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Tidal Datum Distributions in Puget Sound, Washington, Based on a Tidal Model

H.O. Mofjeld[1], A.J. Venturato[2], V.V. Titov[2], F.I. González[1], J.C. Newman[2]

[1]Pacific Marine Environmental Laboratory
7600 Sand Point Way NE
Seattle, WA 98115

[2]Joint Institute for the Study of the Atmosphere and Ocean (JISAO)
University of Washington
Box 351640
Seattle, WA 98195

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Contents

List of Figures

List of Tables

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Abstract. To improve the spatial estimates of tidal datums in Puget Sound, Washington, the harmonic constant datum method has been applied to the harmonic constants from a channel tide model of the Sound. This was done using the FORM180 Version 1.8 program. The model datums, harmonic constants, and associated geospatial information are available on the website `www.pmel.noaa.gov/tsunami/TIME/`. Focusing on mean high water (MHW) relative to mean lower low water, it increases in height from 2.16 m at Port Townsend to 4.10 m at Olympia and 4.17 m at the head of Oakland Bay. Larger increases per km occur in Admiralty Inlet (1.66 cm/km) and the Tacoma Narrows (2.92 cm/km); smaller gradients occur in the Main Basin (0.44 cm/km) and South Sound (0.70 cm/km). The model MHW in Hood Canal closely follows MHW along the main axis with distance away from the main entrance to the Sound, to a maximum of 3.23 m at the head of Lynch Cove. This is also true for MHW in Whidbey Basin, except for a maximum of 3.17 m in southern Skagit Bay before decreasing northward toward Deception Pass. The model datums relative to MLLW tend to be slightly less than values derived from tide gage observations. For MHW, an average deviation of −3.6 cm occurs in the Main Basin, with smaller deviations in Admiralty Inlet (−1.1 cm) and the South Sound (−1.8 cm) and larger ones in Whidbey Basin (−7.8 cm) and Hood Canal (−8.5 cm). Further improvements to the datums should include adjusting the model datums to tide gage observations and applying high-resolution models to high-current areas and large tideflats.

1. Introduction

This technical memorandum focuses on improving the estimates of tidal datums in Puget Sound, Washington. It is part of a project undertaken by the NOAA/Center for Tsunami Inundation Modeling Efforts (TIME) in support of Washington State's ongoing tsunami mitigation program. The goal of the project is to map potential tsunami inundation in and near communities bordering the Sound. The tsunami inundation maps are created from the results of numerical models that simulate the behavior of real tsunamis. Essential to the accuracy of these simulations are high-resolution digital elevation models (DEMs) that approximate the water depths and coastal land elevations over which the tsunami waves propagate. The DEMs are formed by merging high-resolution grids of depth and elevation. Since the available land elevations are referenced to mean high water (MHW) and the water depths to mean lower low water (MLLW), an accurate estimate of the difference in height between these datums is required at each grid point, in order to develop the DEM for the region of interest. Puget Sound (Fig. 1.1) is a region in which the tides, and hence the tidal datums, vary considerably with location. Descriptions of the tides in Puget Sound have been published by Mofjeld and Larsen (1984) and Lavelle *et al.* (1988). Figure 1.2 shows an example of tides and tidal datums for the Seattle tide station, which is

[1]NOAA/Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115

[2]Joint Institute for the Study of the Atmosphere and Ocean (JISAO), University of Washington, Box 351640, Seattle, WA 98195

the primary reference station for Puget Sound. A general discussion of tidal datums is given by Marmer (1951) and NOAA/NOS (2000).

To estimate the distribution of tidal datums in the Sound, we applied the harmonic constant datum (HCD) method. As input to the method, we used the distribution of harmonic constants from the channel tide model of Lavelle *et al.* (1988). This model divides Puget Sound into 545 segments that extend across individual channels or form junctions between them. The tidal datums, harmonic constants, and associated geospatial information are available on the website `www.pmel.noaa.gov/tsunami/TIME/`, with the understanding that they are for research purposes only. A description of the NOAA/TIME Center's activities (`www.pmel.noaa.gov/tsunami/`) and the U.S. National Tsunami Hazard Mitigation Program (`www.pmel.noaa.gov/tsunami-hazard/`) that funds this work can be found on the World Wide Web.

This memorandum is organized into the following sections: 1. Introduction, 2. Harmonic Constant Datum Method, 3. Channel Tide Model, 4. Computational Procedures, 5. Results and Products, 6. Discussion, 7. Summary, 8. Acknowledgments, 9. Appendix, and 10. References.

