-1.128	-1.130	-1.131	-1.128	0.004
OA0655	43.40833	-124.22055	-1.129	-1.134	-1.136	-1.136	-1.134	0.003

Bench-mark	Latitude	Longitude	From MLLW (m)	From MLW (m)	From MHW (m)	From MHHW (m)	Average (m)	Std. Dev. (m)
OA0656	43.40833	-124.22027	-1.126	-1.131	-1.133	-1.133	-1.131	0.003
QE1613	44.62277	-124.04638	-1.159	-1.160	-1.160	-1.167	-1.162	0.004
QE1616	44.62333	-124.04527	-1.145	-1.145	-1.145	-1.151	-1.146	0.003
QE1615	44.62361	-124.04277	-1.135	-1.135	-1.134	-1.136	-1.135	0.001
QE1210	44.62527	-124.05777	-1.102	-1.102	-1.104	-1.100	-1.102	0.002
QE1114	44.62555	-124.04388	-1.129	-1.129	-1.129	-1.132	-1.130	0.002
QE1425	44.80777	-124.05777	-1.151	-1.151	-1.151	-1.152	-1.151	0.001
QE1424	44.80861	-124.05805	-1.154	-1.154	-1.154	-1.155	-1.154	0.001
QE1423	44.80888	-124.05805	-1.151	-1.151	-1.151	-1.152	-1.151	0.001
QE1165	44.80944	-124.05777	-1.154	-1.154	-1.154	-1.155	-1.154	0.001
QE1426	44.80972	-124.05888	-1.154	-1.154	-1.154	-1.155	-1.154	0.001
QE1421	44.81000	-124.06055	-1.154	-1.154	-1.154	-1.155	-1.154	0.001
QE1164	44.81000	-124.06083	-1.151	-1.151	-1.151	-1.152	-1.151	0.001
QE1418	44.81000	-124.06083	-1.151	-1.151	-1.151	-1.152	-1.151	0.001
QE1419	44.81027	-124.06055	-1.151	-1.151	-1.151	-1.152	-1.151	0.001
QE1420	44.81027	-124.05805	-1.154	-1.154	-1.154	-1.155	-1.154	0.001
QE1422	44.81055	-124.05833	-1.154	-1.154	-1.154	-1.155	-1.154	0.001
RD1243	45.56083	-123.90777	-1.216	-1.236	-1.252	-1.251	-1.239	0.017
SC1026	46.17111	-123.83611	-1.371	-1.372	-1.371	-1.371	-1.371	0.001
SC0509	46.17138	-123.84250	-1.378	-1.379	-1.380	-1.380	-1.380	0.001
SC1025	46.17305	-123.84277	-1.374	-1.375	-1.378	-1.378	-1.376	0.002
SC1024	46.17333	-123.84277	-1.374	-1.375	-1.378	-1.378	-1.376	0.002
SC0447	46.18611	-123.58694	-1.546	-1.545	-1.545	-1.545	-1.545	0.001
AC5404	46.19972	-123.94666	-1.360	-1.359	-1.358	-1.359	-1.359	0.001
AC5403	46.20000	-123.94638	-1.359	-1.358	-1.358	-1.359	-1.359	0.001
AC5405	46.20083	-123.94944	-1.379	-1.375	-1.336	-1.334	-1.356	0.024
SC1048	46.20277	-123.76555	-1.428	-1.442	-1.449	-1.447	-1.441	0.010
SC1050	46.20527	-123.76555	-1.432	-1.439	-1.441	-1.440	-1.438	0.004
AC5406	46.20583	-123.95138	-1.397	-1.390	-1.314	-1.310	-1.352	0.047
SC1051	46.20611	-123.76472	-1.425	-1.438	-1.445	-1.444	-1.438	0.009
SC0586	46.20638	-123.95333	-1.314	-1.314	-1.331	-1.330	-1.322	0.010
SC0478	46.20694	-123.76472	-1.433	-1.439	-1.440	-1.439	-1.438	0.003
SC0583	46.20694	-123.96083	-1.339	-1.333	-1.356	-1.354	-1.345	0.011
SC0480	46.20750	-123.76500	-1.441	-1.442	-1.440	-1.440	-1.440	0.001
SC1053	46.20750	-123.76472	-1.431	-1.435	-1.436	-1.436	-1.434	0.003
SC1055	46.20750	-123.76555	-1.441	-1.442	-1.440	-1.440	-1.440	0.001
SC0479	46.20777	-123.76500	-1.443	-1.444	-1.442	-1.442	-1.443	0.001
SC1054	46.20777	-123.76472	-1.424	-1.429	-1.430	-1.430	-1.428	0.003
