NOAA Technical Report NOS CS 25

VDATUM FOR THE SAN JUAN ISLANDS AND THE STRAIT OF JUAN DE FUCA WITH UPDATES FOR PUGET SOUND: TIDAL DATUM MODELING AND POPULATION OF THE GRIDS

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
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ABSTRACT

The generation and population of the VDatum marine grids for the Strait of Juan de Fuca, Northern Puget Sound and Southern Puget Sound are discussed. For the Strait of Juan de Fuca region, the tidal datum information used to populate the VDatum marine grids came from a harmonic constant data set derived from a hydrodynamic model of the area developed at Fisheries & Oceans Canada Institute of Ocean Sciences. For the northern and southern reaches of Puget Sound, beyond the extent of the hydrodynamic model, a spatial interpolation of the datums computed at NOAA water level stations was used to determine tidal datum fields. The model of southern Puget Sound is an update to a previously generated spatial interpolation from 2004. All three sources were then used to populate the VDatum marine grids for those regions. A continuous topography of the sea surface was calculated across the three regions for inclusion in the VDatum software package.

Key Words: tides, tidal datums, San Juan Islands, Strait of Juan de Fuca, Puget Sound, North American Vertical Datum of 1988, mean sea level, spatial interpolation.

1. INTRODUCTION

A vertical datum transformation tool called VDatum is being developed by the National Ocean Service (NOS) to allow for the transformation between ellipsoidal, orthometric, and tidal datums (Milbert, 2002; Parker, 2002). The ellipsoidal and orthometric datum fields, and the transformations between these two types of datums, have already been established on national-scale grids. The transformations among tidal datums relative to Local Mean Sea Level (LMSL) and the transformations between LMSL and the North American Vertical Datum of 1988 (NAVD 88) are under development. This paper discusses the continuing work on the tidal datum transformations and the connection between LMSL and NAVD 88 for the following areas:

- the Strait of Juan de Fuca (including the San Juan Islands and the southern Strait of Georgia),
- Northern Puget Sound (including Padilla Bay, Deception Pass, Skagit Bay, Saratoga Passage, and Port Susan), and
- Southern Puget Sound (including Admiralty Inlet, Possession Sound, Hood Canal, East Passage, Colvos Passage, The Narrows, Cast Inlet, and Carr Inlet).

These areas are shown in Figure 1.

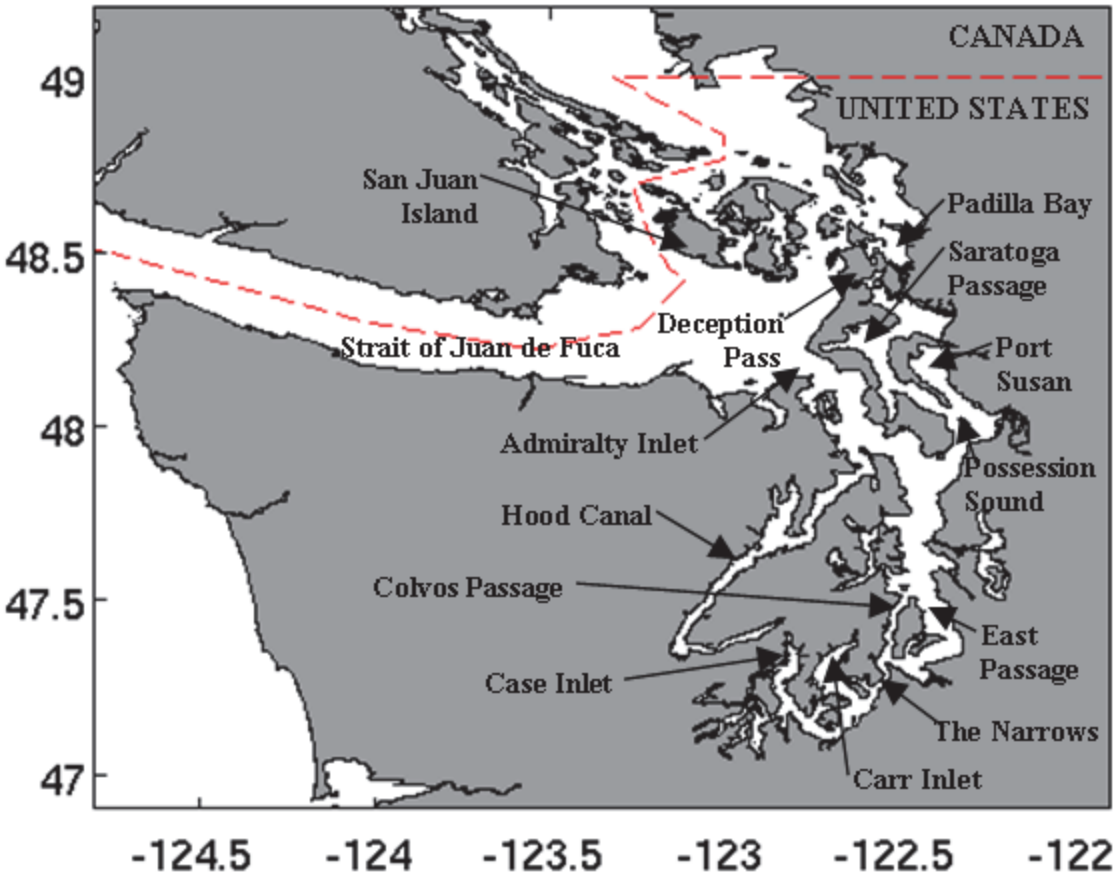

Figure 1. VDatum region with border between the United States and Canada delineated.

For the Strait of Juan de Fuca region, the tidal datums were computed from a harmonic constant database derived from a two-dimensional model of the region. The harmonic analysis results were used to construct a water level time series at each node in the model grid. These water level records were then analyzed to compute the tidal datums for that point. The modeled tidal datum fields were corrected to match datum information at NOS water level stations using a spatial interpolation method. Details of this process will be discussed in section 2 of this report. For both Puget Sound regions, a spatial interpolation method was used to compute the tidal datum fields directly from the NOS water level stations in the areas. The datums created from the spatial interpolation in both Northern and Southern Puget Sound were adjusted to match the corrected tidal datums in the Strait of Juan de Fuca region. This guaranteed there were no discontinuities at the boundaries. Section 3 of this report details the modeling efforts in Northern Puget Sound, and the model of the Southern Puget Sound region is discussed in Section 4.

After the modeling efforts were completed, the VDatum marine grids, used in the VDatum software package, were created and populated with the final model results. Two regularly spaced VDatum marine grids were created; one that combined the Strait of Juan de Fuca and Northern Puget Sound modeling efforts and a second marine grid was populated with tidal datum fields from the Southern Puget Sound model. Details of this process will be discussed in Section 5 of this report.

To complete the files need for the VDatum transformation software, a gridded Topography of the Sea Surface (TSS) was created for each of the VDatum marine grids using the available benchmark data. The two surfaces were checked to guarantee a continuous surface across the interface of the two grids. This process is explained in Section 6.

2. STRAIT OF JUAN DE FUCA REGION TIDAL DATUM MODELING

2.1. Selecting a Model

Sets of harmonic constants from three different shelf-scale hydrodynamic models of the Eastern North Pacific Ocean were available for use in this study. These models will be referred to as the Foreman model (Foreman et al., 2000), the Myers model (Myers and Baptista., 2001), and the Spargo model (Spargo et al., 2004). These models all covered approximately the same area: the northern boundaries run along the Aleutian Islands in Alaska and they all cover the western Canadian and U.S. shorelines. They are all finite element models; the Foreman model ran the FUNDY5SP code and the other two models ran the ADCIRC 2DDI code. The Foreman model assimilated TOPEX/POSEIDON data, the Myers model used an inversion technique to incorporate the same data, and the Spargo model did not use any data assimilation techniques.

Twenty-two NOS water level stations with tidal datum values were found that reside within, or very near to the boundaries of, the areas common to all three models or very near to the boundaries of one or more of the models. A root mean square (RMS) error analysis was conducted of the model results as compared to the station data for the four main tidal datums (Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Low Water (MLW), and Mean Lower Low Water (MLLW)). The Foreman model had the lowest RMS error (15.1 cm), the Myers model had a slightly larger error (17.9 cm), and the Spargo model had the largest error (28.3 cm). An analysis of the absolute average error between the models and the station data at the same 22 locations for the four main datums provided another metric for model comparison. Again, the Foreman model performed the best with the lowest absolute average error (13.2 cm). This time the Spargo model was the second best (22.0 cm) and the Myers model had the largest error (31.6 cm). Due to the results of these analyses, the Foreman model results were chosen to be used for this project. The errors at each of the 22 stations are listed in Appendix A, Table A.1.

2.2. Original Model Results

The Foreman model was originally run for a tidal modeling study of the northeast Pacific Ocean. This model assimilated tidal harmonics computed from the analysis of TOPEX/Poseidon satellite altimeter observations. Details of the model set-up and run for the original study can be found in Foreman et al. (2000). The triangulated mesh for this model covered the coastal and open ocean waters along the southern side of the Aleutian Islands, Alaska, in the north down to southern California in the south. A subsection of the larger grid was extracted for this project (Figure 2). This smaller mesh contains 13,656 nodes and 22,900 elements. The MHW shoreline, also shown in Figure 2, is the Extracted Vector Shoreline (EVS) along the U.S. coastline and the World Vector Shoreline (WVS) from the National Geophysical Data Center (NGDC) along the Canadian coastline. As evident by the figure, the Foreman model domain did not cover the entire VDatum region; it only provided coverage for the Strait of Juan de Fuca and the San Juan Islands regions.

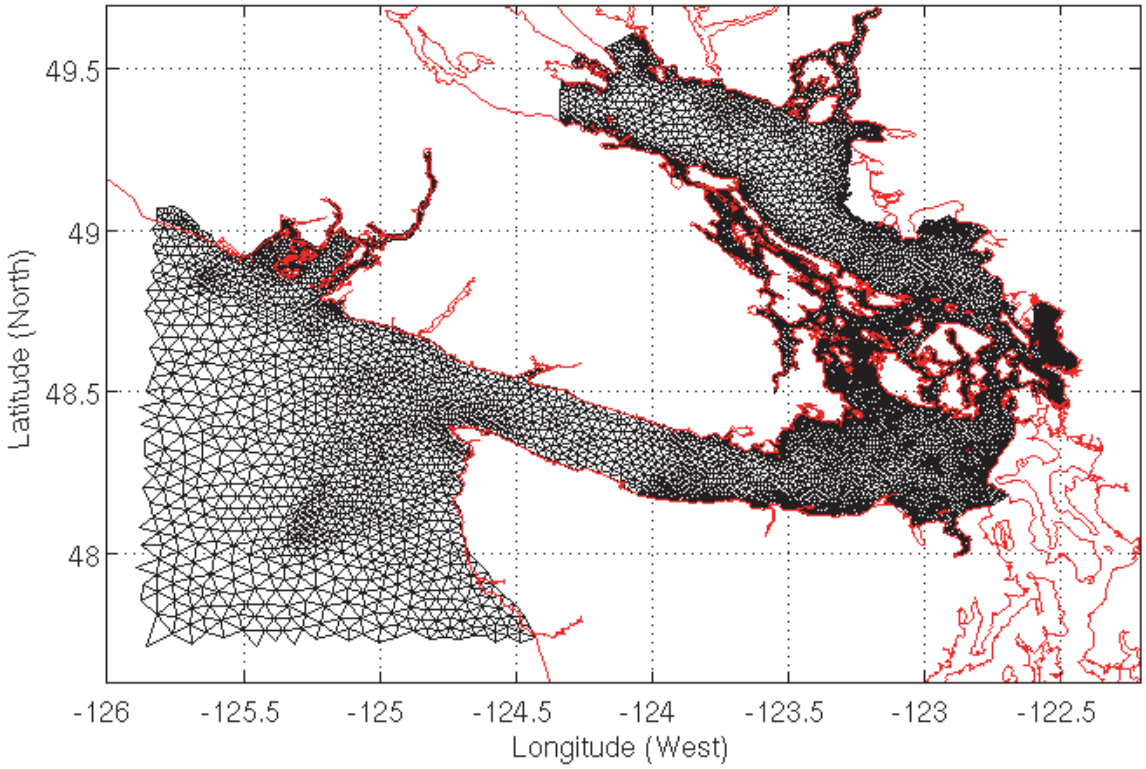

Figure 2. Section of the Foreman grid used for computing the tidal datums for the VDatum grid with the MHW shoreline.

The Foreman model provided amplitude and Greenwich phase values of the following harmonic constants at every node in the mesh: K_1, O_1, P_1, Q_1, M_2, S_2, N_2, and K_2. A Center for Operational Oceanographic Products and Services' (CO-OPS) prediction program (pred.f) was used to construct 30-day long, 6-minute interval water surface elevation time series for each node in the mesh from this data (Zervas, 1999). The equilibrium arguments and node factors for the time series were set to match those for the end of 1992, which is the middle year of the 1983 – 2001 National Tidal Datum Epoch when the node factors for the major harmonic constants is close to 1.0. Each time series was then analyzed to calculate the tidal datums at every node by picking off the higher-high, lower-high, higher-low, and lower-high waters. The datums computed were MHW, MHHW, MLW and MLLW, all relative to MSL.

2.3. Comparison to NOS Water Level Stations and Model Correction

Initially, all NOS water level stations within the Foreman model boundary were selected from a Coast Survey Development Laboratory (CSDL) database from August 2005. For this task, the boundary was defined as a box between 48.0º N and 49.0º N latitude and between 126.3º W and 122.4º W longitude. If more than one station occupied the same location, the station with the largest NOS identification number (presumably having the most recent or longest-running record) was kept and the other stations were eliminated. In total, 41 stations were found. These stations were then compared to the Foreman model mesh, and stations that were more than 800 m from the boundary of the grid as compared to the nearest grid

point were eliminated. Thirty-one NOS water level stations remained. Next, station data were examined for completeness and redundancy. The Argyle North Bay station (#9449822) on San Juan Island was eliminated from this group because of incomplete data: there is tidal datum information for MHHW, MHW, MLW, and MLLW, but no reference for MSL, Mean Tide Level (MTL) or Diurnal Tide Level (DTL). The Shannon Point station (#9448773) was also eliminated due to its redundancy with the Ship Harbor, Fidalgo Island station (#9448772). These two stations have the same datums, and are in close proximity to each other. The remaining 29 stations are shown in Figure 3. The points are labeled with the last four digits of the station identification number. (The first three digits of this number are "944".) The locations and names are listed in Table 1, and tidal datum values are listed in Appendix A, Table A.2.

Of the 29 stations in this region, 15 stations have been updated to the 1983-2001 NTDE from the 1960-1978 NTDE. (For more information about the updating process see NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) website at: http://140.90.121.76/datum_update.shtml.) Although it would be best to use only data from the latest tidal epoch, it was assumed that if the adjustment to the new epoch was small enough, then the older epoch were still valid, and could be used for model validation and correction. To find that adjustment, the 15 stations with datum records from both epochs were compared. Table 2 shows the results of this analysis. The great diurnal tidal range, which is MHHW minus MLLW, was calculated for each epoch. The ratio of the new range versus the old range, the differences between the two, and the absolute average percent difference were computed as well. The average absolute average percent difference is 0.43%. This is considered to be an insignificant change and it was decided that all the data could be used, no matter which epoch it was associated with.

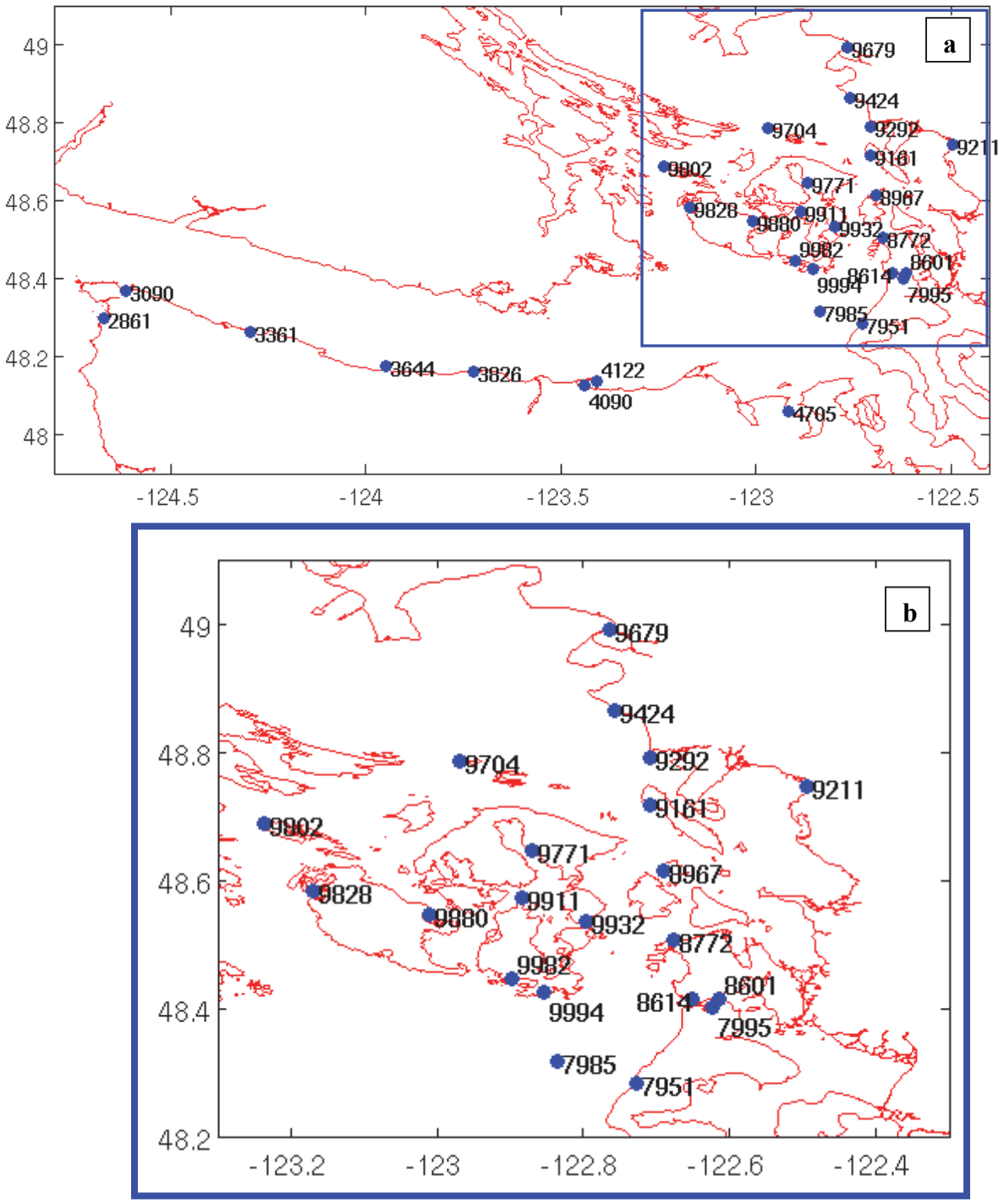

Figure 3. MHW coastline with (a) the location of NOAA tide gages and (b) a zoomed view, with the last four digits of the station identification number listed. The first three digits of this number are "944".