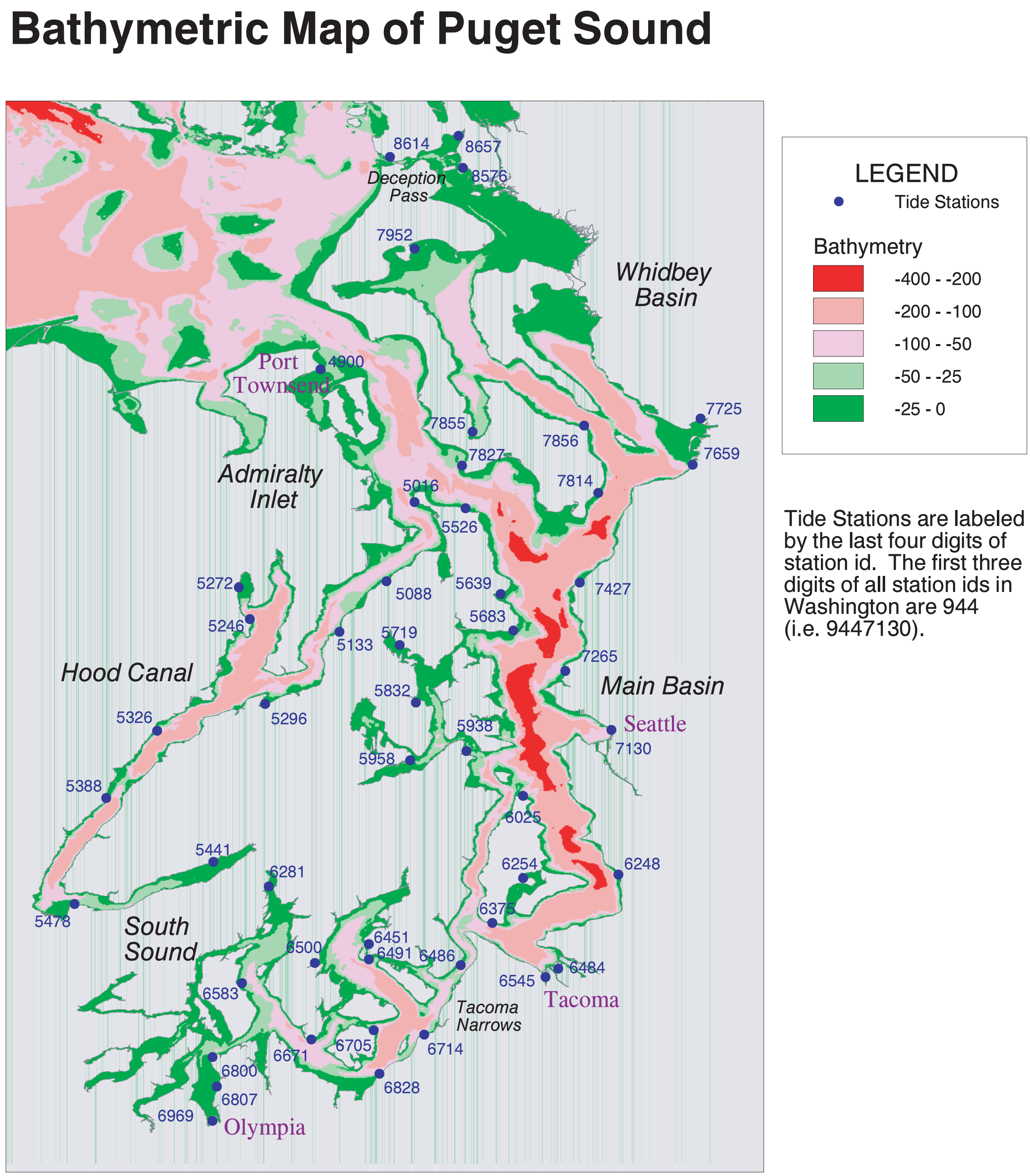


Figure 1.1: Bathymetric map of Puget Sound showing major basins and channels, cities, and NOAA tide stations. The station locations and datums were taken from the NOAA/NGS (`www.ngs.noaa.gov`) and NOAA/NOS/CO-OPS (`www.co-ops.nos.noaa.gov`) websites.