SC0534	46.26638	-123.65500	-1.368	-1.367	-1.367	-1.369	-1.367	0.001
SD0300	46.27222	-124.07000	-1.170	-1.171	-1.169	-1.171	-1.170	0.001
SD0302	46.27222	-124.07000	-1.167	-1.168	-1.166	-1.168	-1.167	0.001
SD0299	46.27305	-124.07250	-1.170	-1.170	-1.165	-1.167	-1.168	0.003

Bench-mark	Latitude	Longitude	From MLLW (m)	From MLW (m)	From MHW (m)	From MHHW (m)	Average (m)	Std. Dev. (m)
SD0298	46.27361	-124.06972	-1.174	-1.174	-1.167	-1.169	-1.171	0.004
SD0297	46.27694	-124.06500	-1.204	-1.193	-1.157	-1.154	-1.177	0.025
SC1021	46.42805	-123.90388	-1.229	-1.229	-1.230	-1.229	-1.229	0.001
SC2839	46.43361	-123.90055	-0.489	-0.490	-0.489	-0.488	-0.489	0.001
SC2840	46.43361	-123.90055	-0.489	-0.490	-0.489	-0.488	-0.489	0.001
SC2841	46.43361	-123.90055	-0.492	-0.493	-0.492	-0.491	-0.492	0.001
SC0953	46.66277	-123.79722	-1.228	-1.227	-1.229	-1.229	-1.228	0.001
SC0954	46.66305	-123.79722	-1.216	-1.215	-1.216	-1.217	-1.216	0.001
SC0956	46.66305	-123.79833	-1.224	-1.223	-1.226	-1.227	-1.225	0.002
SC0955	46.66333	-123.79805	-1.210	-1.209	-1.211	-1.211	-1.210	0.001
SC0957	46.66333	-123.79888	-1.236	-1.235	-1.238	-1.239	-1.237	0.002
SC0916	46.70472	-123.97027	-1.216	-1.213	-1.197	-1.198	-1.206	0.010
SC0917	46.70472	-123.96805	-1.219	-1.218	-1.203	-1.205	-1.211	0.008
SC0795	46.96833	-123.85305	-1.208	-1.207	-1.207	-1.209	-1.208	0.001
SD0157	47.90861	-124.63638	-1.200	-1.187	-1.170	-1.168	-1.181	0.015
SD0158	47.90861	-124.63638	-1.194	-1.181	-1.164	-1.162	-1.175	0.015
SY0868	47.05000	-122.90138	-1.302	-1.305	-1.306	-1.305	-1.304	0.002
SY0865	47.05166	-122.90250	-1.311	-1.314	-1.315	-1.314	-1.313	0.002
SY0866	47.05194	-122.90388	-1.314	-1.317	-1.318	-1.317	-1.316	0.002
SY0535	47.25888	-122.41916	-1.320	-1.320	-1.294	-1.293	-1.307	0.016
SY0536	47.26416	-122.41194	-1.360	-1.357	-1.331	-1.333	-1.345	0.016
SY0536	47.26416	-122.41194	-1.324	-1.324	-1.298	-1.297	-1.311	0.015
SY1272	47.35694	-123.10305	-1.252	-1.252	-1.255	-1.253	-1.253	0.002
SY1274	47.35694	-123.10083	-1.259	-1.259	-1.260	-1.258	-1.259	0.001
SY1271	47.35722	-123.10305	-1.255	-1.255	-1.258	-1.256	-1.256	0.002
SY0805	47.38361	-122.82527	-1.294	-1.295	-1.295	-1.294	-1.295	0.001
SY0804	47.38444	-122.82750	-1.233	-1.234	-1.234	-1.233	-1.234	0.001
SY0920	47.56305	-122.62527	-1.306	-1.307	-1.306	-1.306	-1.306	0.001
SY5718	47.56305	-122.62416	-1.321	-1.322	-1.321	-1.321	-1.321	0.001
SY0270	47.57444	-122.36277	-1.299	-1.299	-1.300	-1.299	-1.299	0.001
SY0271	47.57833	-122.36277	-1.299	-1.299	-1.300	-1.299	-1.299	0.001
SY0272	47.58194	-122.36277	-1.299	-1.299	-1.300	-1.299	-1.299	0.001
SY0273	47.58416	-122.36250	-1.299	-1.299	-1.300	-1.299	-1.299	0.001
SY0283	47.60194	-122.33388	-1.310	-1.312	-1.309	-1.311	-1.311	0.001
SY0286	47.60305	-122.33444	-1.310	-1.312	-1.309	-1.311	-1.311	0.001
SY0290	47.60388	-122.33750	-1.310	-1.312	-1.309	-1.311	-1.311	0.001