Table 1. Station point numbers shown in Figure 3 with station name, station identification number and location. Station numbers marked with an asterisk (*) indicate stations that have been updated to the 1983-2001 National Tidal Datum Epoch.

Point Number	Station ID Number	Station Name	Latitude (degrees)	Longitude (degrees)
1	9442861	Mukkaw Bay	48.2967	-124.6717
2	9443090*	Neah Bay	48.3683	-124.6167
3	9443361*	Sekiu Clallam Bay	48.2633	-124.2967
4	9443644	Twin Rivers	48.1750	-123.9500
5	9443826*	Crescent Bay	48.1617	-123.7250
6	9444090*	Port Angeles	48.1250	-123.4400
7	9444122*	Ediz Hook	48.1367	-123.4083
8	9444705	Gardiner Landing	48.0583	-122.9167
9	9447951	Whidbey Island, Sunset Beach	48.2833	-122.7283
10	9447985	Smith Island	48.3167	-122.8367
11	9447995	Whidbey Island, Coronet Bay	48.4017	-122.6233
12	9448601	Yokeko Point	48.4133	-122.6150
13	9448614*	Reservation Bay	48.4150	-122.6517
14	9448772	Fidalgo Island, Ship Harbor	48.5067	-122.6767
15	9448967	Sinclair Island	48.6150	-122.6917
16	9449161*	Lummi Island	48.7167	-122.7083
17	9449211*	Bellingham	48.7450	-122.4950
18	9449292*	Lummi Bay	48.7900	-122.7083
19	9449424*	Cherry Point	48.8633	-122.7583
20	9449679*	Blaine	48.9917	-122.7650
21	9449704	Patos Island	48.7867	-122.9700
22	9449771	Orcas Island	48.6467	-122.8700
23	9449802	Stuart Island	48.6883	-123.2367
24	9449828*	Hanbury Point	48.5817	-123.1700
25	9449880*	Friday Harbor	48.5467	-123.0100
26	9449911	Lopez Isl., Upright Head	48.5717	-122.8850
27	9449932*	Armitage Island	48.5350	-122.7967
28	9449982*	Lopez Island, Richardson	48.4467	-122.8983
29	9449994	Lopez Island, Aleck Bay	48.4250	-122.8533

Table 2. Great diurnal range of tidal datums from 1960-1978 NTDE and 1983-2001 NTDE for 15 stations, with ratio of range, difference, and absolute average percent difference.

Station	Range(m)	Epoch	Range(m)	Epoch	Ratio	Diff(m)	Pct
9443090	2.425	1960	2.425	1983	1.000	0.000	0.00%
9443361	2.286	1960	2.286	1983	1.000	0.000	0.00%
9443826	2.134	1960	2.151	1983	1.008	-0.017	0.81%
9444090	2.143	1960	2.153	1983	1.005	-0.010	0.48%
9444122	2.124	1960	2.135	1983	1.005	-0.011	0.50%
9448614	2.338	1960	2.352	1983	1.006	-0.014	0.60%
9449161	2.627	1960	2.637	1983	1.004	-0.010	0.37%
9449211	2.579	1960	2.594	1983	1.006	-0.015	0.60%
9449292	2.734	1960	2.749	1983	1.005	-0.015	0.55%
9449424	2.774	1960	2.788	1983	1.005	-0.014	0.51%
9449679	2.89	1960	2.905	1983	1.005	-0.015	0.53%
9449828	2.307	1960	2.325	1983	1.008	-0.018	0.76%
9449880	2.353	1960	2.364	1983	1.005	-0.011	0.46%
9449932	2.387	1960	2.391	1983	1.002	-0.004	0.17%
9449982	2.181	1960	2.185	1983	1.002	-0.004	0.18%
Average =					**1.004**	**0.011**	**0.43%**

The differences between the model results and the data at all 29 NOS water level stations were used to create a spatially interpolated error field. The error for each tidal datum was defined as the difference between the published NOS datum compared to mean sea level (i.e. MHHW-MSL, MHW-MSL, MLW-MSL, and MLLW-MSL) and the modeled datum compared to MSL. The error field was computed using the Tidal Constituent And Residual Interpolation (TCARI) program. TCARI solves Laplace's Equation and takes landforms into account to create smooth, interpolated fields (Hess, 2002). For all runs discussed, the boundary condition parameter (α) was set to the recommended value of 0.9. A finite element implementation of the TCARI program was used so that the spatial interpolation could be computed directly on the section of the unstructured mesh that was extracted from the Foreman model grid. The input to the TCARI program was the error values at the nodes nearest the NOS station locations and the output was the error fields, which were defined at every node in the mesh.

The model results and the station data for every station and every datum are listed in Appendix A, Table A.2. The highest errors are at Yokeko Point (#9448601) and Coronet Bay on Whidbey Island (#9447995), which are both at the very edge of the grid in Deception Pass. The model underpredicts the measured datums by between 22 and 42 cm (or about 26% to 37% of the tidal signal). If these two stations are excluded from the analysis, the average absolute difference is 8.2 cm for MHHW, 7.4 cm for MHW, 5.6 cm for MLW, and 3.7 cm for MLLW. Based on experience from the development of other models for the VDatum project, it has been decided that an absolute average difference error less than 10 cm is acceptable; and ideally, there would be less than 5 cm of error at every station for every datum.

The final tidal datum fields were computed by subtracting the spatially interpolated error results from the Foreman model results. These results will be called the corrected Foreman model results. Figure 4 shows the modeled MLLW field, the error field resulting from the TCARI interpolation of the MLLW error at 29 stations, and the corrected MLLW field. After all the corrected datum fields were computed, the MTL and DTL fields were created by calculating MTL and DTL at every node in the mesh based on the following formulas: MTL=1/2[MHW + MLW] and DTL=1/2[MHHW + MLLW].

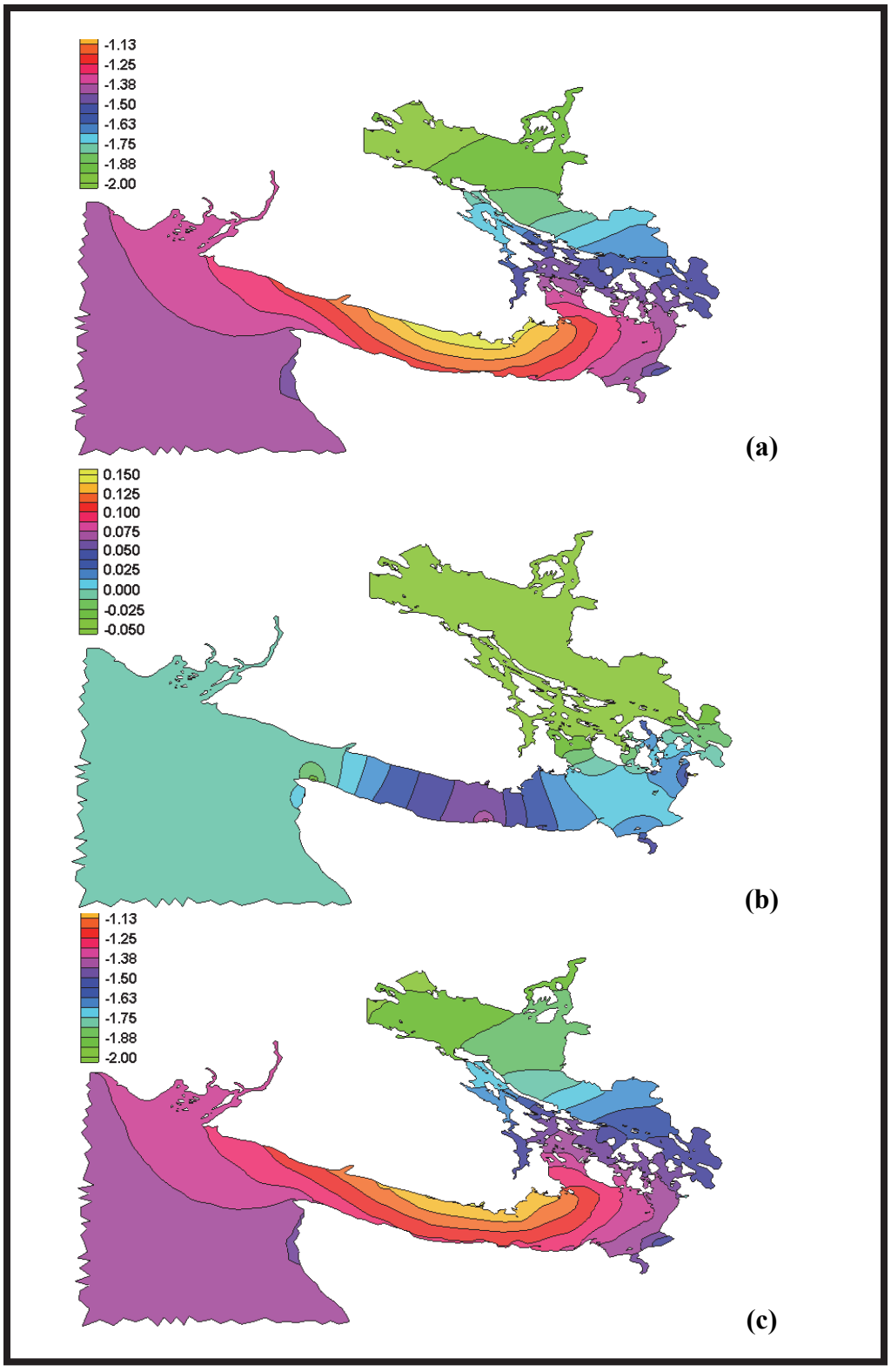

Figure 4. (a) Modeled MLLW (meters) field, (b) spatially interpolated error between modeled results and NOS water level station MLLW values (meters), and (c) corrected MLLW (meters) field over the Foreman model domain.

3. NORTHERN PUGET SOUND TIDAL DATUM MODELING

As Foreman model does not extend into Northern Puget Sound (nor do the Myers and Spargo tide models), another approach for computing tidal datums was developed for this area. The TCARI method, briefly discussed in the previous section, was applied in this region. In the previous section, the TCARI method was used to spatially interpolate the error between the hydrodynamic model results and the NOS water level station data. For the Northern Puget Sound region, TCARI was used to spatially interpolate the actual tidal datums directly from NOS water level data throughout the domain. The resulting datum fields match the datums at the NOS water level station locations and follow the solution to Laplace's Equation elsewhere.

Since the TCARI model can be implemented using the finite element method, a triangular mesh was created for this region which includes all of the Northern Puget Sound Region (i.e. Padilla Bay, Deception Pass, Skagit Bay, Saratoga Passage, and Port Susan. See Figure 1 for locations) and extends further south into Southern Puget Sound to include Possession Inlet and Admiralty Inlet. The triangulated mesh and the EVS MHW shoreline are shown in Figure 5. The elements range in size from about 1 km down to 50 m with an average node to node spacing of 550 m. The nodal locations of the boundaries in Admiralty Inlet, Padilla Bay and in the Strait of Juan de Fuca just west of Deception Pass match those on the Foreman model mesh.

To identify NOS water level stations available for the TCARI model, a region was defined by the area between 47.72º N and 48.51º N latitude and between 122.80º W and 122.18º W longitude using a CSDL database from August 2005. If more than one station occupied the same location, the station with the largest NOS identification number (presumably having the most recent or longest-running record) was kept and the other stations were eliminated. In total, 33 stations were found. These stations were then compared to the triangulated mesh developed for this area, and stations that were more than 800 m off the grid were eliminated. Twenty-six NOS water level stations remained. These stations are shown as blue dots in Figure 6 labeled with the last 4 digits of the station identification number. (The first three digits of this number are "944".) The location and names of these stations are listed in Table 3, and the 3 stations that are duplicates of those in the Foreman model region (as listed in Table 1) are marked as such. In order to make sure that the TCARI model output matched the corrected Foreman model discussed in the previous section, the tidal datum results from the corrected Foreman model were used at the northern boundaries (in Admiralty Inlet, west of Deception Pass and in Padilla Bay) as data points for the TCARI model run. (No data points were used at the southern boundary into southern Puget Sound.) These boundary points are shown as red dots in Figure 6 and are numbered from one to thirty. Only the locations of the NOS water level stations (blue dots in Figure 6) are listed in Table 3. The locations of the other points, as well as the datum information used for every point shown in Figure 6, are listed in Appendix A, Table A.3.

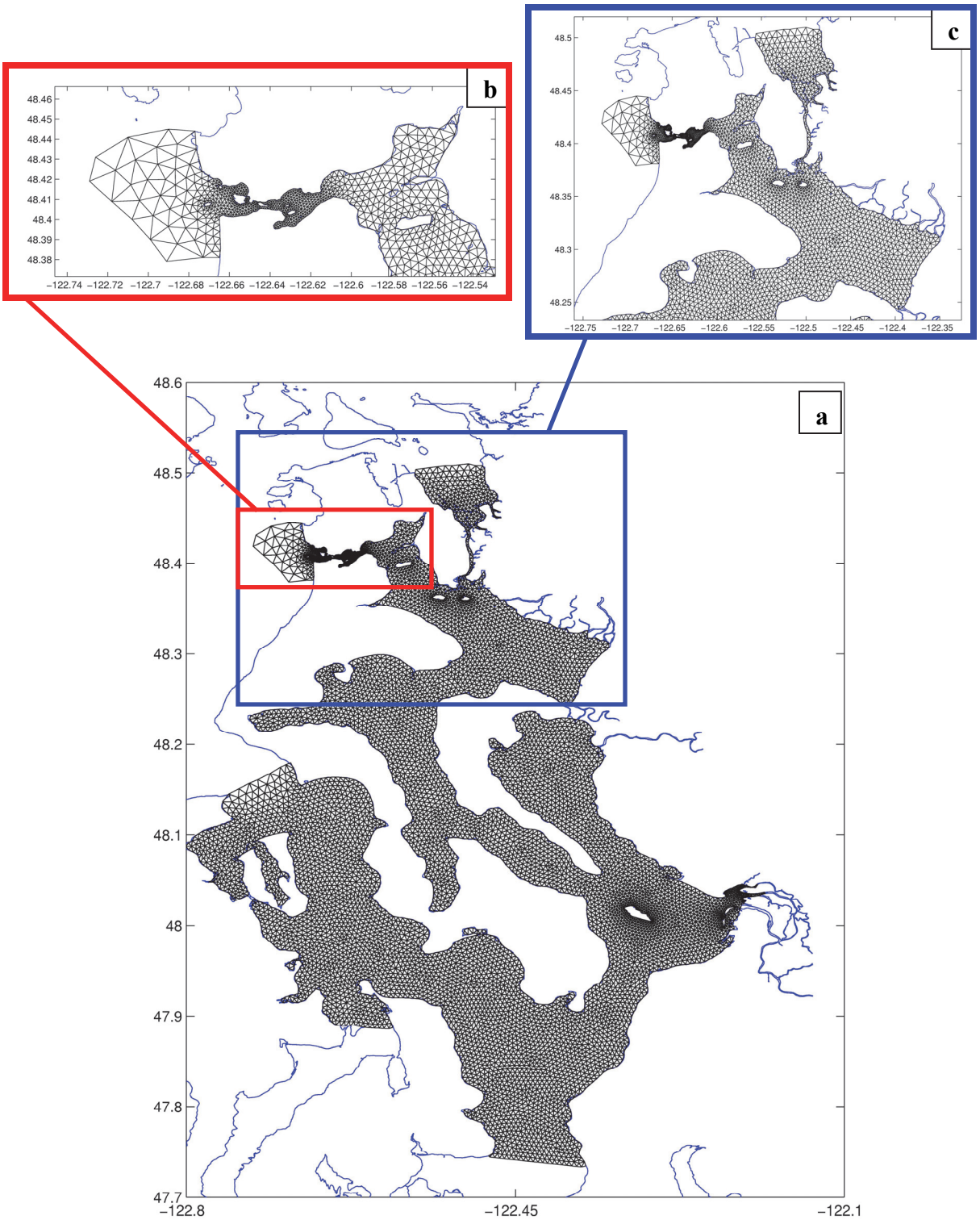

Figure 5. Finite element mesh for the TCARI model for the (a) entire northern Puget Sound area with the MHW shoreline in blue, and (b), (c) zoomed views of the mesh.