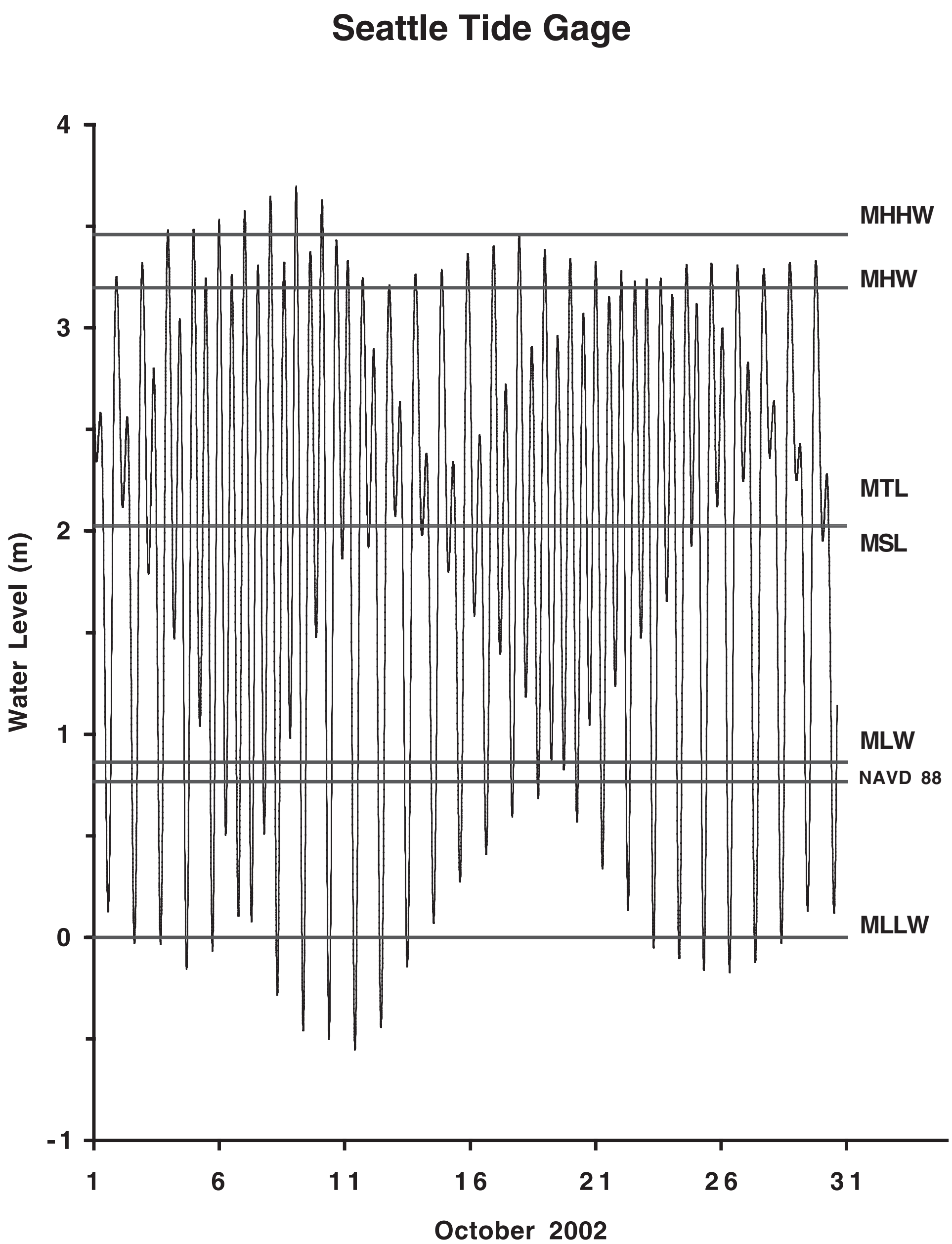


Figure 1.2: Official tidal datums and sample observations of water at the 9447130 Seattle tide gage (47° 36.3′N 122° 20.3′W), relative to MLLW. The datums were computed from the 19-year tidal epoch 1960–1978, and the water levels were sampled every 6 minutes. The values were taken from the NOAA/NOS/CO-OPS (`www.co-ops.nos.noaa.gov`) website.