SY0289	47.60444	-122.33500	-1.310	-1.312	-1.309	-1.311	-1.311	0.001
SY0959	47.74666	-122.72638	-1.253	-1.254	-1.253	-1.253	-1.253	0.001
SY1164	47.76138	-122.85000	-1.253	-1.254	-1.252	-1.253	-1.253	0.001
SY1162	47.76194	-122.85000	-1.253	-1.254	-1.252	-1.253	-1.253	0.001
SY0225	47.93916	-122.35666	-1.351	-1.351	-1.352	-1.352	-1.352	0.001
SY0227	47.93916	-122.35666	-1.360	-1.360	-1.361	-1.361	-1.361	0.001

Bench-mark	Latitude	Longitude	From MLLW (m)	From MLW (m)	From MHW (m)	From MHHW (m)	Average (m)	Std. Dev. (m)
TR2726	48.11138	-122.76166	-1.198	-1.191	-1.194	-1.190	-1.193	0.004
TR0559	48.11583	-122.75194	-1.195	-1.190	-1.198	-1.196	-1.195	0.003
TR0791	48.11972	-123.43416	-1.159	-1.122	-1.186	-1.167	-1.159	0.027
TR0790	48.12333	-123.44472	-1.163	-1.154	-1.168	-1.164	-1.162	0.006
TR0789	48.12722	-123.45777	-1.165	-1.150	-1.175	-1.167	-1.165	0.011
TR0782	48.14000	-123.40194	-1.178	-1.216	-1.169	-1.198	-1.190	0.021
TR0783	48.14000	-123.40138	-1.178	-1.216	-1.169	-1.198	-1.190	0.021
TR0784	48.14055	-123.40888	-1.178	-1.221	-1.172	-1.205	-1.194	0.023
TR0785	48.14055	-123.40972	-1.177	-1.221	-1.172	-1.206	-1.194	0.024
TR0779	48.14055	-123.40250	-1.181	-1.220	-1.173	-1.203	-1.194	0.022
TR0911	48.16138	-123.72722	-1.152	-1.153	-1.162	-1.161	-1.157	0.005
TS0095	48.26055	-124.29861	-1.096	-1.100	-1.124	-1.112	-1.108	0.013
TS0099	48.26194	-124.30000	-1.098	-1.100	-1.123	-1.111	-1.108	0.012
TS0098	48.26361	-124.29944	-1.101	-1.102	-1.121	-1.109	-1.108	0.010
TS0101	48.26416	-124.29972	-1.101	-1.103	-1.121	-1.109	-1.108	0.009
TR0438	48.28444	-122.62166	-1.387	-1.389	-1.399	-1.400	-1.394	0.007
TR0440	48.28472	-122.61916	-1.394	-1.396	-1.404	-1.405	-1.400	0.006
TS0156	48.36555	-124.61666	-1.057	-1.047	-1.079	-1.071	-1.063	0.014
TS0161	48.36555	-124.62083	-1.058	-1.052	-1.070	-1.066	-1.061	0.008
AF8871	48.36583	-124.61722	-1.057	-1.049	-1.075	-1.068	-1.062	0.011
TS0154	48.36638	-124.61138	-1.058	-1.046	-1.080	-1.071	-1.064	0.015
TS0152	48.36694	-124.60416	-1.063	-1.052	-1.080	-1.072	-1.067	0.012
TS0340	48.36694	-124.61944	-1.058	-1.052	-1.070	-1.065	-1.061	0.008
TS0340	48.36694	-124.61944	-1.058	-1.052	-1.070	-1.065	-1.061	0.008
TS0150	48.36694	-124.60416	-1.063	-1.052	-1.080	-1.072	-1.067	0.012
AF8872	48.36805	-124.62388	-1.058	-1.054	-1.067	-1.064	-1.061	0.006
AF8873	48.36805	-124.62666	-1.058	-1.055	-1.064	-1.063	-1.060	0.004
TS0171	48.36833	-124.62305	-1.058	-1.054	-1.067	-1.064	-1.061	0.006
TR0236	48.39305	-122.49444	-1.351	-1.354	-1.362	-1.365	-1.358	0.006
TR0033	48.75055	-122.48138	-1.371	-1.363	-1.373	-1.370	-1.369	0.004
TR0031	48.75222	-122.48277	-1.368	-1.358	-1.371	-1.368	-1.366	0.006
TR0029	48.75333	-122.48472	-1.363	-1.352	-1.365	-1.362	-1.361	0.006
TR0628	48.99277	-122.76277	-1.353	-1.352	-1.367	-1.369	-1.360	0.009
TR0630	48.99277	-122.76305	-1.356	-1.355	-1.370	-1.372	-1.363	0.009