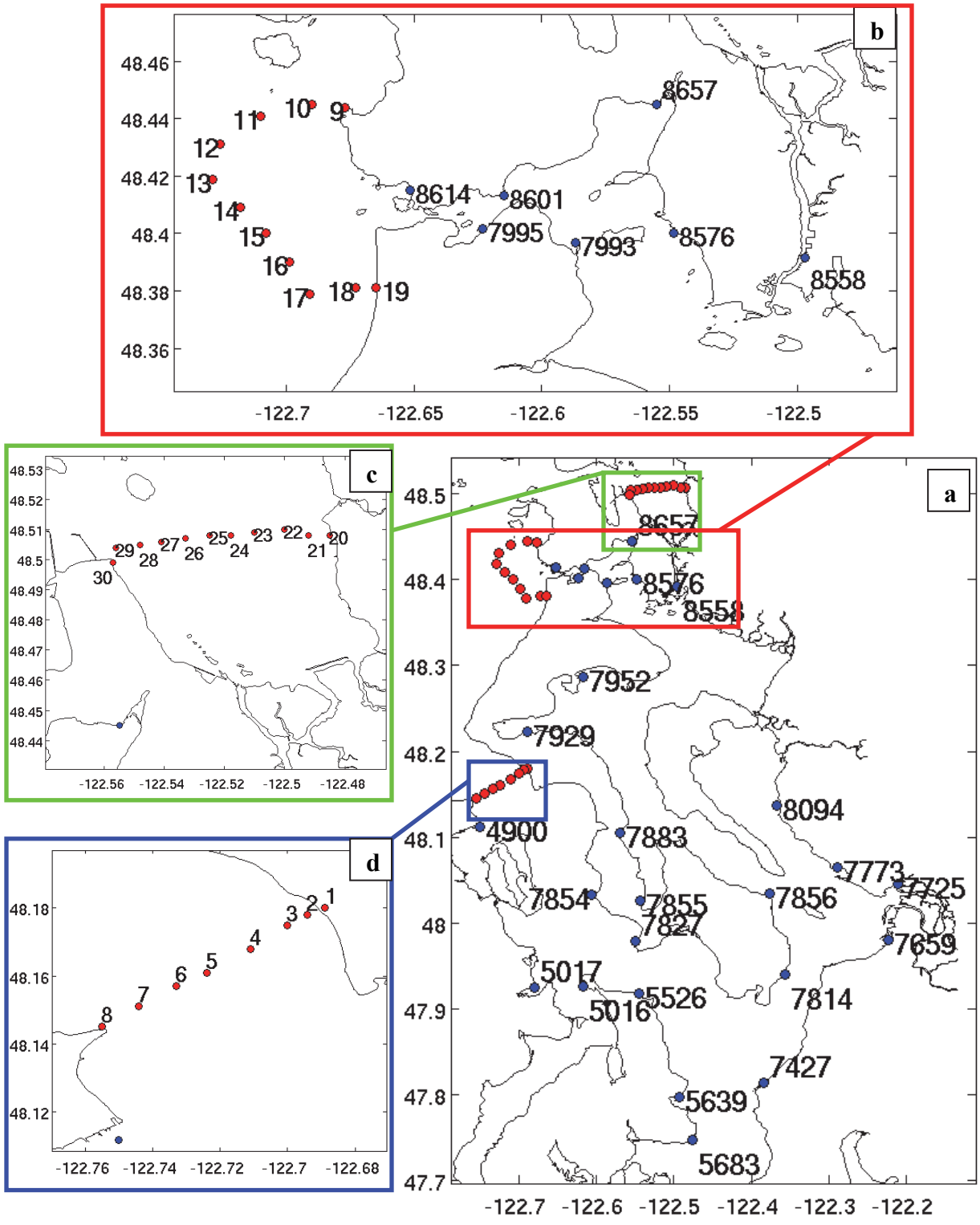

Figure 6. MWH coastline with (a) the location of NOAA tide gages (in blue) referenced by the last 4 digits of the station identification number where the first 3 digits are "944" and boundary forcing points (in red) labeled from one to thirty, and (b), (c), and (d) zoomed views of the other forcing stations.

Table 3. Stations shown in Figure 6 (as blue dots) with station name and identification number, and location. Stations marked with an asterisk (*) indicate stations that have been updated to the 1983-2001 National Tidal Datum Epoch, and station numbers marked with a plus (+) indicated stations that duplicate those listed in Table 1.

	Station ID Number	Station Name	Longitude (degrees)	Latitude (degrees)
1	9444900*	Port Townsend	48.1117	-122.7500
2	9445016	Foulweather Bluff	47.9267	-122.6167
3	9445017	Port Ludlow	47.9250	-122.6800
4	9445526*	Hansville	47.9183	-122.5450
5	9445639	Apple Tree Cove	47.7967	-122.4933
6	9445683	Point Jefferson	47.7467	-122.4767
7	9447427	Edmonds	47.8133	-122.3833
8	9447659*	Everett	47.9800	-122.2233
9	9447725	Ebey Slough	48.0450	-122.2100
10	9447773	Tulalip Bay	48.0650	-122.2883
11	9447814*	Glendale	47.9400	-122.3567
12	9447827	Double Bluff	47.9783	-122.5500
13	9447854*	Bush Point	48.0333	-122.6067
14	9447855	Holly Harbor Farms	48.0267	-122.5433
15	9447856	Sandy Point	48.0350	-122.3767
16	9447883	Greenbank	48.1050	-122.5700
17	9447929	Coupeville Penn Cove	48.2233	-122.6900
18	9447952*	Crescent Harbor	48.2867	-122.6167
19	9447993	Ala Spit	48.3967	-122.5867
20	9447995+	Coronet Bay	48.4017	-122.6233
21	9448094	Port Susan	48.1367	-122.3667
22	9448558*	Swinomish Slough	48.3917	-122.4967
23	9448576*	Sneeoosh Point	48.4000	-122.5483
24	9448601+	Yokeko Point	48.4133	-122.6150
25	9448614*+	Reservation Bay	48.4150	-122.6517
26	9448657*	Turner Bay	48.4450	-122.5550

Of the 26 stations in this region, 10 stations have been updated to the 1983-2001 NTDE from the 1960-1978 NTDE. The 10 stations with datum records from both epochs were compared. Table 4 shows the results of this analysis. The great diurnal tidal range, which is the difference between MHHW and MLLW, was calculated for each epoch. The ratio of the new range versus the old range, the differences between the two and the absolute average percent difference were computed as well. The average absolute mean percent difference is 0.26%. This was considered to be an insignificant change and it was decided that all the data could be used, no matter which epoch it was associated with.

The TCARI model was run once for each tidal datum with input stations at the 26 NOS water level gage locations and the 30 Foreman model nodes. Once these datum fields were computed, the MTL and DTL fields were calculated as: MTL=1/2[(MHW)+(MLW)] and DTL=1/2[(MHHW)+(MLLW)].

Table 4. Great diurnal range of tidal datums from 1960-1978 NTDE and 1983-2001 NTDE for 10 stations in Northern Puget Sound, with ratio of range, difference, and absolute average percent difference.

Station	Range(m)	Epoch	Range(m)	Epoch	Ratio	Diff(m)	Pct
9444900	2.576	1960	2.596	1983	1.008	-0.020	0.77%
9445526	3.182	1960	3.18	1983	0.999	0.002	0.06%
9447659	3.386	1960	3.38	1983	0.998	0.006	0.18%
9447814	3.359	1960	3.364	1983	1.002	-0.005	0.15%
9447854	2.848	1960	2.85	1983	1.001	-0.002	0.07%
9447952	3.551	1960	3.554	1983	1.001	-0.003	0.08%
9448558	3.152	1960	3.154	1983	1.001	-0.002	0.06%
9448576	3.377	1960	3.369	1983	0.998	0.008	0.24%
9448614	2.338	1960	2.352	1983	1.006	-0.014	0.60%
9448657	3.165	1960	3.152	1983	0.996	0.013	0.41%
Average =					**1.001**	**0.008**	**0.26%**

The results from the spatially interpolated MLLW field are shown in Figure 7. The TCARI model results match the data from the corrected Foreman model at the boundaries in Admiralty Inlet, west of Deception Pass and in Padilla Bay .

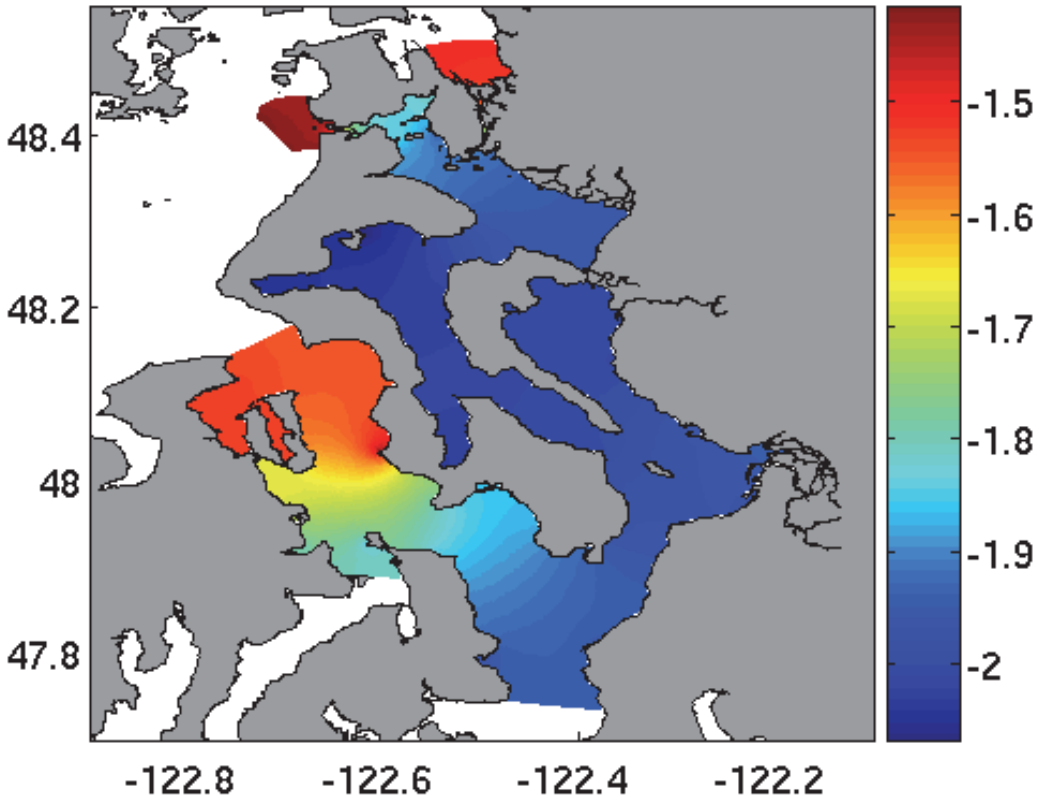

Figure 7. MLLW tidal datum field (in meters) from the TCARI model using 56 input data stations (30 nodes along the boundary and 26 interior points at NOS water level gages).

4. SOUTHERN PUGET SOUND TIDAL DATUM MODELING

In response to the development of VDatum for the Strait of Juan de Fuca and Northern Puget Sound, the existing tidal datum fields initially generated for Southern Puget Sound (Hess and White, 2004) were updated using input data from (1) the new tidal datum fields in Admiralty Inlet from the corrected Strait of Juan de Fuca regional model and in Saratoga Passage, and Port Susan from the Northern Puget Sound regional model (see Figure 1), and (2) the data at tide stations with updates to the latest National Tidal Datum Epoch (1983-2001) in the interior of the domain. Using these new input stations at the boundary and the updated datums at stations in the interior of the domain, revised tidal datum fields were generated by TCARI spatial interpolation for the Southern Puget Sound region.

4.1. Input Tidal Datum Values

A CSDL database (from June 2005) of NOS water level stations was searched to select all available stations between 47.0167º N and 48.1833º N latitude and between 123.1833º W and 122.1667º W longitude. Seventy total stations were found. Revised datum values (from January 2006) were used for the station at Bush Point (#9447854) because the older datums appeared to be inconsistent when compared to datums at nearby stations. Also, the location of the Holly Harbor Farms station (#9447855) was revised slightly (from a longitude of 122.54333° W to 122.53333° W) to ensure that it is in the grid. Two additional stations, those at Duwamish River (#9447029) and Ebey Slough, Qwuloolt (#9447729), were not used because they were too far up narrow rivers. Another station, at Gardiner Landing (#9444705), was not used since it was outside the model area. In total, 67 stations remained. The locations of these stations are shown in Figure 8 and the station identification number, name, and location are listed in Table 5. Two stations that were not used for the TCARI model runs, but were used in the final evaluation process at Commencement Bay (#9446484) and Tacoma (#9446545), are specially delineated in both Figure 8 and Table 5. To guarantee matching datums at the interface with the other models, an additional 158 nodes along the northern boundary of the grid were used in the TCARI model runs with datum information extracted from the corrected Strait of Juan de Fuca and Northern Puget Sound model results for all four datums (MHHW, MHW, MLW, and MLLW). The locations of these nodes are also shown in Figure 8. The tidal datum information for all 67 NOS stations are listed in Appendix A, Table A.4. Note that Lake Washington was not included in the VDatum area since water levels there are not strictly tidal because it is separated from Puget Sound proper by a system of locks.

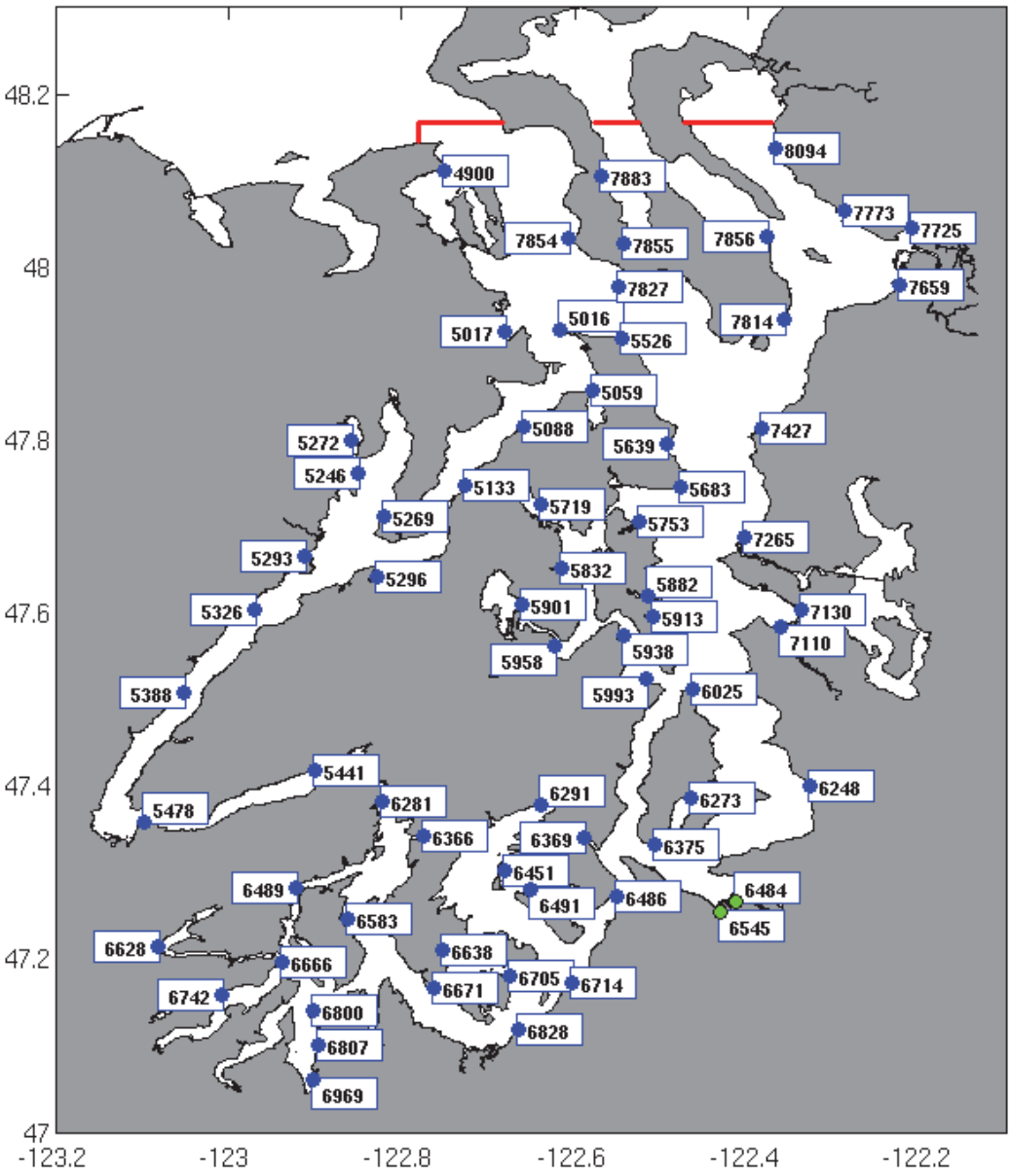

Figure 8. The 65 water level stations in the Puget Sound region used in developing the TCARI solution are shown in blue, and the additional 2 stations used for final model evaluation are shown in green. Only the last four digits of the station numbers are shown; the first three digits are "944". The locations of the 158 points along the boundary of the TCARI model grid are shown in red.

Table 5. Identification numbers, names, and location of stations in southern Puget Sound. Station ID numbers marked with an asterisk (*) indicate stations that are referenced to the 1983-2001 National Tidal Datum Epoch, and with a plus (+) were not used in generating the TCARI tidal datums but for model comparison.