2. Harmonic Constant Datum Method

The harmonic constant datum (HCD) method estimates the heights of tidal datums relative to mean sea level from tidal harmonic constants (Harris, 1894; C&GS, 1952; Mofjeld *et al.*, in review). The method is based on the fact that these heights are most often controlled by the M2, K1, and O1 tides, with smaller contributions from the other constituents. These three constituents form a fixed pattern in time, called the average tidal curve. This is because the sum of the K1 and O1 frequencies exactly equals that of the M2 tide. Averaged over a 19-year tidal epoch, the high and low waters associated with the average tidal curve dominate the values of the tidal datums. The HCD method uses explicit corrections for P1, N2, S2, μ2, M4, and M6, while the effects of the other constituents are included via empirical coefficients. The theory underlying the method is given in detail by Harris (1894) and C&GS (1952). One merit of this method is that it is very efficient, since it does not require the generation of long time series in order to compute tidal datums.

Developed well before the advent of computers, the HCD method was rendered into the C&GS Form 180 to guide the calculations. Associated with the form are look-up tables that use various amplitude ratios and phase differences as input; C&GS (1952) provides listings of these tables. The form and tables have been converted into a set of Fortran subroutines. Except for its Table 17, each of the tables is replaced by an iterative process derived from the original implicit formulas in C&GS (1952). The computer code has been verified by comparison with the examples provided by C&GS (1952).

3. Puget Sound Channel Tide Model

3.1 Description of the channel tide model

The Puget Sound channel tide model (Lavelle *et al.*, 1988) divides the Sound into 545 segments (Fig. 3.1). The linearized equations of motion with friction are used in finite difference form. The instantaneous water level is approximated by its average value within a given segment, and the tidal current between adjacent segments by its cross-sectional average. Assuming sinusoidal forms for time dependence, the model separately estimates the spatial distributions of the tidal and current harmonic constants for each of the major tidal constituents O1, P1, K1, N2, M2, and S2, as well as the M4 tide.

Solving the one-dimensional equations in each of the 79 channels representing Puget Sound produces two sets of conditions at the 43 junctions that lie between three or more channels. The first set is that the instantaneous water level is the same in a given junction as it is in the channel segments immediately adjacent to it. The second is that the sum of the instantaneous tidal transport into the junction must equal the time rate of change of the water level within the junction times its surface area. A boundary condition of no horizontal transport is used at the heads of embayments.

All these conditions are solved simultaneously to give the spatial distribution for the complex amplitudes throughout the Sound, relative to a given constituent's amplitude at the northern end of Admiralty Inlet and Deception Pass (Fig. 1.1). Admiralty Inlet is the main entrance by which the tides enter Puget Sound from the Strait of Juan de Fuca. Deception Pass is a much smaller entrance at the northern end of Whidbey Basin which affects the local tides in the northern part of Skagit Bay. The model neglects the tidal exchange through Swinomish Channel, a very narrow (minimum width of 100 m) and shallow (navigation channel control depth of 3 m below MLLW) that is also at the northern end of Whidbey Basin.

The tuning of the friction coefficients was done on the M2 tide. After setting the friction coefficient to a uniform value, the entrance M2 harmonic constants and the friction coefficients in the high-current channel were adjusted to match the observed M2 harmonic constants. This was done at 47 tide stations (Fig. 1.1) throughout the Sound. M2 is the largest tidal constituent in the region and dominates the tidal currents; it therefore controls the frictional effects on the other constituents. Using this same distribution of friction coefficients, the entrance harmonic constant of the other constituents were then adjusted to get a best fit to their observed values at the tide stations. The modulus of the complex amplitude is the amplitude of the harmonic constants while its phase gives the phase lag. The details of the model equations, the fitting procedures, and the comparison with observations are given by Lavelle *et al.* (1988). A brief summary of the tidal distributions is provided in the Appendix.

3.2 Adjustments for computing the tidal datums

Because the segment indices used by Lavelle *et al.* (1988) are often non-sequential within individual channels, it was necessary to develop the new index scheme shown in Fig. 3.1 and Table 3.1. The two-digital integer indices for the junctions were not changed. Internally within the database, 10000 is added to the indices (e.g., the internal index of junction 43 is 10043 and that of the channel segment 5601 is 15601) so that the index of each junction and channel segment has five significant figures. For efficiency of presentation and clarity of figures and tables, this prefix is left off the indices shown in figures and tables.

Since there is a close relationship between P1 and K1 (separated in frequency by two cycles per year), we use the following formulas to compute the P1 amplitude and phase lag based on the observed tides at Seattle

$$\mathrm{P1} = 0.303\ \mathrm{K1} \tag{1}$$

$$\mathrm{P1}^\circ = \mathrm{K1}^\circ - 0.128(\mathrm{K1}^\circ - \mathrm{O1}^\circ) \tag{2}$$

The HCD method also requires estimates of the small $\mu 2$ harmonic constant. For $\mu 2$, we also estimate its amplitude and phase lag on the following relationships at Seattle:

$$\mu 2 = 0.030\ \mathrm{M2} \tag{3}$$

$$\mu 2^\circ = \mathrm{S2}^\circ - 6.309(\mathrm{S2}^\circ - \mathrm{M2}^\circ) \tag{4}$$

where 360° is added to S2° when S2°<M2° .