TR0632	48.99722	-122.75222	-1.357	-1.353	-1.393	-1.395	-1.375	0.023
TR0633	48.99722	-122.75222	-1.366	-1.362	-1.402	-1.404	-1.384	0.023
DC1339	32.57888	-117.13138	-0.763	-0.763	-0.763	-0.763	-0.763	0.000
DC1340	32.57972	-117.13111	-0.763	-0.763	-0.763	-0.763	-0.763	0.000
DC0888	32.71388	-117.17333	-0.760	-0.764	-0.765	-0.761	-0.763	0.002
DC1322	32.71555	-117.17250	-0.755	-0.768	-0.773	-0.771	-0.767	0.008
DC1313	32.86527	-117.25333	-0.772	-0.772	-0.777	-0.777	-0.774	0.003
DC1312	32.86583	-117.25305	-0.775	-0.775	-0.780	-0.780	-0.777	0.003

Bench-mark	Latitude	Longitude	From MLLW (m)	From MLW (m)	From MHW (m)	From MHHW (m)	Average (m)	Std. Dev. (m)
DC0986	32.86611	-117.25277	-0.774	-0.775	-0.780	-0.780	-0.777	0.003
DC1308	32.86611	-117.25305	-0.771	-0.772	-0.777	-0.777	-0.774	0.003
DC0990	32.86638	-117.25305	-0.771	-0.772	-0.777	-0.777	-0.774	0.003
DC1310	32.86638	-117.25250	-0.768	-0.769	-0.774	-0.774	-0.771	0.003
DX1969	33.60250	-117.88388	-0.790	-0.791	-0.790	-0.791	-0.790	0.001
DX3663	33.60250	-117.88333	-0.790	-0.791	-0.790	-0.791	-0.790	0.001
DX1968	33.60277	-117.88333	-0.790	-0.791	-0.790	-0.790	-0.790	0.001
DX3420	33.60305	-117.88222	-0.787	-0.788	-0.787	-0.787	-0.787	0.001
DX1967	33.60333	-117.88277	-0.790	-0.791	-0.790	-0.790	-0.790	0.001
DX1970	33.60361	-117.88416	-0.790	-0.791	-0.789	-0.790	-0.790	0.001
DY2509	33.70722	-118.27388	-0.787	-0.788	-0.786	-0.786	-0.787	0.001
DY2508	33.70777	-118.27500	-0.781	-0.782	-0.780	-0.780	-0.781	0.001
DY2507	33.70805	-118.27638	-0.778	-0.779	-0.777	-0.777	-0.778	0.001
DY2506	33.70861	-118.27722	-0.785	-0.787	-0.787	-0.787	-0.787	0.001
DY2505	33.70916	-118.27944	-0.775	-0.778	-0.785	-0.785	-0.781	0.005
DY1100	33.70944	-118.28277	-0.772	-0.776	-0.788	-0.787	-0.781	0.008
DY1099	33.71000	-118.28333	-0.790	-0.791	-0.789	-0.789	-0.790	0.001
DY1083	33.71972	-118.27166	-0.796	-0.797	-0.797	-0.797	-0.797	0.000
DY2515	33.72000	-118.27138	-0.796	-0.797	-0.797	-0.797	-0.797	0.000
DY1080	33.72055	-118.27138	-0.799	-0.800	-0.800	-0.800	-0.800	0.000
DY2514	33.72250	-118.27250	-0.799	-0.799	-0.800	-0.800	-0.800	0.000
DY2513	33.72472	-118.27333	-0.799	-0.799	-0.800	-0.800	-0.800	0.001
DY1085	33.72527	-118.27611	-0.796	-0.797	-0.798	-0.798	-0.797	0.001
DY9300	33.72666	-118.27138	-0.802	-0.801	-0.803	-0.803	-0.802	0.001
DY2512	33.72694	-118.27361	-0.796	-0.795	-0.797	-0.797	-0.796	0.001
EW1586	34.01027	-118.49555	-0.787	-0.784	-0.793	-0.787	-0.788	0.004
EW6485	34.34750	-119.44361	-0.834	-0.835	-0.833	-0.835	-0.834	0.001
EW6484	34.34777	-119.44388	-0.834	-0.835	-0.833	-0.835	-0.834	0.001
EW6804	34.35555	-119.44083	-0.824	-0.825	-0.823	-0.825	-0.824	0.001
EW6807	34.35555	-119.44000	-0.797	-0.798	-0.796	-0.798	-0.797	0.001
EW6481	34.35583	-119.44138	-0.821	-0.822	-0.820	-0.822	-0.821	0.001
EW6480	34.35611	-119.44138	-0.803	-0.804	-0.802	-0.804	-0.803	0.001