N	Station ID	Station Name	Latitude	Longitude
1	9444900 *	PORT TOWNSEND ADMIRALTY INLET	48.1117	-122.7500
2	9445016	FOULWEATHER BLUFF TWIN SPITS	47.9267	-122.6167
3	9445017	PORT LUDLOW ADMIRALY INLET	47.9250	-122.6800
4	9445059	PORT GAMBLE HOOD CANAL WA	47.8583	-122.5800
5	9445088	LOFALL WA	47.8150	-122.6583
6	9445133 *	BANGOR	47.7483	-122.7267
7	9445246 *	WHITNEY POINT	47.7617	-122.8500
8	9445269	ZELATCHED POINT DABOB BAY	47.7117	-122.8217
9	9445272 *	QUILCENE DABOB BAY HOOD CANAL	47.8000	-122.8583
10	9445293	PLEASANT HARBOR HOOD CANAL	47.6650	-122.9117
11	9445296 *	SEABECK HOOD CANAL	47.6417	-122.8283
12	9445326	TRITON HEAD WA	47.6033	-122.9700
13	9445388	AYOCK POINT WA	47.5083	-123.0517
14	9445441	LYNCH COVE DOCK WA	47.4183	-122.9000
15	9445478 *	UNION HOOD CANAL	47.3583	-123.0983
16	9445526 *	HANSVILLE	47.9183	-122.5450
17	9445639	KINGSTON APPLE TREE COVE	47.7967	-122.4933
18	9445683	POINT JEFFERSON PUGET SOUND	47.7467	-122.4767
19	9445719 *	POULSBO	47.7250	-122.6383
20	9445753	PORT MADISON BAINBRIDGE ISLAND	47.7050	-122.5250
21	9445832 *	BROWNSVILLE	47.6517	-122.6150
22	9445882	EAGLE HARBOR BAINBRIDGE ISL	47.6200	-122.5150
23	9445901	TRACYTON DYES INLET PUGET	47.6100	-122.6600
24	9445913	PORT BLAKELY PUGET SOUND	47.5967	-122.5100
25	9445938	CLAM BAY WA	47.5733	-122.5433
26	9445958 *	BREMERTON WA	47.5617	-122.6233
27	9445993	SOUTH COLBY-HARPER YUKON	47.5233	-122.5167
28	9446025	POINT VASHON WA	47.5117	-122.4633
29	9446248	DES MOINES WA	47.4000	-122.3283
30	9446273	BURTON QUARTERMASTER HBR	47.3867	-122.4650
31	9446281 *	ALLYN	47.3833	-122.8233
32	9446291	WAUNA CARR INLET PUGET SOUND	47.3783	-122.6400
33	9446366	VAUGHN CASE INELT PUGET SOUND	47.3417	-122.7750
34	9446369	GIG HARBOR PUGET SOUND WA	47.3400	-122.5883
35	9446375	NEILL POINT WA	47.3333	-122.5067
36	9446451 *	GREEN POINT	47.3017	-122.6817
37	9446484 * +	TACOMA COMMENCEMENT BAY	47.2667	-122.4133
38	9446486	TACOMA NARROWS BRIDGE WA	47.2717	-122.5517
39	9446489	WALKERS LANDING WA	47.2817	-122.9233
40	9446491 *	ARLETTA	47.2800	-122.6517
41	9446545 * +	TACOMA	47.2550	-122.4317
42	9446583	BALLOW	47.2467	-122.8617
43	9446628	SHELTON OAKLAND BAY WA	47.2150	-123.0833
44	9446638	LONGBRACH FILUCE B PUGET SOUND	47.2100	-122.7533

Table 5. Continued

N	Station ID	Station Name	Latitude	Longitude
45	9446666	ARCADIA TOTTEN INLET WA	47.1967	-122.9383
46	9446671	DEVIL'S HEAD WA	47.1667	-122.7633
47	9446705 *	YOMAN POINT ANDERSON ISLAND	47.1800	-122.6750
48	9446714	STEILACOOM WA	47.1733	-122.6033
49	9446742 *	BARRON POINT	47.1583	-123.0083
50	9446800	DOFFLEMEYER POINT WA	47.1417	-122.9033
51	9446807 *	BUDD INLET , GULL HARBOR	47.1000	-122.8967
52	9446828	DUPONT NISQUALLY REACH WA	47.1183	-122.6650
53	9446969 *	OLYMPIA BUD INLET PUGET SOUND	47.0600	-122.9033
54	9447110 *	LOCKHEED SHIPYARD	47.5850	-122.3617
55	9447130 *	SEATTLE PUGET SOUND WA	47.6050	-122.3383
56	9447265	MEADOW POINT WA	47.6883	-122.4033
57	9447427	EDMONDS	47.8133	-122.3833
58	9447659 *	EVERETT WA	47.9800	-122.2233
59	9447725	EBEY SLOUGH POSSESSION SOUND	48.0450	-122.2100
60	9447773	TULALIP BAY WA	48.0650	-122.2883
61	9447814 *	GLENDALE POSSESSION SOUN	47.9400	-122.3567
62	9447827	DOUBLE BLUFF ADMIRALTY IN	47.9783	-122.5500
63	9447854 *	BUSH POINT WHIDBEY ISLAND	48.0333	-122.6067
64	9447855	HOLLY HARBOR FARMS WA	48.0267	-122.5333
65	9447856	SANDY POINT SARATOGA PASS	48.0350	-122.3767
66	9447883	GREENBANK WHIDBEY ISLAND	48.1050	-122.5700
67	9448094	KAYAK PT PORT SUSAN WA	48.1367	-122.3667

Of the 67 stations in southern Puget Sound, only 23 stations are referenced to the 1983-2001 NTDE. By comparing the mean tide range, which is assumed to be representative of all tidal datums, from the previous NTDE (1960-1978) to the present (1983-2001) at stations in Puget Sound where both are available, it was determined that the mean change was 0.5 cm, which is only 0.14% of the mean range, 3.624 m. It was decided to use all data, even if it came from an older National Tidal Datum Epochs, since changes in range since the previous tidal epoch were small. See Table 6 for the comparison at 22 stations (since one station, #9446742, was installed recently, it is referenced only to the current 1983-2001 NTDE.)

Table 6. Great diurnal range of tidal datums from 1960-1978 NTDE and 1983-2001 NTDE for 22 stations, with ratio of range, difference, and absolute average percent difference.

Station	Range(m)	Epoch	Range(m)	Epoch	Ratio	Diff(m)	Pct
9444900	2.576	1960	2.596	1983	1.008	-0.020	0.77%
9445133	3.375	1960	3.374	1983	1.000	0.001	0.03%
9445246	3.52	1960	3.523	1983	1.001	-0.003	0.09%
9445272	3.475	1960	3.468	1983	0.998	0.007	0.20%
9445296	3.514	1960	3.504	1983	0.997	0.010	0.28%
9445478	3.609	1960	3.613	1983	1.001	-0.004	0.11%
9445526	3.182	1960	3.18	1983	0.999	0.002	0.06%
9445719	3.578	1960	3.575	1983	0.999	0.003	0.08%
9445832	3.603	1960	3.607	1983	1.001	-0.004	0.11%
9445958	3.575	1960	3.578	1983	1.001	-0.003	0.08%
9446281	4.316	1960	4.334	1983	1.004	-0.018	0.42%
9446451	4.109	1960	4.105	1983	0.999	0.004	0.10%
9446484	3.604	1960	3.605	1983	1.000	-0.001	0.03%
9446491	4.057	1960	4.055	1983	1.000	0.002	0.05%
9446545	3.609	1960	3.605	1983	0.999	0.004	0.11%
9446705	4.105	1960	4.108	1983	1.001	-0.003	0.07%
9446807	4.415	1960	4.414	1983	1.000	0.001	0.02%
9446969	4.438	1960	4.438	1983	1.000	0.000	0.00%
9447130	3.459	1960	3.462	1983	1.001	-0.003	0.09%
9447659	3.386	1960	3.38	1983	0.998	0.006	0.18%
9447814	3.359	1960	3.364	1983	1.002	-0.005	0.15%
9447854	2.848	1960	2.85	1983	1.001	-0.002	0.07%
Average =					**1.000**	**-0.005**	**0.14%**

4.2. Generation of Tidal Datum Fields

The finite difference version of the TCARI model was used to generate the datum fields for Southern Puget Sound. A structured grid similar to the original model grid was created (Hess and White, 2004). The new grid was generated using the newer EVS shoreline. The grid spacing was 0.075 nmi (about 140 m) in the northward and eastward directions and covered water areas of Southern Puget Sound. The grid has 109,252 water cells.

The TCARI model was run once for each tidal datum with input stations at the NOS water level gage locations and the 158 boundary nodes. Two of the 67 stations were not used to generate the tidal fields because they were too far up rivers: #9446484 and #9446545. Once the MHHW, MHW, MLW and MLLW datum fields were computed, the MTL and DTL fields were calculated as: MTL=1/2[MHW + MLW] and DTL=1/2[MHHW + MLLW].

The results from the spatially interpolated MLLW field are shown in Figure 9. The TCARI model results match the data from the corrected Foreman model at the boundary in Admiralty Inlet, and the results match the Northern Puget Sound TCARI model results in Saratoga Passage and Port Susan.

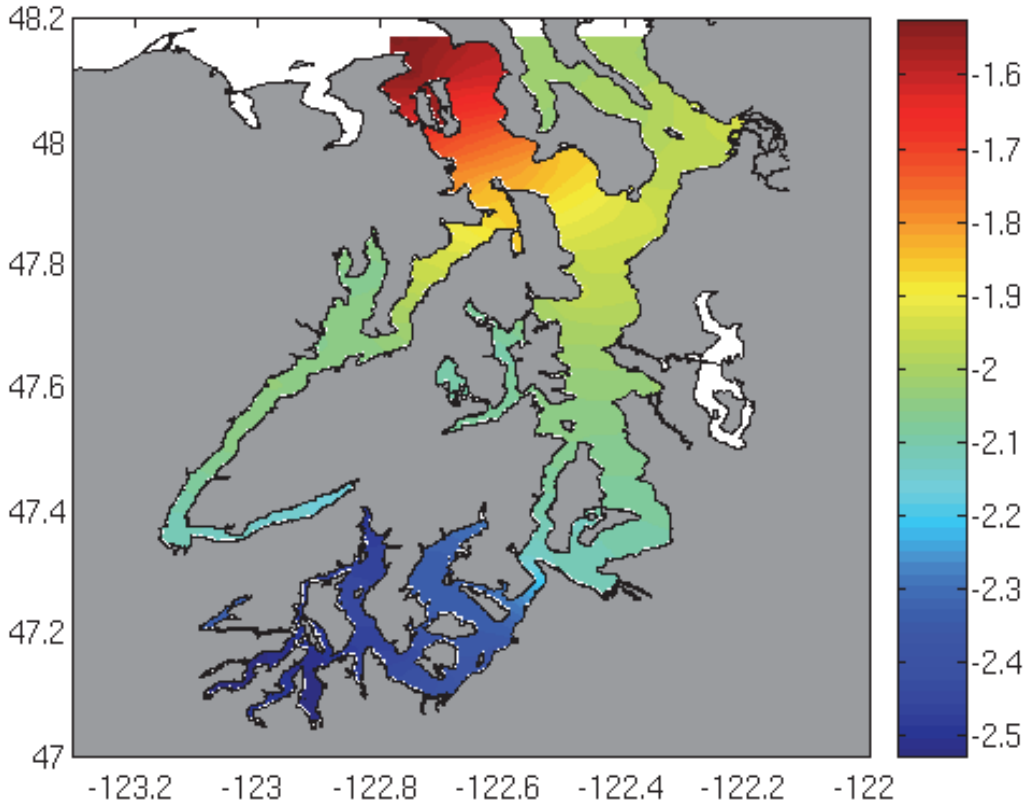

Figure 9. VDatum marine grid populated with MLLW tidal datum field (in meters) for the southern Puget Sound area.

5. GENERATION AND POPULATION OF VDATUM MARINE GRIDS

The VDatum software program requires regularly spaced (in arc degrees) input grids that cover both land and water in a given region. Due to a current restraint with the software, the grid files must contain less than 1 million points. A grid with approximately 200m x 200m resolution that covers all three regions (the Strait of Juan de Fuca, Northern Puget Sound and Southern Puget Sound) would have over 1 million points, so this area was divided into two sub-regions. The Northern Puget Sound and Strait of Juan de Fuca regions were combined to create one VDatum marine grid that covers both of those regions. Another VDatum marine grid was created for Southern Puget Sound. The following sections will discuss the VDatum marine grid generation and then the population of those grids.

5.1. Generation of the VDatum Marine Grids

The VDatum marine grids were generated using a program which requires a MHW coastline and a bounding polygon input file. This program creates a grid array for a user-specified area, then identifies nodes as land or water points. Only nodes completely within the bounding polygon or up to one half of a cell size outside the coastline are delineated as water nodes. All nodes outside the bounding polygon or those more than one half of a cell size away from the coastline are marked as land nodes. (A further description of this process can be found in the paper by Hess and White (2004) describing the VDatum process for the original Southern Puget Sound grid.)

Both of the grids have a zonal spacing of 0.0025º and a meridional spacing of 0.00175º (for, approximately, a spacing of 0.1 nmi or 200 m in each direction). The first grid covers the Strait of Juan de Fuca and Northern Puget Sound. The origin of the grid is at 47.9897º N and 122.3483º W, which is the southwest corner of the grid. The resulting grid has a width of 1,577 nodes and a height of 578 nodes for a total of 911,506 nodes. The second grid covers only Southern Puget Sound; and the origin is at 47.016667° N and 123.183333° W, which again is the southwest corner of the grid. The resulting grid has a width of 408 nodes and a height of 668 nodes for a total of 275,544 nodes.

5.2. Population of the VDatum Marine Grids with Tidal Datums

5.2.1. Population of the Southern Puget Sound Marine Grid

The grid used to generate the tidal datum fields in Southern Puget Sound using the TCARI program had a denser spacing and a different configuration than the VDatum marine grid created for the region. Values in the marine grid for the locations within the bounding polygon (Figure 10) were obtained by bi-linearly interpolating the four surrounding TCARI grid values for MHHW, MHW, MLW, and MLLW. If there were three or fewer surrounding values, inverse distance squared weighting was used for the interpolation. The fields for MTL and DTL were generated by averaging the MHW and MLW fields and the MHHW and MLLW fields, respectively.

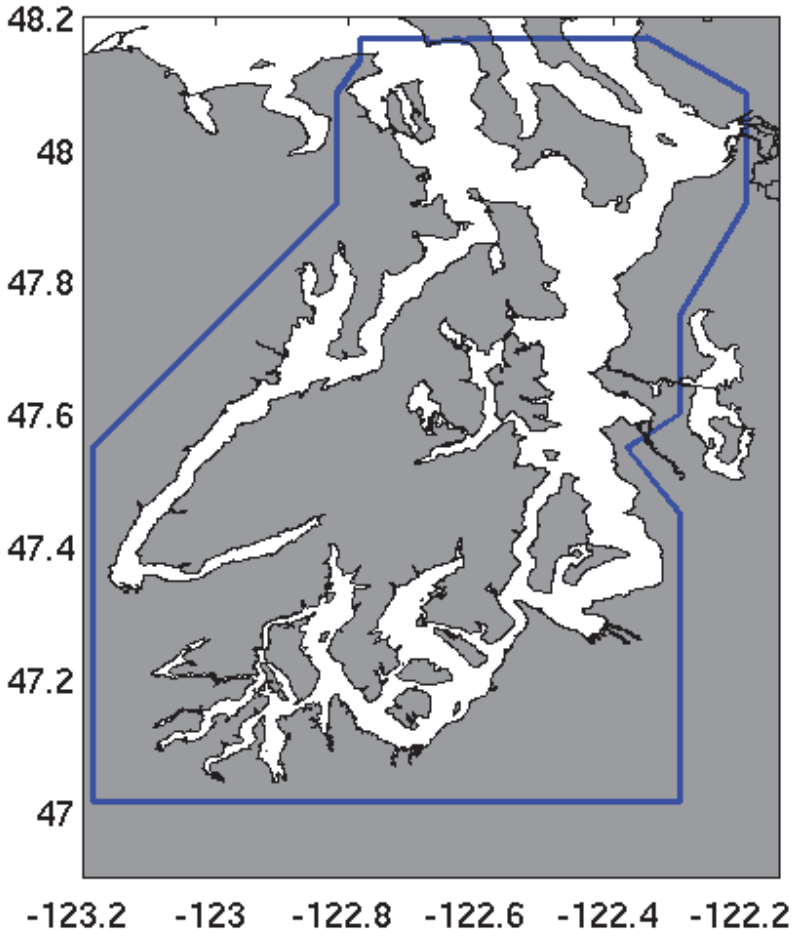

Figure 10. VDatum bounding polygon (blue line) for Southern Puget Sound.

5.2.2. Population of the Combined Juan de Fuca and Northern Puget Sound Marine Grid

Population of the VDatum marine grid with the final tidal datum fields for the Juan de Fuca and Northern Puget Sound areas was done by a two-step process. First, the large marine grid was divided into two smaller regions (marked by two bounding polygons as shown in Figure 11) to delineate where the corrected Juan de Fuca hydrodynamic model results would be used and where the Northern Puget Sound spatial interpolation results would be used. The regions do not exactly match the boundaries of either of the two model grids, but most closely follow the boundary of the grid used for the TCARI spatial interpolation of the datums in Northern Puget Sound.

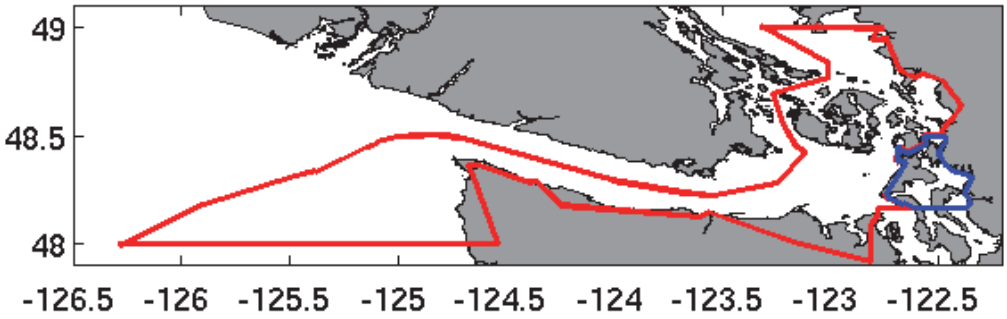

Figure 11. The area of the VDatum marine grid populated by the corrected Strait of Juan de Fuca model results outlined by the red bounding polygon and the area populated by the Northern Puget Sound spatial interpolation model results outlined by the blue bounding polygon.

Values in the marine grid for locations within the Northern Puget Sound bounding polygon were obtained by linearly averaging the values for MHHW, MHW, MLW, and MLLW at the unstructured grid nodes attached to the cluster of elements that surround the marine grid node. If the marine grid node was outside of the boundary of the unstructured grid (but still within the Northern Puget Sound bounding polygon), the tidal datum value at the nearest node in the unstructured grid was used as the value of the marine grid node. The fields for MTL and DTL were generated by averaging the MHW and MLW fields and the MHHW and MLLW fields, respectively. For the values in the marine grid at locations within the Strait of Juan de Fuca bounding polygon, the same process was followed using values from the corrected Strait of Juan de Fuca model results.

The results from both the Southern Puget Sound VDatum marine grid and the combined Northern Puget Sound and Strait of Juan de Fuca marine grid are shown together in Appendix B.