While the channel tide model estimates the distribution of the M4 harmonic constants, there are significant deviations between the model and observed M4 harmonic constants, particularly in the South Sound. For this reason the computation of datums presented here used average observed M4 values for the basins, while smooth transitions were used in the channels connecting these basins. The small M6 tide is assumed to have a negligible effect on the datums in Puget Sound, and its amplitude was set to zero in the input to the HCD method.

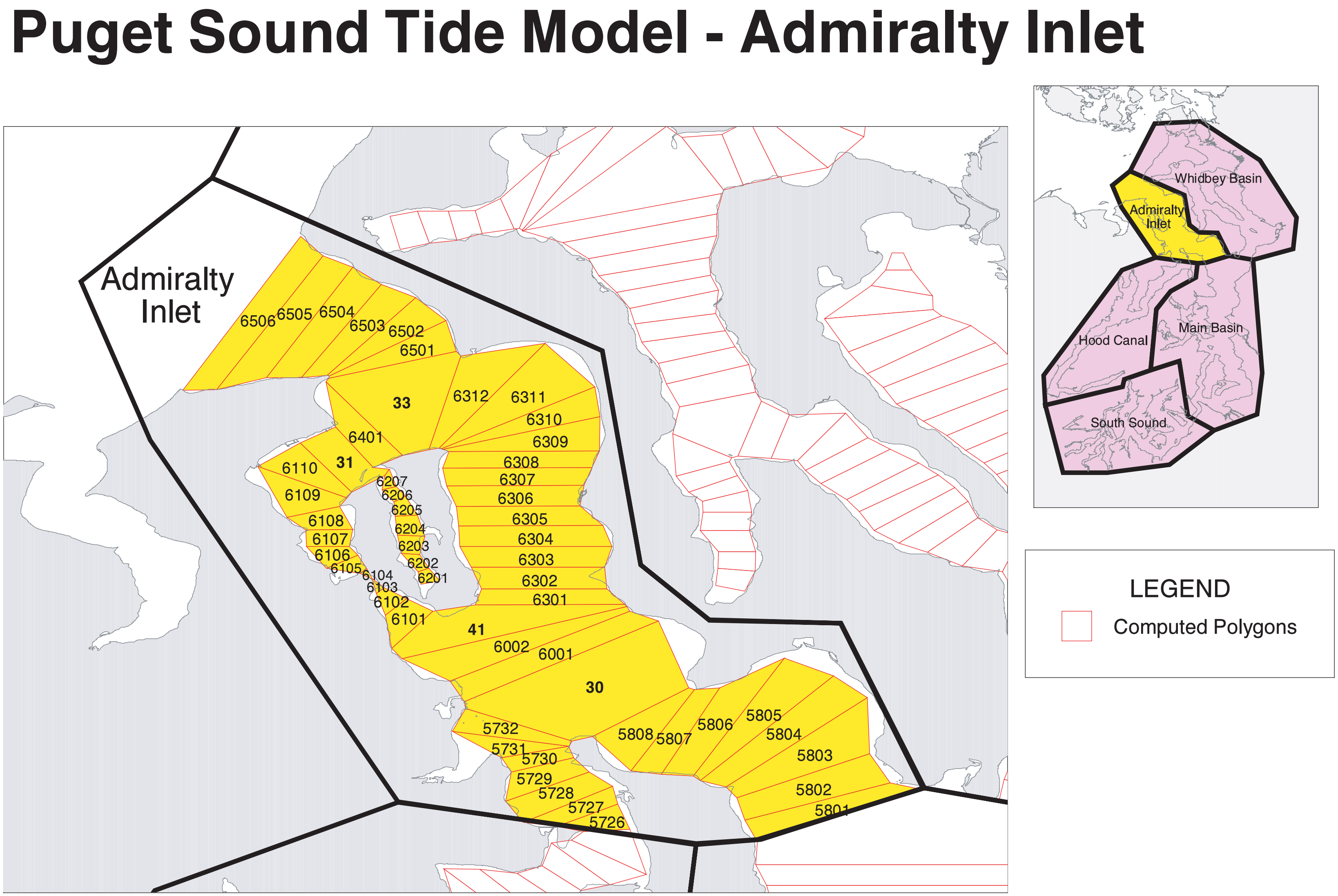


Figure 3.1a: Map of Admiralty Inlet showing segments from the Puget Sound channel tide model (Lavelle *et al.*, 1988).