EW6488	34.35666	-119.43861	-0.827	-0.828	-0.826	-0.828	-0.827	0.001
EW6801	34.35666	-119.44083	-0.812	-0.813	-0.811	-0.813	-0.812	0.001
EW7026	34.41000	-119.69055	-0.823	-0.822	-0.824	-0.823	-0.823	0.001
EW3742	34.41250	-119.68750	-0.824	-0.823	-0.823	-0.823	-0.823	0.001
EW6796	34.41388	-119.68583	-0.827	-0.826	-0.826	-0.826	-0.826	0.000
EW3748	34.41472	-119.68472	-0.824	-0.823	-0.823	-0.823	-0.823	0.001

Table C2. Location and elevation information for NOAA tide gauges used to create the West Coast of the Continental United States TSS grids. MSL data are from CO-OPS and NAVD88 heights were calculated by NGS.

Station ID	Latitude (deg)	Longitude (deg)	MSL (m)	NAVD88 [GEOID03] (m)	NAVD88 [GEOID99] (m)	TSS [GEOID03] (m)	TSS [GEOID99] (m)
9410120	32.57830	-117.13500	1.695	0.930	0.946	-0.765	-0.749
9410170	32.71419	-117.17358	2.052	1.287	1.271	-0.765	-0.781
9410230	32.86670	-117.25800	2.163	1.389	1.353	-0.774	-0.811
9410580	33.60330	-117.88300	1.861	1.071	1.103	-0.790	-0.758
9410650	33.70670	-118.27300	11.029	10.244	10.233	-0.785	-0.796
9410660	33.72000	-118.27200	2.028	1.229	1.213	-0.799	-0.815
9410840	34.00830	-118.50000	1.594	0.802	0.802	-0.792	-0.792
9411270	34.34830	-119.44300	2.178	1.347	1.346	-0.831	-0.832
9411340	34.40830	-119.68500	1.824	1.003	1.017	-0.821	-0.807
9412110	35.17670	-120.76000	2.149	1.320	1.287	-0.829	-0.863
9412553	35.64170	-121.18800	1.523	0.615	0.542	-0.908	-0.981
9413450	36.60500	-121.88800	1.893	0.988	0.979	-0.905	-0.914
9413631	36.81830	-121.74700	2.662	1.788	1.793	-0.874	-0.869
9413663	36.85667	-121.75500	6.383	5.485	5.492	-0.898	-0.891
9414290	37.80670	-122.46500	2.773	1.804	1.736	-0.969	-1.036
9414317	37.79000	-122.38700	2.057	1.068	1.001	-0.989	-1.056
9414392	37.66500	-122.37700	1.711	0.730	0.691	-0.981	-1.020
9414458	37.58000	-122.25300	5.737	4.746	4.733	-0.991	-1.004
9414575	37.46500	-122.02300	1.388	0.123	0.136	-1.265	-1.252
9414632	37.59500	-122.14500	1.488	0.351	0.344	-1.137	-1.144
9414688	37.69500	-122.19200	2.634	1.627	1.596	-1.007	-1.038
9414711	37.73170	-122.20800	1.620	0.606	0.564	-1.014	-1.056
9414746	37.77170	-122.23500	1.542	0.561	0.507	-0.981	-1.035
9414750	37.77167	-122.29833	2.067	1.086	1.027	-0.981	-1.040
9414764	37.79500	-122.28200	2.369	1.385	1.321	-0.984	-1.048
9414782	37.81000	-122.36000	3.817	2.782	2.711	-1.035	-1.106
9414806	37.84670	-122.47700	1.890	0.903	0.831	-0.987	-1.059
9414816	37.86500	-122.30700	2.488	1.448	1.368	-1.040	-1.120
9414819	37.86500	-122.49300	4.247	3.251	3.179	-0.996	-1.068
9414837	37.89170	-122.44300	4.921	3.906	3.826	-1.015	-1.095
9414849	37.91000	-122.35800	16.048	15.060	14.973	-0.988	-1.075
9414863	37.92830	-122.40000	4.520	3.530	3.444	-0.990	-1.076
9414873	37.94500	-122.47500	3.411	2.423	2.345	-0.988	-1.066
9414881	37.95830	-122.42500	3.213	2.220	2.135	-0.993	-1.078
9414958	37.91000	-122.68200	1.437	0.328	0.303	-1.109	-1.134