5.3. Errors in the Marine Grid

Possible errors in the VDatum tidal transformation fields can be traced to several sources. Errors in the hydrodynamic model results and the interpolation of those errors at the tide stations can be evaluated in the Foreman model (the Strait of Juan de Fuca region) only. For all of the models, the error associated with the interpolation of the model results onto the VDatum marine grid can be examined.

The error in the Foreman hydrodynamic model results, which cover the Strait of Juan de Fuca region, has been examined in Section 2.1, and the RMS error for four datums at 22 stations is 15.1 cm. An expansion of this analysis to all of the 29 stations in just the Foreman model domain (versus the Myers or Spargo model domains) lowers the RMS error to 10.9 cm. The error in the TCARI models or Northern and Southern Puget Sound cannot be quantified in the same way since the models were designed to match the datums at every node.

Errors in the Foreman model results were compensated for by subtracting an interpolated error field that matches the error value at the tide stations. This makes a nearly exact match

right at each tide station, but the effect on the error throughout the rest of the domain is unknown. It can be noted, though, as shown in Figure 4, that the error field created (in this figure for the MLLW datum) is generally smooth, which is desirable to create smooth final tidal datum fields.

Another source of error can be introduced when transferring the modeled datums from their native grids onto the structured VDatum marine grid. A check was done to compare the combined datum field results as projected onto the VDatum marine grid with datum information at the NOS water level stations in the region. The root mean squared error (RMSE) and standard deviation were computed for the four datums (MHHW, MHW, MLW, and MLLW) at each station. For the combined Northern Puget Sound and Strait of Juan de Fuca marine grid, the maximum RMSE was 1.83 cm at Sneesh Point in Skagit Bay (station #9448576). The average RMSE was 0.54 cm. The stations used for this analysis are shown in Figures 3 and 6 and listed in Tables 1 and 3, and the RMSE and standard deviation for each individual station are listed in Appendix A, Table A.5. For the Southern Puget Sound marine grid, the results were compared to the 67 tide gages shown in Figure 8 and listed in Table 5. The mean RMS difference was under 0.06 cm, and the maximum RMS difference at a single station was 2 cm. The results for each station are shown in Appendix A, Table A.6.

This error was eliminated through a final adjustment of all water nodes (up to four) in the marine grid surrounding a tide station location so the values match the observed datum at that station. This way the RMSE and standard deviation for each NOS station was reduced to zero since the average of the datums at the water nodes surrounding a given NOS station would exactly equal the datum value at that station.

Another check was done to look for maximum point-to-point differences in the marine grid. The maximum point-to-point difference in the combined Northern Puget Sound and Strait of Juan de Fuca marine grid was found in the MLLW datum and was 1.1 cm. All other datums had maximum differences less than 1 cm. The maximum point-to-point differences in the Southern Puget Sound marine grid occurred at the southern end of Marrowstone Island east of the Quimper Penninsula. Differences over the 0.1 nmi cell spacing for the MHHW field were 3.4 cm, in the MHW field were 2.4 cm, in the MLW were 4.2 cm, and in the MLLW field were 5.3 cm.

For the Southern Puget Sound VDatum marine grid, the new results can be compared to the previously published results (Hess and White, 2004). The maximum changes in any one datum field were from 14 to 17 cm, depending on the datum. The maximum changes were located in the northern portion of Admiralty Inlet, where two significant changes in input data occurred. The revised tidal datums from Bush Point were used in the new tidal datum interpolation, and input values were used at the boundary with the Strait of Juan de Fuca. These changes account for the differences between the VDatum marine grid results.

6. TOPOGRAPHY OF THE SEA SURFACE

The Topography of the Sea Surface (TSS) is a gridded surface that models the elevation of the North American Vertical Datum of 1988 (NAVD 88) relative to local mean sea level (LMSL). The gridded TSS surface was generated by interpolating the observed values using commercial contouring software. In the Strait of Juan de Fuca-Puget Sound area, the observed values at various locations range from approximately -1.4 to -0.9 m. A positive value specifies that the NAVD 88 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 tide stations and tidal benchmarks used are illustrated in Figure 12.

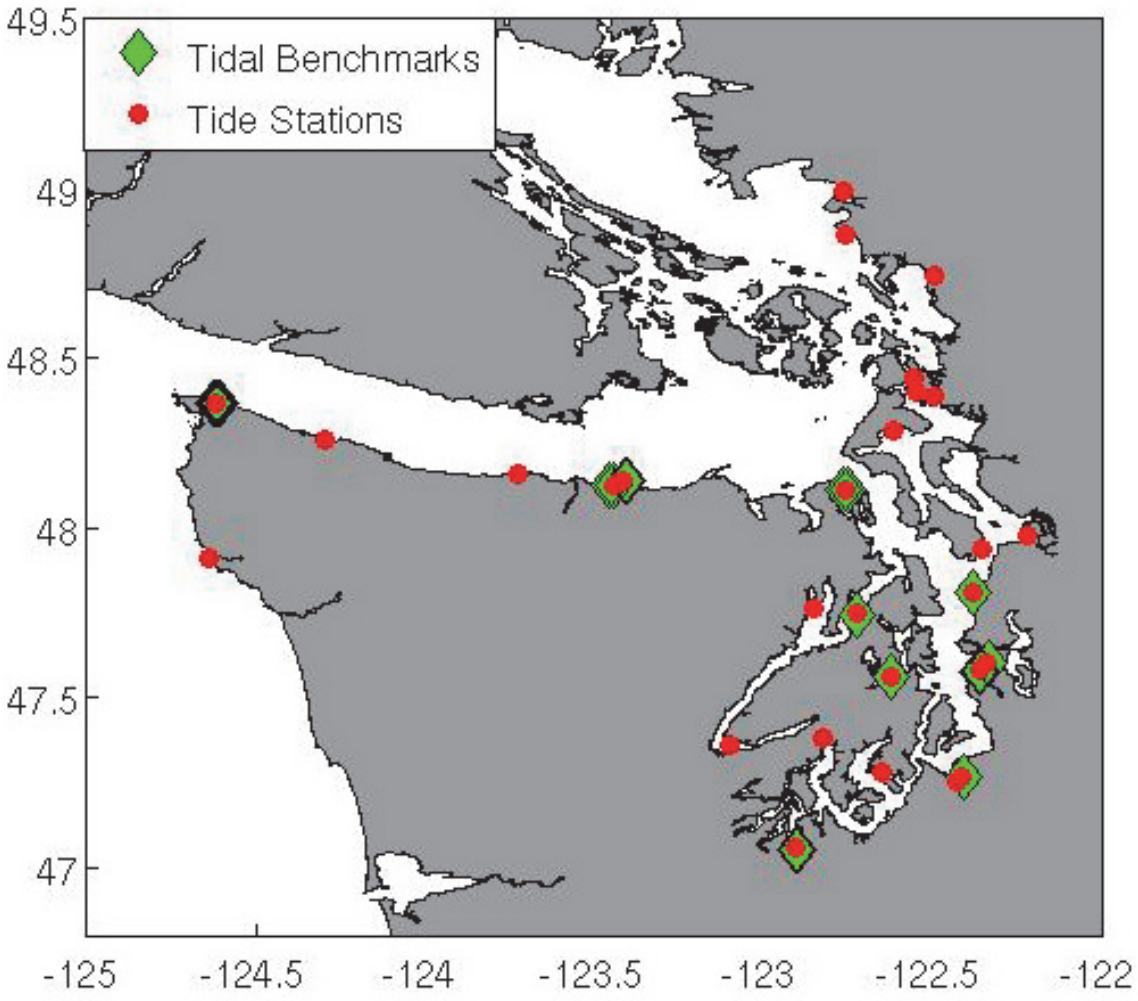

Figure 12. Location of tidal benchmarks and tide stations used to compute the Juan de Fuca and Puget Sound TSS grid.

The TSS grid was generated as follows. At each NGS benchmark location, there is a set of four TBM_{datum} values, each of which is the elevation at the Tidal Benchmark of a datum

relative to MLLW (i.e., Datum – MLLW). Also, from the four tidal datum grids (see Section 5), there is a set of VD_{datum} values, each of which is the difference between the tidal datum and MSL (i.e., Datum – MSL).

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

$$R_{datum} = TBM_{navd88} - TBM_{datum} - VD_{datum}$$

Note that the VD values were interpolated to the location of the benchmark. The four residuals at the benchmark were averaged to produce the mean. Note that this mean is an estimate of the quantity MSL – NAVD88. The residuals are listed in Tables 7 and 8.

Table 7. Derived residual values for each tidal datum at NGS benchmarks from the combined Strait of Juan de Fuca and Northern Puget Sound Tidal Grids.

Bench-mark	Latitude (deg)	Longitude (deg)	From MLLW (m)	From MLW (m)	From MHW (m)	From MHHW (m)	Average (m)	Std. Dev. (m)
TR0790	48.12333	-123.44472	-1.1629	-1.1542	-1.1682	-1.1629	-1.1621	0.0058
TR0789	48.12722	-123.45777	-1.1621	-1.1470	-1.1724	-1.1634	-1.1612	0.0105
TR0782	48.14000	-123.40194	-1.1792	-1.2161	-1.1699	-1.1976	-1.1907	0.0205
TR0783	48.14000	-123.40138	-1.1789	-1.2163	-1.1698	-1.1980	-1.1908	0.0207
TR0784	48.14055	-123.40888	-1.1749	-1.2171	-1.1694	-1.2014	-1.1907	0.0225
TR0785	48.14055	-123.40972	-1.1740	-1.2174	-1.1692	-1.2021	-1.1907	0.0230
TR0779	48.14055	-123.40250	-1.1776	-1.2163	-1.1699	-1.1991	-1.1907	0.0211
TS0156	48.36555	-124.61666	-1.0543	-1.0426	-1.0757	-1.0676	-1.0601	0.0146
TS0161	48.36555	-124.62083	-1.0545	-1.0479	-1.0674	-1.0625	-1.0581	0.0086
AF8871	48.36583	-124.61722	-1.0574	-1.0482	-1.0747	-1.0681	-1.0621	0.0117
TS0154	48.36638	-124.61138	-1.0551	-1.0422	-1.0768	-1.0682	-1.0606	0.0152
TS0152	48.36694	-124.60416	-1.0597	-1.0477	-1.0769	-1.0691	-1.0634	0.0126
TS0340	48.36694	-124.61944	-1.0546	-1.0484	-1.0665	-1.0620	-1.0579	0.0080
TS0340	48.36694	-124.61944	-1.0546	-1.0484	-1.0665	-1.0620	-1.0579	0.0080
TS0150	48.36694	-124.60416	-1.0597	-1.0477	-1.0769	-1.0691	-1.0634	0.0126
AF8872	48.36805	-124.62388	-1.0577	-1.0530	-1.0666	-1.0636	-1.0602	0.0061
AF8873	48.36805	-124.62666	-1.0550	-1.0511	-1.0614	-1.0595	-1.0568	0.0046
TS0171	48.36833	-124.62305	-1.0577	-1.0529	-1.0666	-1.0636	-1.0602	0.0061

Table 8. Derived NAVD 88-to-LMSL values for each tidal datum at NGS benchmarks from the Southern Puget Sound Tidal Grids.

Bench-mark	Latitude (deg)	Longitude (deg)	From MLLW (m)	From MLW (m)	From MHW (m)	From MHHW (m)	Average (m)	Std. Dev. (m)
SY0868	47.05000	-122.90138	-1.3021	-1.3038	-1.3057	-1.3036	-1.3038	0.0015
SY0865	47.05166	-122.90250	-1.3111	-1.3128	-1.3147	-1.3126	-1.3128	0.0015
SY0866	47.05194	-122.90388	-1.3141	-1.3158	-1.3177	-1.3156	-1.3158	0.0015
SY0536	47.26416	-122.41194	-1.3613	-1.3568	-1.3311	-1.3326	-1.3455	0.0158
SY0920	47.56305	-122.62527	-1.3030	-1.3030	-1.3030	-1.3030	-1.3030	0.0000
SY5718	47.56305	-122.62416	-1.3180	-1.3180	-1.3180	-1.3180	-1.3180	0.0000
SY0270	47.57444	-122.36277	-1.2990	-1.2980	-1.2991	-1.2981	-1.2986	0.0006
SY0271	47.57833	-122.36277	-1.2960	-1.2950	-1.2961	-1.2951	-1.2956	0.0006
SY0272	47.58194	-122.36277	-1.2960	-1.2950	-1.2961	-1.2950	-1.2955	0.0006
SY0273	47.58416	-122.36250	-1.2990	-1.2980	-1.2990	-1.2980	-1.2985	0.0006
SY0283	47.60194	-122.33388	-1.3071	-1.3081	-1.3059	-1.3069	-1.3070	0.0009
SY0286	47.60305	-122.33444	-1.3100	-1.3110	-1.3090	-1.3100	-1.3100	0.0008
SY0290	47.60388	-122.33750	-1.3100	-1.3110	-1.3090	-1.3100	-1.3100	0.0008
SY0289	47.60444	-122.33500	-1.3100	-1.3110	-1.3090	-1.3100	-1.3100	0.0008
SY0959	47.74666	-122.72638	-1.2500	-1.2500	-1.2490	-1.2500	-1.2498	0.0005
SY0128	47.81138	-122.38250	-1.3190	-1.3180	-1.3190	-1.3200	-1.3190	0.0008
SY0126	47.81305	-122.38027	-1.3219	-1.3209	-1.3220	-1.3230	-1.3220	0.0009
TR2726	48.11138	-122.76166	-1.1950	-1.1865	-1.1897	-1.1863	-1.1894	0.0041
TR0559	48.11583	-122.75194	-1.1951	-1.1892	-1.1965	-1.1948	-1.1939	0.0032

Next, a gridded sea surface topography field was generated. The mean residuals at all benchmarks were merged with values of the quantity NAVD88 – MSL at CO-OPS' water level stations to produce input data for contouring. The tide stations and associated elevation information used in the computation of the TSS are presented in Table 9. A mesh covering the entire area of benchmarks and water level stations with a spatial resolution similar to that of the tidal marine grids was created. Break lines were inserted to represent the influence of land. A sea surface topography field was 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 0.0001 meters. To control the amount of bowing on the interior and at the edges of the grid, an internal and boundary tension value of 0.3 was utilized. Once the gridded topography field was generated, null values were obtained from the marine tidal grids and were inserted to denote the presence of land. The continuous surface produced this way is shown in Figure 13.

Then a set of 'Delta' values were 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, then Delta (D) for each tidal datum is computed as:

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

The averaged Delta at each benchmark should be less than 0.01 m. If it is not, the input data and grids must be checked, appropriate changes made, and the Deltas recomputed until the criterion is met.

Table 9. Location and elevation information for NOAA tide gages used to create the TSS. All datums are in meters and are relative to MLLW. Data are from CO-OPS. Station numbers marked with an asterisk have NAVD 88 elevations from NGS.

Station Number	Latitude (deg)	Longitude (deg)	MHHW	MHW	LMSL	MLW	NAVD88	LMSL-NAVD88
9440574	46.27333	-124.07167	2.361	2.156	1.246	0.374	0.077	-1.169
9442396*	47.91333	-124.63667	2.651	2.43	1.423	0.428	0.258	-1.165
9443090	48.36833	-124.61667	2.425	2.167	1.315	0.486	0.256	-1.059
9443361	48.26333	-124.29667	2.286	2.03	1.269	0.545	0.176	-1.093
9443826*	48.16167	-123.72500	2.151	1.971	1.285	0.659	0.127	-1.158
9444090	48.12500	-123.44000	2.153	1.987	1.295	0.586	0.129	-1.166
9444122	48.14000	-123.41333	2.135	1.926	1.282	0.684	0.097	-1.185
9444900*	48.11167	-122.75833	2.596	2.389	1.522	0.76	0.3325	-1.1895
9445133*	47.74833	-122.72667	3.374	3.103	1.978	0.877	0.728	-1.25
9445246	47.76167	-122.85000	3.523	3.229	2.067	0.916	0.814	-1.253
9445478	47.35833	-123.09833	3.613	3.312	2.122	0.917	0.865	-1.257
9445958	47.56167	-122.62333	3.578	3.31	2.08	0.868	0.769	-1.311
9446281*	47.38333	-122.82333	4.334	4.05	2.492	0.929	1.2285	-1.2635
9446484	47.26667	-122.41333	3.605	3.336	2.094	0.87	0.758	-1.336
9446491*	47.28000	-122.65167	4.055	3.78	2.316	0.898	1.202	-1.114
9446545	47.25500	-122.43167	3.605	3.337	2.097	0.873	0.795	-1.302
9446969	47.06000	-122.90333	4.437	4.129	2.546	0.935	1.227	-1.319
9447110	47.58500	-122.36167	3.47	3.206	2.028	0.867	0.727	-1.301
9447130	47.60500	-122.33833	3.462	3.198	2.023	0.864	0.715	-1.308
9447427	47.81333	-122.38333	3.333	3.069	1.959	0.857	0.637	-1.322
9447659	47.98000	-122.22333	3.38	3.114	1.976	0.854	0.62	-1.356
9447814*	47.94000	-122.35667	3.364	3.108	1.976	0.86	0.6205	-1.3555
9447952	48.28667	-122.61667	3.554	3.281	2.072	0.855	0.675	-1.397
9448558*	48.39167	-122.49667	3.154	2.874	1.817	0.822	0.461	-1.356
9448576	48.40000	-122.54833	3.369	3.108	1.946	0.781	0.615	-1.331
9448657	48.44500	-122.55500	3.152	2.888	1.812	0.761	0.465	-1.347
9449211	48.74500	-122.49500	2.594	2.375	1.51	0.718	0.147	-1.363
9449424*	48.86333	-122.75833	2.788	2.535	1.61	0.796	0.293	-1.317
9449679	48.99167	-122.76500	2.905	2.643	1.67	0.81	0.31	-1.36

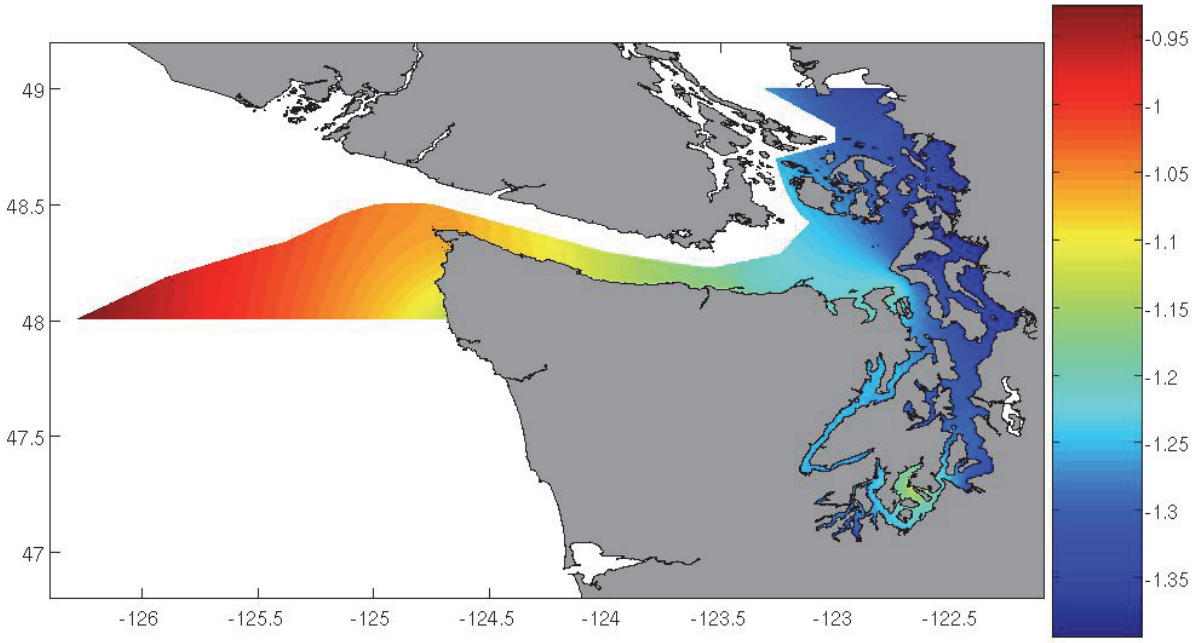

Figure 13. Combined Strait of Juan de Fuca, Northern Puget Sound and Southern Puget Sound gridded TSS.