9415020	37.99610	-122.97670	2.152	1.214	1.328	-0.938	-0.824
9415111	38.04330	-122.13000	9.621	8.560	8.454	-1.061	-1.167
9415112	38.04330	-121.91800	1.687	0.568	0.461	-1.119	-1.226
9415193	38.08670	-121.68500	3.998	2.639	2.526	-1.359	-1.472
9415218	38.07000	-122.25000	1.864	0.784	0.680	-1.080	-1.184
9415228	38.11330	-122.86800	2.980	2.037	2.128	-0.943	-0.852
9415252	38.11170	-122.49800	1.990	0.932	0.873	-1.058	-1.117
9415477	38.23170	-122.96800	4.843	3.514	3.661	-1.329	-1.182

Station ID	Latitude (deg)	Longitude (deg)	MSL (m)	NAVD88 [GEOID03] (m)	NAVD88 [GEOID99] (m)	TSS [GEOID03] (m)	TSS [GEOID99] (m)
9416841	38.91330	-123.70800	9.786	8.863	8.872	-0.923	-0.914
9418686	40.68670	-124.22200	1.879	0.923	0.798	-0.956	-1.081
9418723	40.72330	-124.22200	1.635	0.694	0.569	-0.941	-1.066
9418739	40.74000	-124.21200	2.170	1.221	1.100	-0.949	-1.070
9418767	40.76670	-124.21700	5.562	4.537	4.416	-1.025	-1.146
9418799	40.79830	-124.12000	1.350	0.377	0.290	-0.973	-1.060
9418801	40.80670	-124.16700	5.175	4.233	4.133	-0.942	-1.043
9418802	40.80670	-124.14200	2.017	1.041	0.948	-0.976	-1.069
9418817	40.82670	-124.18000	1.811	0.756	0.655	-1.055	-1.157
9418865	40.86500	-124.14800	1.816	0.826	0.741	-0.990	-1.075
9419059	41.05670	-124.14700	2.617	1.594	1.559	-1.023	-1.058
9419750	41.74500	-124.18300	2.254	1.240	1.342	-1.014	-0.912
9431647	42.73897	-124.49828	8.224	7.176	7.127	-1.048	-1.097
9432373	43.12000	-124.41300	0.968	-0.144	-0.215	-1.112	-1.183
9432780	43.34500	-124.32200	2.390	1.298	1.236	-1.092	-1.154
9432879	43.37670	-124.29700	2.140	1.045	0.982	-1.095	-1.158
9432895	43.41000	-124.21800	4.155	3.026	2.961	-1.129	-1.194
9435362	44.61670	-123.93700	2.051	0.866	0.907	-1.185	-1.144
9435380	44.62500	-124.04300	2.806	1.673	1.702	-1.133	-1.104
9435385	44.62670	-124.05500	2.785	1.679	1.707	-1.106	-1.079
9435827	44.81000	-124.05800	2.382	1.229	1.237	-1.153	-1.145
9439008	46.20670	-123.95000	3.902	2.571	2.539	-1.331	-1.363
9439011	46.20170	-123.94500	2.137	0.783	0.749	-1.354	-1.388
9439026	46.17170	-123.84200	1.969	0.595	0.551	-1.374	-1.418
9439040	46.20731	-123.76831	2.054	0.615	0.587	-1.439	-1.468
9439069	46.18670	-123.58800	2.199	0.654	0.629	-1.545	-1.570
9439201	45.86500	-122.79700	1.047	-1.281	-1.347	-2.328	-2.394
9440422	46.10830	-122.95700	1.382	-0.745	-0.797	-2.127	-2.179
9440569	46.26670	-123.45200	1.269	-0.286	-0.274	-1.555	-1.543
9440571	46.26500	-123.65300	2.311	0.941	0.943	-1.370	-1.368
9440574	46.27330	-124.07200	2.356	1.187	1.181	-1.169	-1.175
9440691	46.43000	-123.90300	2.514	2.020	2.067	-0.494	-0.447
9440747	46.50170	-124.02300	1.993	0.904	0.957	-1.089	-1.036
9440875	46.66330	-123.79800	3.046	1.821	1.888	-1.225	-1.158
9440910	46.70747	-123.96692	2.836	1.627	1.676	-1.209	-1.161
9441102	46.90431	-124.10508	2.386	1.215	1.205	-1.171	-1.181
9441187	46.96830	-123.85300	3.854	2.646	2.642	-1.208	-1.212
9442396	47.91330	-124.63700	2.943	1.773	1.767	-1.170	-1.176
9443090	48.36667	-124.61167	1.925	0.866	0.949	-1.059	-0.977
9443361	48.26330	-124.29700	6.326	5.233	5.284	-1.093	-1.042
9444090	48.12500	-123.44000	10.534	9.369	9.438	-1.165	-1.097
9444122	48.14000	-123.41300	2.519	1.334	1.402	-1.185	-1.118
9445133	47.74830	-122.72700	2.809	1.559	1.601	-1.250	-1.208

Station ID	Latitude (deg)	Longitude (deg)	MSL (m)	NAVD88 [GEOID03] (m)	NAVD88 [GEOID99] (m)	TSS [GEOID03] (m)	TSS [GEOID99] (m)
9445246	47.76170	-122.85000	2.660	1.407	1.467	-1.253	-1.193
9445478	47.35830	-123.09800	2.616	1.359	1.387	-1.257	-1.229
9445958	47.56170	-122.62300	2.719	1.408	1.413	-1.311	-1.306
9446281	47.38330	-122.82300	3.547	2.240	2.245	-1.307	-1.302
9446484	47.26667	-122.41333	2.268	0.932	0.879	-1.336	-1.389
9446545	47.25500	-122.43200	2.239	0.937	0.886	-1.302	-1.353
9446969	47.06000	-122.90300	2.281	0.962	0.980	-1.319	-1.301
9447110	47.58500	-122.36200	3.600	2.299	2.271	-1.301	-1.330
9447130	47.60264	-122.33931	4.443	3.134	3.105	-1.309	-1.338
9447427	47.81330	-122.38300	2.886	1.564	1.552	-1.322	-1.334
9447659	47.98000	-122.22300	1.896	0.540	0.508	-1.356	-1.388
9447729	48.04000	-122.16800	0.000	0.739	0.708	0.739	0.708
9447952	48.28670	-122.61700	2.687	1.290	1.279	-1.397	-1.408
9448576	48.40000	-122.54800	3.017	1.686	1.664	-1.331	-1.353
9448657	48.44500	-122.55500	2.667	1.320	1.296	-1.347	-1.371
9449211	48.74500	-122.49500	6.398	5.035	4.980	-1.363	-1.418
9449679	48.99170	-122.76500	2.238	0.878	0.763	-1.360	-1.476

APPENDIX D. Columbia River Datum to NAVD88 Data

Table D1. Columbia River Datum relative to NAVD88 along the river channel.

River Mile	Northing	Easting	CRD Relative to NAVD88 (feet)
Columbia River			
23	958799.9	7399110	-0.45
24	960371.5	7404198	-0.50
25	960654.8	7409387	-0.57
26	959901	7414658	-0.65
27	959147.4	7419930	-0.74
28	958990.8	7425258	-0.81
29	959380.9	7430605	-0.87
30	960791.2	7435722	-0.89
31	962718.5	7440685	-0.92
32	963946.3	7445778	-0.92
33	962925.2	7450907	-0.92
34	959469.3	7454810	-0.97
35	955224.7	7458025	-1.01
36	950862	7460962	-1.09
37	945599.3	7461774	-1.16
38	940365.2	7461371	-1.25
39	935145.5	7460331	-1.35
40	929959.4	7460340	-1.42
41	925811.5	7463671	-1.46
42	921720.7	7467080	-1.50
43	918149.6	7470831	-1.51
44	916632.6	7475935	-1.47
45	915261.1	7481073	-1.46
46	915023.9	7486388	-1.47
47	915206	7491699	-1.51
48	916327.2	7496902	-1.58
49	917769.6	7501980	-1.63
50	920738.9	7506400	-1.69
51	923668.1	7510760	-1.76
52	925872.1	7515687	-1.86
53	928046.7	7520547	-1.97
54	930221.3	7525408	-2.07
55	930634.9	7530568	-2.18
56	929840.1	7535833	-2.31
57	927594.3	7540443	-2.40
58	924170.7	7544522	-2.49
59	920747.2	7548601	-2.55
60	918359.1	7553303	-2.58
61	915164.6	7557505	-2.62
62	912026.7	7561757	-2.65
63	909667.9	7566507	-2.68

64	905678.1	7570034	-2.75
65	901688.2	7573561	-2.82