The TSS grid was created to assure a continuous field across the boundary of the Strait of Juan de Fuca and Northern Puget Sound area with the Southern Puget Sound region. For use in the VDatum utility, however, this continuous TSS field was subdivided into two separate TSS grid files with boundaries that correspond with those used to divide the tidal datum fields.

Quality control was carried out by comparing observed benchmarks values to those predicted. After the TSS was created, it was incorporated into VDatum. For the first test, conversions between NAVD 88 and the tidal datums MLLW, MLW, MHW, and MHHW at tidal benchmarks were computed. All Delta values tabulated for both the Southern Puget Sound TSS and the Strait of Juan de Fuca and Northern Puget Sound TSS are listed for each station in Appendix A, Table A.7. The RMS error was 1.03 cm. For the second test, the mean difference between known NAVD 88 to MSL relationships and that predicted by VDatum was computed. For the San Juan Islands VDatum the RMS difference was 0.125 cm, the mean was 0.03 cm, and the standard deviation was 0.12 cm, and for the Puget Sound VDatum, the RMS difference was 0.091 cm, the mean difference was 0.020 cm, and the standard deviation was 0.02 cm. Individual station results are listed in Appendix A, Table A.8 and Table A.9.

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APPENDIX A. STATION INFORMATION AND ERROR ANALYSIS

Table A.1. Station identification number, location, and error (difference between model results {for the Foreman, Myers, and Spargo models} and station data) for four datums at 22 NOS water level stations. Total RMS and absolute average error for each model is also given.

	Station ID	Longitude (deg)	Latitude (deg)	MHHW Error (cm)	MHW Error (cm)	MLW Error (cm)	MLLW Error (cm)	Model
1	9442861	-124.668317	48.294021	-4.14	-9.72	-24.02	18.55	Foreman
				45.91	3.17	5.51	-20.33	Myers
				-20.74	-16.86	-21.77	-8.16	Spargo
2	9443090	-124.621009	48.363939	11.75	7.50	-6.12	33.90	Foreman
				60.26	19.74	22.16	-6.12	Myers
				-7.64	-1.21	-5.94	1.50	Spargo
3	9443361	-124.299453	48.261804	15.76	14.63	-1.18	30.04	Foreman
				83.85	41.13	38.69	5.78	Myers
				9.36	10.11	3.62	6.17	Spargo
4	9443644	-123.945229	48.164904	19.13	17.57	6.15	23.59	Foreman
				79.37	34.28	35.34	-3.28	Myers
				26.81	20.81	15.11	11.97	Spargo
5	9443826	-123.708153	48.167967	24.39	16.72	8.01	23.31	Foreman
				70.57	23.81	33.39	-13.29	Myers
				34.38	23.39	24.82	14.75	Spargo
6	9444090	-123.439732	48.112821	18.08	15.35	5.64	14.07	Foreman
				74.15	25.83	26.79	-12.32	Myers
				13.91	12.29	2.07	10.16	Spargo
7	9444122	-123.408964	48.151134	16.29	20.05	22.40	13.17	Foreman
				94.43	46.94	50.30	2.77	Myers
				48.76	43.46	45.35	26.46	Spargo
8	9447951	-122.724501	48.296276	17.23	17.97	9.40	4.73	Foreman
				55.37	11.77	11.91	-43.81	Myers
				12.41	15.31	8.83	-4.56	Spargo
9	9447985	-122.831746	48.327882	30.94	24.11	8.58	21.21	Foreman
				74.36	29.85	33.21	-18.84	Myers
				45.74	38.35	35.31	15.64	Spargo
10	9448614	-122.653705	48.418655	12.33	9.06	2.75	6.65	Foreman
				58.62	14.65	26.26	-29.32	Myers
				4.71	6.86	7.91	-6.38	Spargo
11	9448772	-122.682335	48.504810	0.84	7.54	2.35	-16.72	Foreman
				88.74	40.24	35.58	-22.55	Myers
				3.39	8.35	1.59	-16.00	Spargo
12	9448967	-122.697502	48.617693	0.14	5.16	-5.37	-12.32	Foreman
				51.97	12.32	16.12	-41.01	Myers
				-2.62	3.82	-4.81	-13.96	Spargo
13	9449161	-122.727517	48.718246	-14.94	-7.57	-1.64	-17.45	Foreman
				16.94	-18.66	-7.54	-69.75	Myers
				-12.08	-5.49	-0.32	-17.49	Spargo

Table A.1. (Continued)

	Station ID	Longitude (deg)	Latitude (deg)	MHHW Error (cm)	MHW Error (cm)	MLW Error (cm)	MLLW Error (cm)	Model
14	9449211	-122.518051	48.712912	-11.07	-7.26	-9.51	-15.48	Foreman
				37.93	-3.10	8.52	-44.51	Myers
				-27.48	-21.17	-28.70	-50.08	Spargo
15	9449424	-122.772523	48.842827	-18.58	-12.47	-12.22	-23.36	Foreman
				32.99	-5.14	9.53	-51.12	Myers
				-0.52	-8.20	3.38	-15.35	Spargo
16	9449704	-122.984318	48.778176	-12.39	-5.67	-5.83	-33.57	Foreman
				38.31	-2.52	5.47	-55.28	Myers
				-8.39	-8.27	-18.80	-25.55	Spargo
17	9449802	-123.249872	48.683484	6.01	7.89	5.45	-18.16	Foreman
				50.82	8.05	13.56	-44.56	Myers
				-3.03	-4.43	-15.48	-53.22	Spargo
18	9449828	-123.168774	48.592953	-2.97	-2.38	7.03	-17.78	Foreman
				51.16	8.42	21.81	-30.19	Myers
				20.35	6.82	7.39	6.50	Spargo
19	9449880	-123.014674	48.549839	-0.60	-3.36	1.60	-18.25	Foreman
				49.79	6.47	19.09	-31.78	Myers
				57.65	32.62	34.20	49.69	Spargo
20	9449932	-122.773907	48.533452	7.71	-2.41	1.17	-17.39	Foreman
				36.11	-8.98	0.81	-54.73	Myers
				-57.02	-46.98	-41.83	-90.17	Spargo
21	9449982	-122.907732	48.429925	30.51	18.00	19.59	5.05	Foreman
				46.84	-3.91	3.43	-47.49	Myers
				69.06	39.66	35.72	57.08	Spargo
22	9449994	-122.850802	48.414931	37.80	33.71	30.76	3.18	Foreman
				62.20	20.63	24.07	-33.22	Myers
				73.73	49.63	42.59	52.12	Spargo
Total RMS error (cm)				15.32				Foreman
				18.25				Myers
				28.87				Spargo
Total Absolute Average Error (cm)				13.23				Foreman
				31.61				Myers
				22.07				Spargo

Table A.2. Station identification numbers (as shown in Figure 3 plus the "944" beginning digits), station name, and tidal datums for NOAA tide gages, the hydrodynamic model results at that location, the difference between the two, and the absolute average percent difference.

Station ID Number	Station Name	MHHW (cm)	MHW (cm)	MLW (cm)	MLLW (cm)	Data
9442861	Mukkaw Bay	124.30	101.00	-98.90	-145.00	NOAA
		123.20	97.71	-94.76	-143.38	Model
		-1.10	-3.29	4.14	1.62	Difference
		0.89%	3.31%	4.28%	1.12%	% Diff
9443090	Neah Bay	111.00	85.20	-82.90	-131.50	NOAA
		117.71	89.00	-87.19	-136.35	Model
		6.71	3.80	-4.29	-4.85	Difference
		5.87%	4.36%	5.04%	3.62%	% Diff
9443361	Sekiu Clallam Bay	100.30	74.40	-74.40	-128.30	NOAA
		104.61	75.79	-72.57	-124.81	Model
		4.31	1.39	1.83	3.49	Difference
		4.21%	1.85%	2.49%	2.76%	% Diff
9443644	Twin Rivers	88.10	67.30	-67.10	-125.60	NOAA
		97.10	74.64	-70.50	-120.45	Model
		9.00	7.34	-3.40	5.15	Difference
		9.72%	10.34%	4.94%	4.19%	% Diff
9443826	Crescent Bay	86.60	68.60	-62.60	-128.50	NOAA
		92.83	73.22	-72.83	-118.92	Model
		6.23	4.62	-10.23	9.58	Difference
		6.94%	6.52%	15.11%	7.74%	% Diff
9444090	Port Angeles	85.80	69.20	-70.90	-129.50	NOAA
		91.31	74.89	-72.55	-125.14	Model
		5.51	5.69	-1.65	4.36	Difference
		6.22%	7.90%	2.30%	3.42%	% Diff
9444122	Ediz Hook	85.30	64.40	-59.80	-128.20	NOAA
		91.21	76.63	-73.47	-124.93	Model
		5.91	12.23	-13.67	3.27	Difference
		6.70%	17.34%	20.51%	2.58%	% Diff
9444705	Gardiner Landing	94.50	73.20	-73.10	-146.30	NOAA
		101.15	81.05	-71.22	-141.32	Model
		6.65	7.85	1.88	4.98	Difference
		6.80%	10.18%	2.61%	3.46%	% Diff
9447951	Whidbey Island, Sunset Beach	86.50	65.80	-65.20	-138.70	NOAA
		99.22	80.03	-69.18	-137.64	Model
		12.72	14.23	-3.98	1.06	Difference
		13.70%	19.52%	5.92%	0.77%	% Diff
9447985	Smith Island	83.20	63.10	-62.80	-134.10	NOAA
		97.33	79.24	-69.69	-135.52	Model
		14.13	16.14	-6.89	-1.42	Difference
		15.65%	22.68%	10.40%	1.05%	% Diff

Table A.2. (Continued)

Station ID Number	Station Name	MHHW (cm)	MHW (cm)	MLW (cm)	MLLW (cm)	Data
9447995	Whidbey Island, Coronet Bay	131.10	103.70	-97.50	-179.80	NOAA
		100.68	81.29	-70.80	-139.95	Model
		-30.42	-22.41	26.70	39.85	Difference
		26.25%	24.23%	31.73%	24.93%	% Diff
9448601	Yokeko Point	138.00	107.60	-102.80	-182.00	NOAA
		100.68	81.30	-70.80	-139.95	Model
		-37.32	-26.30	32.00	42.05	Difference
		31.27%	27.85%	36.87%	26.12%	% Diff
9448614	Reservation Bay	94.20	74.40	-66.40	-141.00	NOAA
		100.74	81.36	-70.83	-140.08	Model
		6.54	6.96	-4.43	0.92	Difference
		6.71%	8.94%	6.46%	0.65%	% Diff
9448772	Fidalgo Island, Ship Harbor	95.10	72.50	-72.30	-150.30	NOAA
		106.53	83.46	-69.15	-147.65	Model
		11.43	10.96	3.15	2.65	Difference
		11.34%	14.05%	4.45%	1.78%	% Diff
9448967	Sinclair Island	100.60	76.20	-76.20	-152.40	NOAA
		110.99	85.32	-70.61	-151.81	Model
		10.39	9.12	5.59	0.59	Difference
		9.82%	11.29%	7.62%	0.39%	% Diff
9449161	Lummi Island	111.30	86.90	-74.70	-152.40	NOAA
		116.06	89.03	-73.22	-158.34	Model
		4.76	2.13	1.48	-5.94	Difference
		4.19%	2.42%	2.00%	3.82%	% Diff
9449211	Bellingham	108.40	86.50	-79.20	-151.00	NOAA
		114.14	87.21	-71.38	-155.31	Model
		5.74	0.71	7.82	-4.31	Difference
		5.16%	0.82%	10.39%	2.81%	% Diff
9449292	Lummi Bay	116.30	91.50	-79.70	-158.60	NOAA
		120.68	91.18	-75.07	-163.12	Model
		4.38	-0.32	4.63	-4.52	Difference
		3.70%	0.35%	5.98%	2.81%	% Diff
9449424	Cherry Point	117.80	92.50	-81.40	-161.00	NOAA
		122.75	92.70	-76.78	-165.40	Model
		4.95	0.20	4.62	-4.40	Difference
		4.12%	0.22%	5.84%	2.70%	% Diff
9449679	Blaine	123.50	97.30	-86.00	-167.00	NOAA
		126.02	95.35	-79.70	-169.40	Model
		2.52	-1.95	6.30	-2.40	Difference
		2.02%	2.02%	7.60%	1.43%	% Diff
9449704	Patos Island	103.60	82.30	-79.30	-158.50	NOAA
		120.16	91.28	-74.88	-163.55	Model
		16.56	8.98	4.42	-5.05	Difference
		14.80%	10.35%	5.73%	3.14%	% Diff

Table A.2. (Continued)

Station ID Number	Station Name	MHHW (cm)	MHW (cm)	MLW (cm)	MLLW (cm)	Data
9449771	Orcas Island	97.50	76.20	-73.20	-149.40	NOAA
		105.95	82.24	-68.06	-145.55	Model
		8.45	6.04	5.14	3.85	Difference
		8.31%	7.62%	7.28%	2.61%	% Diff
9449802	Stuart Island	85.30	67.00	-67.10	-143.30	NOAA
		107.23	84.87	-73.25	-149.19	Model
		21.93	17.87	-6.15	-5.89	Difference
		22.78%	23.53%	8.76%	4.03%	% Diff
9449828	Hanbury Point	95.80	75.60	-65.80	-136.70	NOAA
		101.59	84.45	-82.20	-141.37	Model
		5.79	8.85	-16.40	-4.67	Difference
		5.87%	11.06%	22.16%	3.36%	% Diff
9449880	Friday Harbor	97.70	78.00	-68.90	-138.70	NOAA
		103.88	84.55	-76.54	-143.57	Model
		6.18	6.55	-7.64	-4.87	Difference
		6.13%	8.06%	10.51%	3.45%	% Diff
9449911	Lopez Island, Upright Head	91.40	70.10	-70.10	-146.30	NOAA
		104.99	82.45	-71.68	-144.27	Model
		13.59	12.35	-1.58	2.03	Difference
		13.84%	16.19%	2.23%	1.40%	% Diff
9449932	Armitage Island	96.90	78.20	-71.40	-142.20	NOAA
		103.73	83.77	-74.60	-143.43	Model
		6.83	5.57	-3.20	-1.23	Difference
		6.81%	6.88%	4.38%	0.86%	% Diff
9449982	Lopez Island, Richardson	87.20	71.00	-67.60	-131.30	NOAA
		95.94	80.04	-74.65	-133.58	Model
		8.74	9.04	-7.05	-2.28	Difference
		9.54%	11.97%	9.91%	1.72%	% Diff
9449994	Lopez Island, Aleck Bay	85.40	64.00	-64.00	-140.20	NOAA
		96.36	79.33	-73.06	-134.95	Model
		10.96	15.33	-9.06	5.25	Difference
		12.06%	21.39%	13.22%	3.82%	% Diff

Table A.3. Station identification number or node number (as shown in Figure 5), station name, location in longitude and latitude (in degrees), and datum information (in cm).

Station ID/ Node Number	Station Name	Longitude (degrees)	Latitude (degrees)	MHHW (cm)	MHW (cm)	MLW (cm)	MLLW (cm)
9444900	Port Townsend	-122.7500	48.1117	107.4	86.7	-76.2	-152.2
9445016	Foulweather Bluff	-122.6167	47.9267	125.3	99.7	-99.7	-184.4
9445017	Port Ludlow	-122.6800	47.9250	122.0	97.6	-97.5	-179.8
9445526	Hansville	-122.5450	47.9183	133.5	107.7	-100.4	-184.5
9445639	Apple Tree Cove	-122.4933	47.7967	137.5	111.6	-111.5	-197.5
9445683	Point Jefferson	-122.4767	47.7467	135.9	109.7	-109.8	-194.2
9447427	Edmonds	-122.4767	47.7467	137.4	111.0	-110.2	-195.9
9447659	Everett	-122.3833	47.8133	140.4	113.8	-112.2	-197.6
9447725	Ebey Slough	-122.2233	47.9800	139.6	113.7	-114.0	-190.5
9447773	Tulalip Bay	-122.2100	48.0450	143.2	115.8	-112.8	-195.1
9447814	Glendale	-122.2883	48.0650	138.8	113.2	-111.6	-197.6
9447827	Double Bluff	-122.3567	47.9400	128.0	95.1	-94.8	-179.2
9447854	Bush Point	-122.5500	47.9783	143.3	119.5	-59.3	-141.7
9447855	Holly Harbor Farms	-122.6033	48.0333	145.4	118.3	-118.3	-203.3
9447856	Sandy Point	-122.5433	48.0267	142.8	116.0	-114.4	-200.4
9447883	Greenbank	-122.3767	48.0333	143.2	115.8	-115.9	-201.2
9447929	Coupeville Penn Cove	-122.6900	48.2233	146.3	118.9	-118.9	-204.2
9447951	Sunset Beach	-122.7283	48.2833	148.2	120.9	-121.7	-207.2
9447952	Crescent Harbor	-122.6167	48.2867	137.1	109.7	-100.6	-182.9
9447985	Smith Isl.	-122.8367	48.3167	131.1	103.7	-97.5	-179.8
9447993	Ala Spit	-122.5867	48.3967	141.1	114.3	-116.2	-201.5
9448094	Port Susan	-122.3667	48.1367	133.7	105.7	-99.5	-181.7
9448558	Swinomish Slough	-122.4967	48.3917	142.3	116.2	-116.5	-194.6
9448576	Skagit Bay	-122.5483	48.4000	138.0	107.6	-102.8	-182.0
9448601	Yokeko Point	-122.6150	48.4133	94.2	74.4	-66.4	-141.0
9448657	Turner Bay	-122.5550	48.4450	134.0	107.6	-105.1	-181.2
1		-122.6890	48.1800	101.5	75.0	-68.6	-154.9
2		-122.6940	48.1780	101.2	75.0	-68.5	-154.8
3		-122.7000	48.1750	100.9	75.0	-68.4	-154.8
4		-122.7110	48.1680	100.7	75.0	-68.2	-154.7
5		-122.7240	48.1610	100.0	74.8	-68.0	-154.4
6		-122.7330	48.1570	99.8	74.8	-67.9	-154.4
7		-122.7440	48.1510	99.6	74.7	-67.7	-154.3
8		-122.7550	48.1450	99.9	74.7	-67.6	-154.2
9		-122.6770	48.4440	93.9	73.4	-70.3	-144.2
10		-122.6900	48.4450	93.6	73.2	-70.0	-143.9
11		-122.7100	48.4410	92.8	72.5	-69.2	-143.9
12		-122.7260	48.4310	91.6	71.5	-68.0	-142.6
13		-122.7290	48.4190	91.1	71.5	-69.8	-141.2
14		-122.7180	48.4090	91.2	71.0	-67.5	-141.3
15		-122.7080	48.4000	91.5	71.2	-67.6	-142.3
16		-122.6990	48.3900	91.8	71.4	-67.8	-141.8
17		-122.6910	48.3790	91.8	71.4	-67.7	-141.9
18		-122.6730	48.3810	92.6	72.0	-68.3	-142.5
19		-122.6650	48.3810	92.8	72.2	-68.5	-142.7
20		-122.4850	48.5080	102.6	79.3	-74.8	-150.9

Table A.3. (Continued)

Station ID/ Node Number	Station Name	Longitude (degrees)	Latitude (degrees)	MHHW (cm)	MHW (cm)	MLW (cm)	MLLW (cm)
21		-122.4920	48.5080	102.5	79.2	-74.7	-150.8
22		-122.5000	48.5100	102.5	79.3	-74.7	-150.8
23		-122.5100	48.5090	102.5	79.2	-74.7	-150.8
24		-122.5180	48.5080	102.5	79.2	-74.6	-150.7
25		-122.5250	48.5080	102.4	79.1	-74.6	-150.7
26		-122.5330	48.5070	102.4	79.1	-74.6	-150.7
27		-122.5410	48.5060	102.3	79.0	-74.5	-150.6
28		-122.5480	48.4150	102.2	79.0	-74.4	-150.6
29		-122.5560	48.4450	102.0	78.8	-74.3	-150.4
30		-122.5570	48.2233	102.2	78.9	-74.4	-150.6

Table A.4. Station identification number (as shown in Figure 8), station name, location in longitude and latitude (in degrees), and datum information (in cm).

Station ID	Station Name	Latitude (degrees)	Longitude (degrees)	MHHW (cm)	MHW (cm)	MLW (cm)	MLLW (cm)
9444900	PORT TOWNSEND	48.1117	-122.7500	107.4	86.7	-76.2	-152.2
9445016	FOULWEATHER	47.9267	-122.6167	125.3	99.7	-99.7	-184.4
9445017	PORT LUDLOW	47.9250	-122.6800	122.0	97.6	-97.5	-179.8
9445059	PORT GAMBLE	47.8583	-122.5800	128.0	100.6	-103.6	-185.9
9445088	LOFALL WA	47.8150	-122.6583	133.2	106.1	-106.0	-193.2
9445133	BANGOR	47.7483	-122.7267	139.6	112.5	-110.1	-197.8
9445246	WHITNEY POINT	47.7617	-122.8500	145.6	116.2	-115.1	-206.7
9445269	ZELATCHED POINT	47.7117	-122.8217	146.3	115.8	-115.8	-204.2
9445272	QUILCENE DABOB	47.8000	-122.8583	141.4	115.6	-115.8	-205.4
9445293	PLEASANT	47.6650	-122.9117	146.3	115.8	-118.9	-207.3
9445296	SEABECK HOOD	47.6417	-122.8283	144.6	115.6	-114.6	-205.8
9445326	TRITON HEAD WA	47.6033	-122.9700	143.0	116.1	-115.8	-203.9
9445388	AYOCK POINT WA	47.5083	-123.0517	141.5	112.5	-112.4	-205.1
9445441	LYNCH COVE	47.4183	-122.9000	153.3	122.5	-122.5	-215.8
9445478	UNION HOOD	47.3583	-123.0983	149.1	119.0	-120.5	-212.2
9445526	HANSVILLE	47.9183	-122.5450	133.5	107.7	-100.4	-184.5
9445639	KINGSTON APPLE	47.7967	-122.4933	137.5	111.6	-111.5	-197.5
9445683	POINT JEFFERSON	47.7467	-122.4767	135.9	109.7	-109.8	-194.2
9445719	POULSBO	47.7250	-122.6383	149.4	122.6	-121.0	-208.1
9445753	PORT MADISON	47.7050	-122.5250	146.3	118.8	-115.9	-201.2
9445832	BROWNSVILLE	47.6517	-122.6150	149.7	122.9	-121.9	-211.0
9445882	EAGLE HARBOR	47.6200	-122.5150	140.2	115.8	-115.8	-204.2
9445901	TRACYTON DYES	47.6100	-122.6600	155.5	128.0	-128.0	-210.3
9445913	PORT BLAKELY	47.5967	-122.5100	146.3	118.9	-118.9	-204.2
9445938	CLAM BAY WA	47.5733	-122.5433	144.8	118.6	-118.5	-204.5
9445958	BREMERTON WA	47.5617	-122.6233	149.8	123.0	-121.2	-208.0
9445993	SOUTH COLBY-	47.5233	-122.5167	149.4	121.9	-118.9	-204.2
9446025	POINT VASHON	47.5117	-122.4633	145.4	118.9	-118.8	-206.0
9446248	DES MOINES WA	47.4000	-122.3283	147.5	120.4	-120.7	-207.9
9446273	BURTON	47.3867	-122.4650	154.2	126.4	-125.3	-213.1
9446281	ALLYN	47.3833	-122.8233	184.2	155.8	-156.3	-249.2
9446291	WAUNA CARR	47.3783	-122.6400	170.7	143.3	-143.3	-228.6
9446366	VAUGHN CASE	47.3417	-122.7750	182.9	155.4	-155.5	-246.9
9446369	GIG HARBOR	47.3400	-122.5883	149.4	125.0	-125.0	-210.3
9446375	NEILL POINT WA	47.3333	-122.5067	151.2	124.4	-124.0	-211.2
9446451	GREEN POINT	47.3017	-122.6817	175.1	147.1	-144.9	-235.4
9446484	TACOMA	47.2667	-122.4133	151.1	124.2	-122.4	-209.4
9446486	TACOMA	47.2717	-122.5517	161.2	133.8	-134.1	-222.5

Table A.4. (Continued)

Station ID	Station Name	Latitude (degrees)	Longitude (degrees)	MHHW (cm)	MHW (cm)	MLW (cm)	MLLW (cm)
9446489	WALKERS	47.2817	-122.9233	183.8	155.4	-155.5	-247.5
9446491	ARLETTA	47.2800	-122.6517	173.9	146.4	-141.8	-231.6
9446545	TACOMA	47.2550	-122.4317	150.8	124.0	-122.4	-209.7
9446583	BALLOW	47.2467	-122.8617	181.8	153.1	-151.5	-243.2
9446628	SHELTON	47.2150	-123.0833	199.6	169.1	-154.0	-233.2
9446638	LONGBRACH	47.2100	-122.7533	176.8	149.3	-146.3	-234.7
9446666	ARCADIA TOTTEN INLET	47.1967	-122.9383	189.0	158.5	-158.5	-249.9
9446671	DEVIL'S HEAD	47.1667	-122.7633	185.6	152.1	-152.1	-246.6
9446705	YOMAN POINT	47.1800	-122.6750	175.7	147.5	-145.4	-235.1
9446714	STEILACOOM	47.1733	-122.6033	174.1	146.3	-146.0	-236.8
9446742	BARRON POINT	47.1583	-123.0083	189.9	160.3	-160.7	-252.7
9446800	DOFFLEMEYER	47.1417	-122.9033	185.9	157.6	-157.9	-252.1
9446807	BUDD INLET GULL HARBOR	47.1000	-122.8967	187.9	159.1	-159.8	-253.5
9446828	DUPONT	47.1183	-122.6650	175.0	146.6	-146.9	-236.8
9446969	OLYMPIA BUD	47.0600	-122.9033	190.8	159.7	-159.7	-253.0
9447110	LOCKHEED	47.5850	-122.3617	144.2	117.9	-116.1	-202.7
9447130	SEATTLE	47.6050	-122.3383	143.9	117.5	-115.9	-202.3
9447265	MEADOW	47.6883	-122.4033	140.5	114.3	-114.7	-200.3
9447427	EDMONDS	47.8133	-122.3833	137.4	111.0	-110.2	-195.9
9447659	EVERETT WA	47.9800	-122.2233	140.4	113.8	-112.2	-197.6
9447725	EBEY SLOUGH	48.0450	-122.2100	139.6	113.7	-114.0	-190.5
9447773	TULALIP BAY	48.0650	-122.2883	143.2	115.8	-112.8	-195.1
9447814	GLENDALE	47.9400	-122.3567	138.8	113.2	-111.6	-197.6
9447827	DOUBLE BLUFF	47.9783	-122.5500	128.0	95.1	-94.8	-179.2
9447854	BUSH POINT	48.0333	-122.6067	114.0	90.2	-88.6	-1.710
9447855	HOLLY	48.0267	-122.5333	145.4	118.3	-118.3	-203.3
9447856	SANDY POINT	48.0350	-122.3767	142.8	116.0	-114.4	-200.4
9447883	GREENBANK	48.1050	-122.5700	143.2	115.8	-115.9	-201.2
9448094	KAYAK PT	48.1367	-122.3667	141.1	114.3	-116.2	-201.5

Table A.5. Errors in the VDatum tidal fields at water level stations. Station identification number, location, RMSE (cm) and standard deviation (cm) for all 35 stations in the combined Northern Puget Sound and Strait of Juan de Fuca VDatum domain.

Station ID #	Latitude (degrees)	Longitude (degrees)	RMSE (cm)	Standard Deviation (cm)
9442861	48.296700	-124.671700	0.3020	0.3010
9443090	48.368330	-124.616670	1.1250	1.0570
9443361	48.263300	-124.296700	0.9450	0.8850
9443644	48.175000	-123.950000	0.2550	0.2230
9443826	48.161700	-123.725000	0.5130	0.5120
9444090	48.125000	-123.440000	0.3520	0.3310
9444122	48.136670	-123.408330	1.0670	1.0100
9444705	48.058330	-122.916660	0.6390	0.6300
9447929	48.223330	-122.690000	0.0120	0.0110
9447951	48.283330	-122.728330	0.2850	0.2080
9447952	48.286700	-122.616700	0.4750	0.4640
9447985	48.316670	-122.836670	0.6260	0.6150
9447993	48.396670	-122.586670	0.6950	0.5990
9447995	48.401670	-122.623340	0.2760	0.2670
9448558	48.391700	-122.496700	0.6030	0.5830
9448576	48.400000	-122.548300	1.8340	1.7350
9448601	48.413330	-122.615000	0.8150	0.8030
9448614	48.415000	-122.651700	0.3930	0.3570
9448657	48.445000	-122.555000	0.1000	0.0960
9448772	48.506670	-122.676670	0.5820	0.0860
9448967	48.615000	-122.691670	0.5750	0.1190
9449161	48.716700	-122.708300	0.8550	0.2700
9449211	48.745000	-122.495000	0.4920	0.4510
9449292	48.790000	-122.708300	0.1370	0.0950
9449424	48.863330	-122.758330	0.0880	0.0660
9449679	48.991700	-122.76500	0.5380	0.4850
9449704	48.786670	-122.970000	0.6950	0.3740
9449771	48.646670	-122.870000	0.1770	0.1760
9449802	48.688330	-123.236660	1.3560	1.0700
9449828	48.581700	-123.170000	0.6900	0.4130
9449880	48.546660	-123.010000	0.2760	0.0220
9449911	48.571670	-122.885000	0.3040	0.1610
9449932	48.535000	-122.796670	0.4090	0.0780
9449982	48.446670	-122.898330	0.3020	0.1410
9449994	48.425000	-122.853330	0.1260	0.1180

Table A.6. Errors in the VDatum tidal fields at water level stations. Station identification number, location, RMSE (cm) and standard deviation (cm) for all 66 stations in the Southern Puget Sound VDatum domain.

Station ID Number	Latitude (degrees)	Longitude (degrees)	RMSE (cm)	Standard Deviation (cm)
9444900	48.1117	-122.7500	0.041	0.029
9445016	47.9267	-122.6167	0.000	0.000
9445017	47.9250	-122.6800	0.001	0.001
9445059	47.8583	-122.5800	0.000	0.000
9445088	47.8150	-122.6583	0.000	0.000
9445133	47.7483	-122.7267	0.018	0.015
9445246	47.7617	-122.8500	0.006	0.006
9445269	47.7117	-122.8217	0.000	0.000
9445272	47.8000	-122.8583	0.014	0.012
9445293	47.6650	-122.9117	0.000	0.000
9445296	47.6417	-122.8283	0.000	0.000
9445326	47.6033	-122.9700	0.012	0.011
9445388	47.5083	-123.0517	0.001	0.001
9445441	47.4183	-122.9000	0.000	0.000
9445478	47.3583	-123.0983	0.000	0.000
9445526	47.9183	-122.5450	0.000	0.000
9445639	47.7967	-122.4933	0.002	0.002
9445683	47.7467	-122.4767	0.000	0.000
9445719	47.7250	-122.6383	0.000	0.000
9445753	47.7050	-122.5250	0.012	0.012
9445832	47.6517	-122.6150	0.000	0.000
9445882	47.6200	-122.5150	0.000	0.000
9445901	47.6100	-122.6600	0.000	0.000
9445913	47.5967	-122.5100	0.005	0.005
9445938	47.5733	-122.5433	0.004	0.004
9445958	47.5617	-122.6233	0.000	0.000
9445993	47.5233	-122.5167	0.000	0.000
9446025	47.5117	-122.4633	0.000	0.000
9446248	47.4000	-122.3283	0.000	0.000
9446273	47.3867	-122.4650	0.000	0.000
9446281	47.3833	-122.8233	0.000	0.000
9446291	47.3783	-122.6400	0.026	0.026
9446366	47.3417	-122.7750	0.000	0.000
9446369	47.3400	-122.5883	0.001	0.001
9446375	47.3333	-122.5067	0.004	0.004
9446451	47.3017	-122.6817	0.006	0.006

Table A.6. (Continued)

Station ID Number	Latitude (degrees)	Longitude (degrees)	RMSE (cm)	Standard Deviation (cm)
9446484	47.2667	-122.4133	1.794	1.574
9446486	47.2717	-122.5517	0.018	0.018
9446489	47.2817	-122.9233	0.000	0.000
9446491	47.2800	-122.6517	0.000	0.000
9446545	47.2550	-122.4317	1.768	1.652
9446583	47.2467	-122.8617	0.000	0.000
9446628	47.2150	-123.0833	0.000	0.000
9446638	47.2100	-122.7533	0.000	0.000
9446666	47.1967	-122.9383	0.001	0.001
9446671	47.1667	-122.7633	0.000	0.000
9446705	47.1800	-122.6750	0.015	0.008
9446714	47.1733	-122.6033	0.000	0.000
9446742	47.1583	-123.0083	0.043	0.042
9446800	47.1417	-122.9033	0.029	0.026
9446807	47.1000	-122.8967	0.000	0.000
9446828	47.1183	-122.6650	0.003	0.003
9446969	47.0600	-122.9033	0.000	0.000
9447110	47.5850	-122.3617	0.000	0.000
9447130	47.6050	-122.3383	0.000	0.000
9447265	47.6883	-122.4033	0.000	0.000
9447427	47.8133	-122.3833	0.009	0.008
9447659	47.9800	-122.2233	0.000	0.000
9447725	48.0450	-122.2100	0.009	0.009
9447773	48.0650	-122.2883	0.000	0.000
9447814	47.9400	-122.3567	0.000	0.000
9447827	47.9783	-122.5500	0.000	0.000
9447855	48.0267	-122.5333	0.002	0.002
9447856	48.0350	-122.3767	0.003	0.003
9447883	48.1050	-122.5700	0.000	0.000
9448094	48.1367	-122.3667	0.029	0.013

Table A.7. QA/QC Delta values, or differences between modeled and observed tidal datums, at NOS geodetic benchmarks from the Strait of Juan de Fuca and Northern Puget Sound (North) regional and the Southern Puget Sound (South) regional TSS grid and the four tidal datum grids. The PID is the benchmark identification number. The Std. Dev. is the standard deviation about the mean of the four Deltas at the individual benchmark.