66	898537.8	7577780	-2.86
67	895954.4	7582349	-2.98
68	893531.1	7587006	-3.15
69	890926	7591546	-3.28
70	887041	7595017	-3.39
71	882242.5	7597070	-3.45
72	877046.5	7597671	-3.48
73	871810.7	7597921	-3.5
74	867642.9	7601046	-3.53
75	863470	7604126	-3.54
76	858397.9	7605481	-3.58
77	853325.8	7606836	-3.66
78	849280	7610128	-3.74
79	845310.8	7613564	-3.79
80	840484.4	7615446	-3.82
81	835253.6	7615712	-3.89
82	830103.5	7614864	-3.98
83	824957	7614585	-4.06
84	819776.2	7615435	-4.11
85	815098.8	7617779	-4.14
86	810362.6	7620001	-4.15
87	805157.6	7620059	-4.13
88	800130	7618782	-4.16
89	795244.7	7616878	-4.2
90	790058.1	7616883	-4.22
91	785332.3	7619084	-4.24
92	780817.6	7621763	-4.27
93	776158.8	7624107	-4.3
94	771031.1	7625016	-4.32
95	765781.5	7625077	-4.35
96	760589.2	7624693	-4.34
97	755527.5	7623300	-4.39
98	750465.6	7621907	-4.46
99	745383.6	7620642	-4.54
100	740186.9	7621053	-4.62
101	735171.7	7622606	-4.71
102	731229.7	7625774	-4.86
103	728874.9	7630376	-4.95
104	726957.7	7635253	-5.06
105	724026.8	7639571	-5.15
106	720998.5	7643665	-5.24
107	718630.6	7648384	-5.36
108	716296.6	7653121	-5.48
109	714597.9	7658103	-5.61
110	713201.5	7663200	-5.73
111	712305.1	7668392	-5.83
112	711732.5	7673604	-5.93
113	709847.3	7678514	-6.04

114	707614.5	7683266	-6.16
115	705740.3	7688119	-6.28
116	704635.6	7693250	-6.36
117	702223.6	7697915	-6.42
118	698923.8	7701996	-6.49
119	698130.3	7706983	-6.55
120	699285.2	7712109	-6.61
121	700859	7717099	-6.94
122	701072.6	7722197	-7.07
123	699340.1	7727130	-7.19
124	695015.2	7729768	-7.33
125	692081.3	7733660	-7.46
126	690850.4	7738769	-7.61
127	689701.6	7743869	-7.76
128	689418.5	7749000	-7.92
129	690948.8	7754053	-8.06
130	692964.6	7758927	-8.23
131	695319.6	7763640	-8.42
132	698199	7767913	-8.61
133	701029.4	7772218	-8.68
134	702027.9	7777381	-8.72
135	703083.1	7782535	-8.75
136	702360.1	7787729	-8.8
137	703377.7	7792839	-8.99
138	706154.9	7797319	-9.01
139	708916.5	7801804	-9.04
140	711726	7806287	-9.11
141	713390.9	7811263	-9.17
142	714254.6	7816455	-9.22
143	716082.8	7821361	-9.69
144	718681.2	7825923	-10.77
145	722429.9	7829584	-11.78
Willamette River			
0	733440.9	7623141	-4.77
1	728956.3	7620692	-4.9
2	725511.4	7616856	-5.02
3	720543.6	7616073	-5.14
4	715476.1	7617214	-5.12
5	710842.7	7619555	-5.15
6	706910.3	7622929	-5.17
7	703980.8	7627188	-5.19
8	700363.4	7630936	-5.21
9	696891.3	7634786	-5.22
10	693970.6	7639053	-5.22
11	690141.8	7642576	-5.25
12	686281.7	7645978	-5.26
13	681547.5	7645656	-5.34
14	676226.4	7646980	-5.43
15	671208.6	7645643	-5.5

16	665920.5	7646473	-5.58
17	660862.9	7647052	-5.59
18	656145	7649460	-5.65
19	652711.7	7650040	-5.73
20	648439.3	7648919	-5.81
21	643312.6	7647928	-5.89
22	640007.5	7651965	-5.96
23	636503.6	7655755	-6.02
24	631406.1	7657199	-6.09
25	628249.1	7660897	-6.15
26	624351.6	7660199	-6.23