PID	Latitude (deg)	Longitude (deg)	MHHW Delta (cm)	MHW Delta (cm)	MLW Delta (cm)	MLLW Delat (cm)	Avg. (cm)	Std. Dev. (cm)	Reg.
TS0171	48.36833	-124.62305	-0.10	-0.40	0.97	0.49	0.0024	0.0061	North
AF8873	48.36805	-124.62666	0.26	0.07	1.10	0.71	0.0053	0.0046	North
AF8872	48.36805	-124.62388	-0.03	-0.32	1.04	0.56	0.0031	0.0061	North
TS0340	48.36694	-124.61944	-0.03	-0.48	1.32	0.71	0.0038	0.0080	North
TS0152	48.36694	-124.60416	-0.05	-0.84	2.08	0.88	0.0052	0.0126	North
TS0150	48.36694	-124.60416	-0.05	-0.84	2.08	0.88	0.0052	0.0126	North
TS0154	48.36638	-124.61138	-0.04	-0.91	2.56	1.27	0.0072	0.0152	North
AF8871	48.36583	-124.61722	-0.05	-0.70	1.95	1.03	0.0056	0.0117	North
TS0161	48.36555	-124.62083	0.53	0.04	1.99	1.33	0.0097	0.0086	North
TS0156	48.36555	-124.61666	-0.01	-0.82	2.50	1.33	0.0075	0.0147	North
TR0785	48.14055	-123.40972	-0.05	3.24	-1.58	2.76	0.0109	0.0230	North
TR0784	48.14055	-123.40888	0.06	3.25	-1.51	2.71	0.0113	0.0224	North
TR0779	48.14055	-123.40250	-0.10	2.83	-1.81	2.06	0.0075	0.0211	North
TR0782	48.14000	-123.40194	0.03	2.80	-1.81	1.88	0.0073	0.0205	North
TR0783	48.14000	-123.40138	-0.01	2.81	-1.84	1.90	0.0071	0.0207	North
TR0789	48.12722	-123.45777	0.04	-0.86	1.68	0.17	0.0026	0.0105	North
TR0790	48.12333	-123.44472	0.11	-0.42	0.98	0.11	0.0020	0.0058	North
TR0559	48.11583	-122.75194	0.06	-0.11	0.61	0.03	0.0015	0.0032	South
TR2726	48.11138	-122.76166	0.32	-0.02	0.30	-0.55	0.0001	0.0041	South
SY0126	47.81305	-122.38027	-0.10	0.01	0.11	0.01	0.0001	0.0009	South
SY0128	47.81138	-122.38250	-0.04	0.06	0.16	0.06	0.0006	0.0008	South
SY0959	47.74666	-122.72638	0.02	0.12	0.02	0.02	0.0005	0.0005	South
SY0289	47.60444	-122.33500	-0.01	0.09	-0.11	-0.01	-0.0001	0.0008	South
SY0290	47.60388	-122.33750	-0.09	0.01	-0.19	-0.09	-0.0009	0.0008	South
SY0286	47.60305	-122.33444	-0.01	0.09	-0.11	-0.01	-0.0001	0.0008	South
SY0283	47.60194	-122.33388	0.14	0.24	0.02	0.12	0.0013	0.0009	South
SY0273	47.58416	-122.36250	0.12	0.02	0.12	0.02	0.0007	0.0006	South
SY0272	47.58194	-122.36277	0.29	0.18	0.29	0.19	0.0024	0.0006	South
SY0271	47.57833	-122.36277	0.19	0.09	0.20	0.10	0.0015	0.0006	South
SY0270	47.57444	-122.36277	0.06	-0.04	0.07	-0.03	0.0002	0.0006	South
SY0920	47.56305	-122.62527	0.77	0.77	0.77	0.77	0.0077	0.0000	South
SY5718	47.56305	-122.62416	-0.72	-0.72	-0.72	-0.72	-0.0072	0.0000	South
SY0536	47.26416	-122.41194	0.84	0.99	-1.58	-2.03	-0.0045	0.0158	South
SY0866	47.05194	-122.90388	-0.23	-0.44	-0.25	-0.08	-0.0025	0.0015	South
SY0865	47.05166	-122.90250	-0.06	-0.27	-0.08	0.09	-0.0008	0.0015	South
SY0868	47.05000	-122.90138	0.27	0.06	0.25	0.42	0.0025	0.0015	South

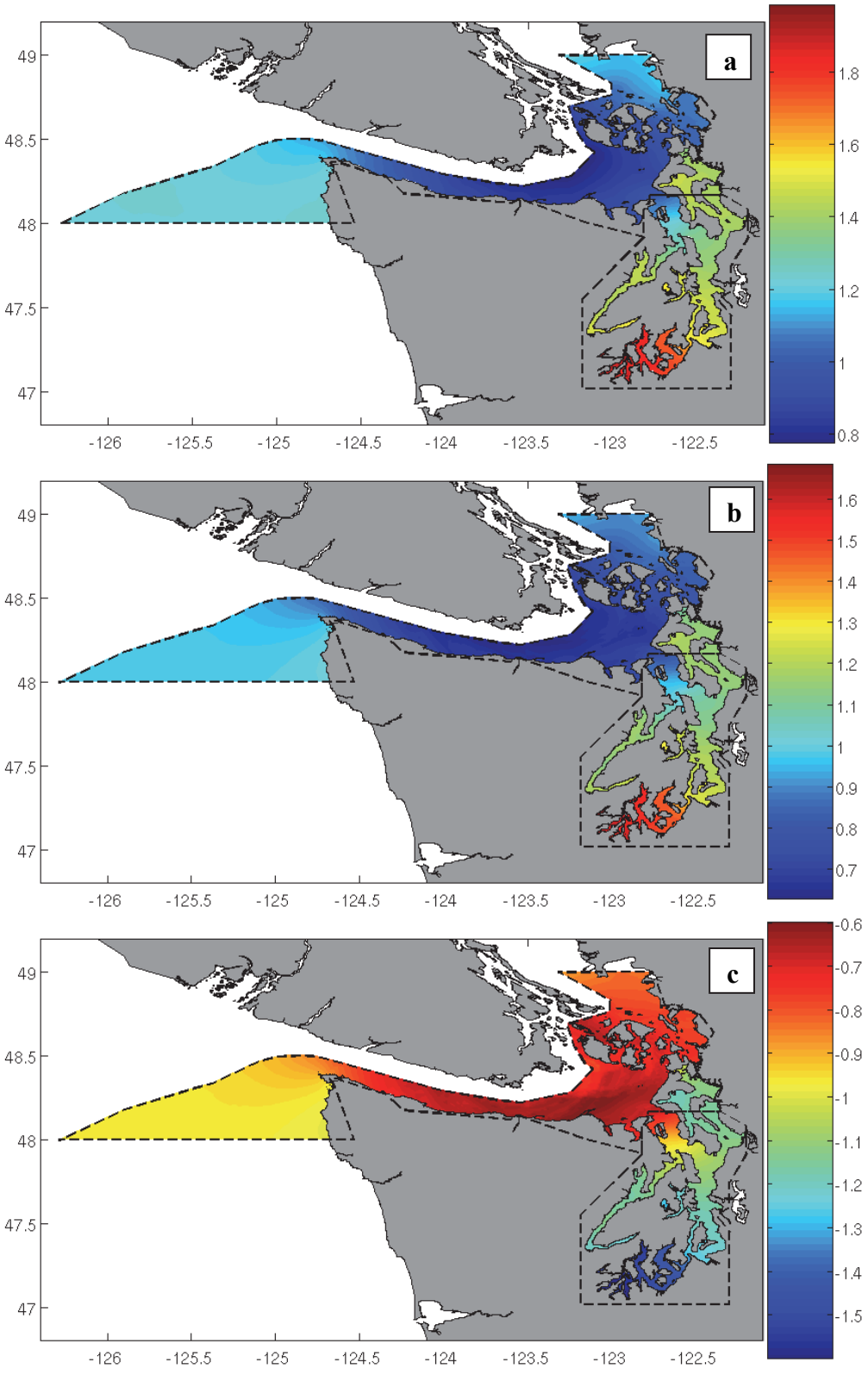
Table A.8. Comparison of modeled TSS and observed values at NOS benchmarks in the Northern Puget Sound and Strait of Juan de Fuca region. The PID is either the water level station number or the benchmark identification number.

PID	Latitude (deg)	Longitude (deg)	Observed NAVD 88 to MSL (m)	TSS Modeled Value (m)	Difference (cm)
9443090	48.36833	-124.61667	-1.0590	-1.0607	0.17
9443361	48.26333	-124.29667	-1.0930	-1.0933	0.03
9443826	48.16167	-123.72500	-1.1580	-1.1581	0.01
9444090	48.12500	-123.44000	-1.1660	-1.1668	0.08
9444122	48.14000	-123.41333	-1.1850	-1.1852	0.02
9444900	48.11167	-122.75833	-1.1895	-1.1899	0.04
9447952	48.28667	-122.61667	-1.3970	-1.3960	-0.10
9448558	48.39167	-122.49667	-1.3560	-1.3563	0.03
9448576	48.40000	-122.54833	-1.3310	-1.3313	0.03
9448657	48.44500	-122.55500	-1.3470	-1.3470	0.00
9449211	48.74500	-122.49500	-1.3630	-1.3632	0.02
9449424	48.86333	-122.75833	-1.3170	-1.3173	0.03
9449679	48.99167	-122.76500	-1.3600	-1.3622	0.22
TR0790	48.12333	-123.44472	-1.1629	-1.1640	0.11
TR0789	48.12722	-123.45777	-1.1634	-1.1638	0.04
TR0782	48.14000	-123.40194	-1.1976	-1.1980	0.04
TR0783	48.14000	-123.40138	-1.1980	-1.1979	-0.01
TR0784	48.14055	-123.40888	-1.2014	-1.2020	0.06
TR0785	48.14055	-123.40972	-1.2021	-1.2016	-0.05
TR0779	48.14055	-123.40250	-1.1991	-1.1982	-0.09
TS0156	48.36555	-124.61666	-1.0676	-1.0675	-0.01
TS0161	48.36555	-124.62083	-1.0625	-1.0678	0.53
AF8871	48.36583	-124.61722	-1.0681	-1.0677	-0.04
TS0154	48.36638	-124.61138	-1.0682	-1.0678	-0.04
TS0152	48.36694	-124.60416	-1.0691	-1.0685	-0.06
TS0340	48.36694	-124.61944	-1.0620	-1.0617	-0.03
TS0340	48.36694	-124.61944	-1.0620	-1.0617	-0.03
TS0150	48.36694	-124.60416	-1.0691	-1.0685	-0.06
AF8872	48.36805	-124.62388	-1.0636	-1.0634	-0.02
AF8873	48.36805	-124.62666	-1.0595	-1.0621	0.26
TS0171	48.36833	-124.62305	-1.0636	-1.0626	-0.10

Table A.9. Comparison of modeled TSS and observed values at NOS benchmarks in the Southern Puget Sound region. The PID is either the water level station number or the benchmark identification number.

PID	Latitude (deg)	Longitude (deg)	Observed NAVD 88 to MSL (m)	TSS Modeled Value (m)	Difference (cm)
9444900	48.11167	-122.75833	-1.1895	-1.1899	0.04
9445133	47.74833	-122.72667	-1.2500	-1.2503	0.03
9445246	47.76167	-122.85000	-1.2530	-1.2530	0.00
9445478	47.35833	-123.09833	-1.2570	-1.2571	0.01
9445958	47.56167	-122.62333	-1.3110	-1.3110	0.00
9446281	47.38333	-122.82333	-1.2635	-1.2633	-0.02
9446484	47.26667	-122.41333	-1.3360	-1.3362	0.02
9446491	47.28000	-122.65167	-1.1140	-1.1163	0.23
9446545	47.25500	-122.43167	-1.3020	-1.3023	0.03
9446969	47.06000	-122.90333	-1.3190	-1.3191	0.01
9447110	47.58500	-122.36167	-1.3010	-1.3002	-0.08
9447130	47.60500	-122.33833	-1.3080	-1.3081	0.01
9447427	47.81333	-122.38333	-1.3220	-1.3223	0.03
9447659	47.98000	-122.22333	-1.3560	-1.3561	0.01
9447814	47.94000	-122.35667	-1.3555	-1.3554	-0.01
SY0868	47.05000	-122.90138	-1.3038	-1.3063	0.25
SY0865	47.05166	-122.90250	-1.3128	-1.3120	-0.08
SY0866	47.05194	-122.90388	-1.3158	-1.3133	-0.25
SY0536	47.26416	-122.41194	-1.3455	-1.3410	-0.45
SY0920	47.56305	-122.62527	-1.3030	-1.3107	0.77
SY5718	47.56305	-122.62416	-1.3180	-1.3108	-0.72
SY0270	47.57444	-122.36277	-1.2986	-1.2987	0.01
SY0271	47.57833	-122.36277	-1.2956	-1.2970	0.14
SY0272	47.58194	-122.36277	-1.2955	-1.2979	0.24
SY0273	47.58416	-122.36250	-1.2985	-1.2992	0.07
SY0283	47.60194	-122.33388	-1.3070	-1.3083	0.13
SY0286	47.60305	-122.33444	-1.3100	-1.3099	-0.01
SY0290	47.60388	-122.33750	-1.3100	-1.3091	-0.09
SY0289	47.60444	-122.33500	-1.3100	-1.3099	-0.01
SY0959	47.74666	-122.72638	-1.2498	-1.2502	0.05
SY0128	47.81138	-122.38250	-1.3190	-1.3196	0.06
SY0126	47.81305	-122.38027	-1.3220	-1.3221	0.01
TR2726	48.11138	-122.76166	-1.1894	-1.1895	0.01
TR0559	48.11583	-122.75194	-1.1939	-1.1954	0.15

APPENDIX B. VDATUM MARINE GRID WITH DATUMS



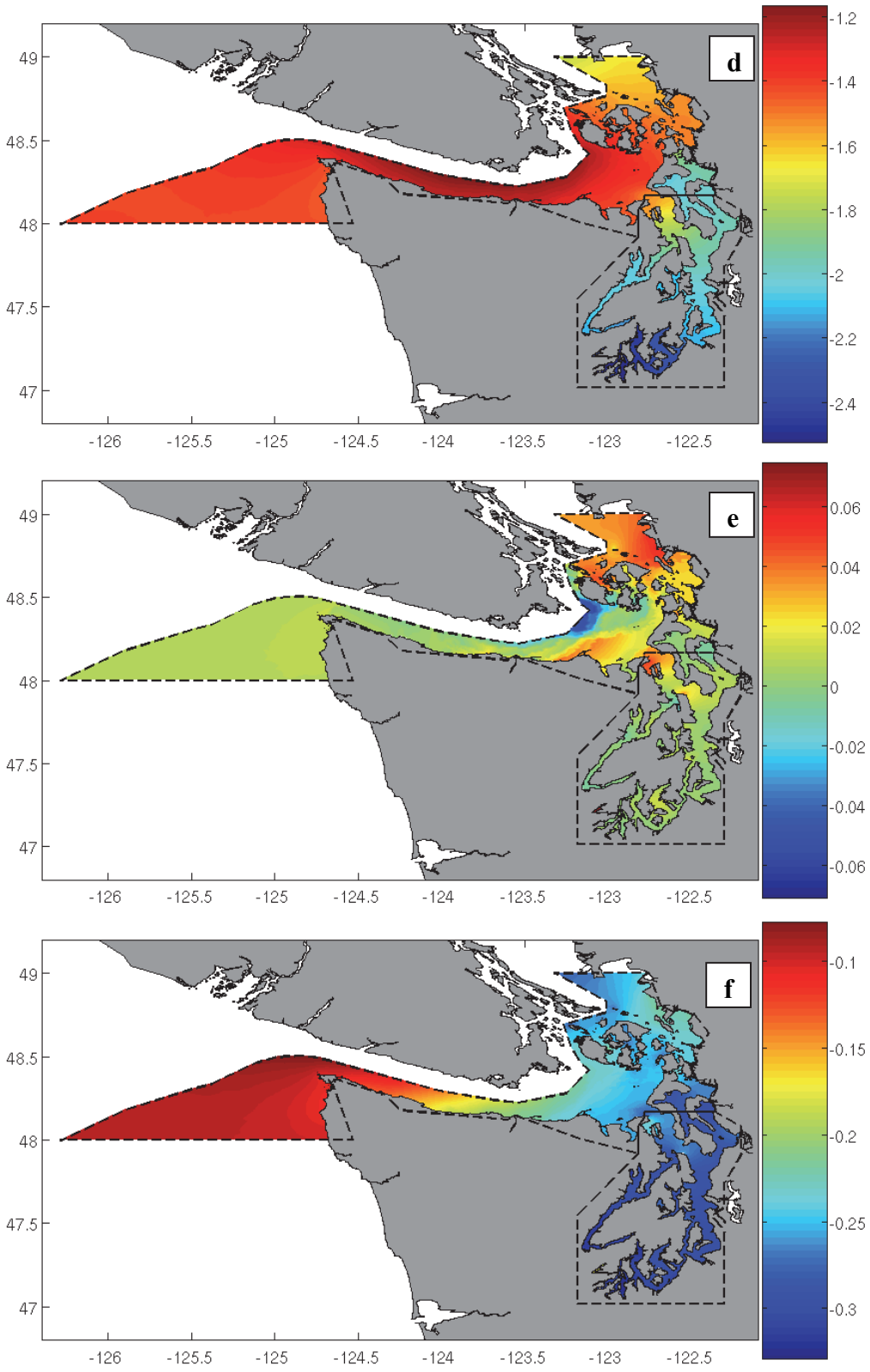


Figure B.1. Combined Northern Puget Sound and Strait of Juan de Fuca, and Southern Puget VDatum marine grids populated by (a) MHHW, (b) MHW, (c) MLW, (d) MLLW, (e) MTL, and (f) DTL tidal datum fields.