Puget Sound Tide Model - Whidbey Basin

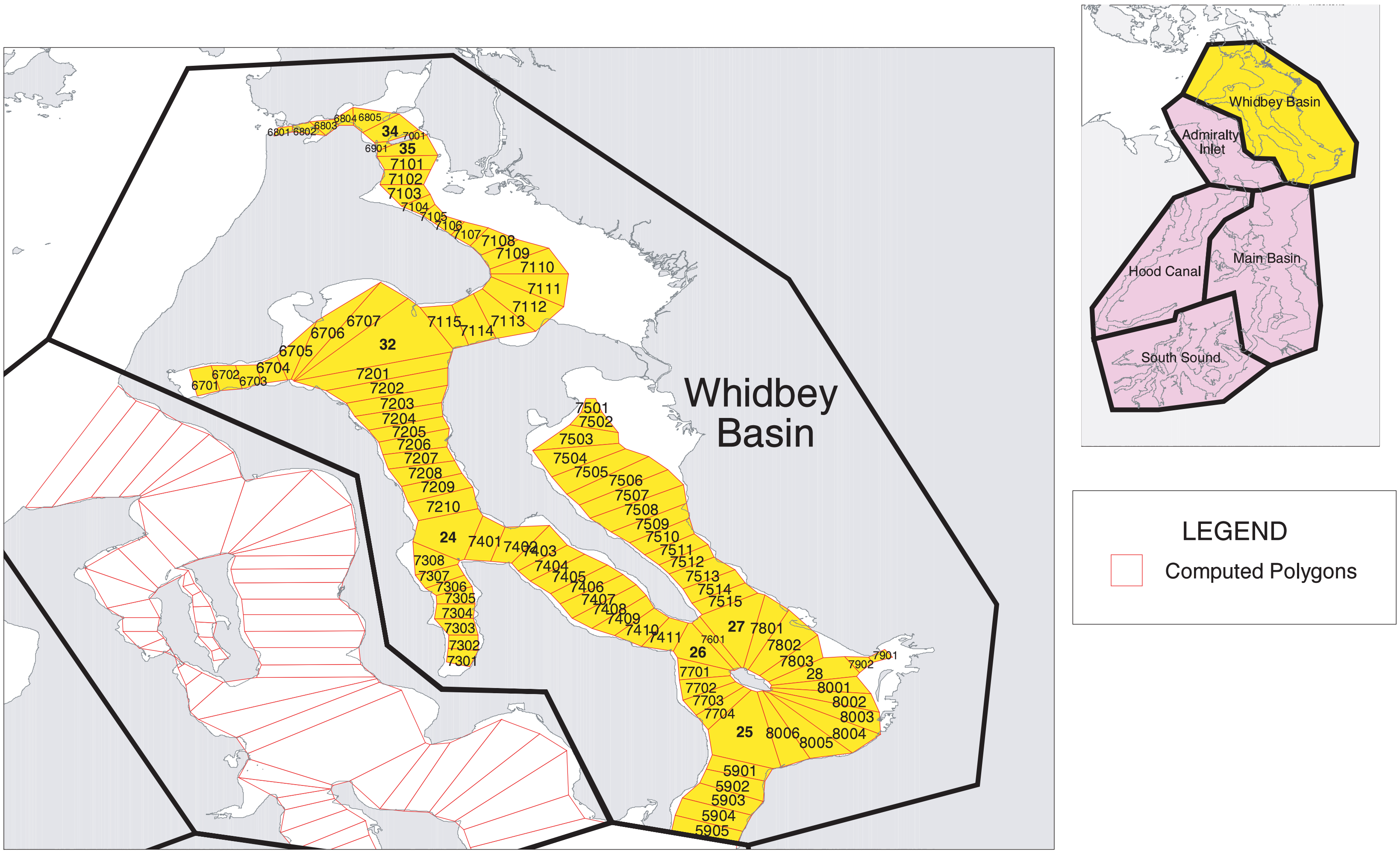


Figure 3.1b: Map of Whidbey Basin showing segments from the Puget Sound channel tide model (Lavelle *et al.*, 1988).

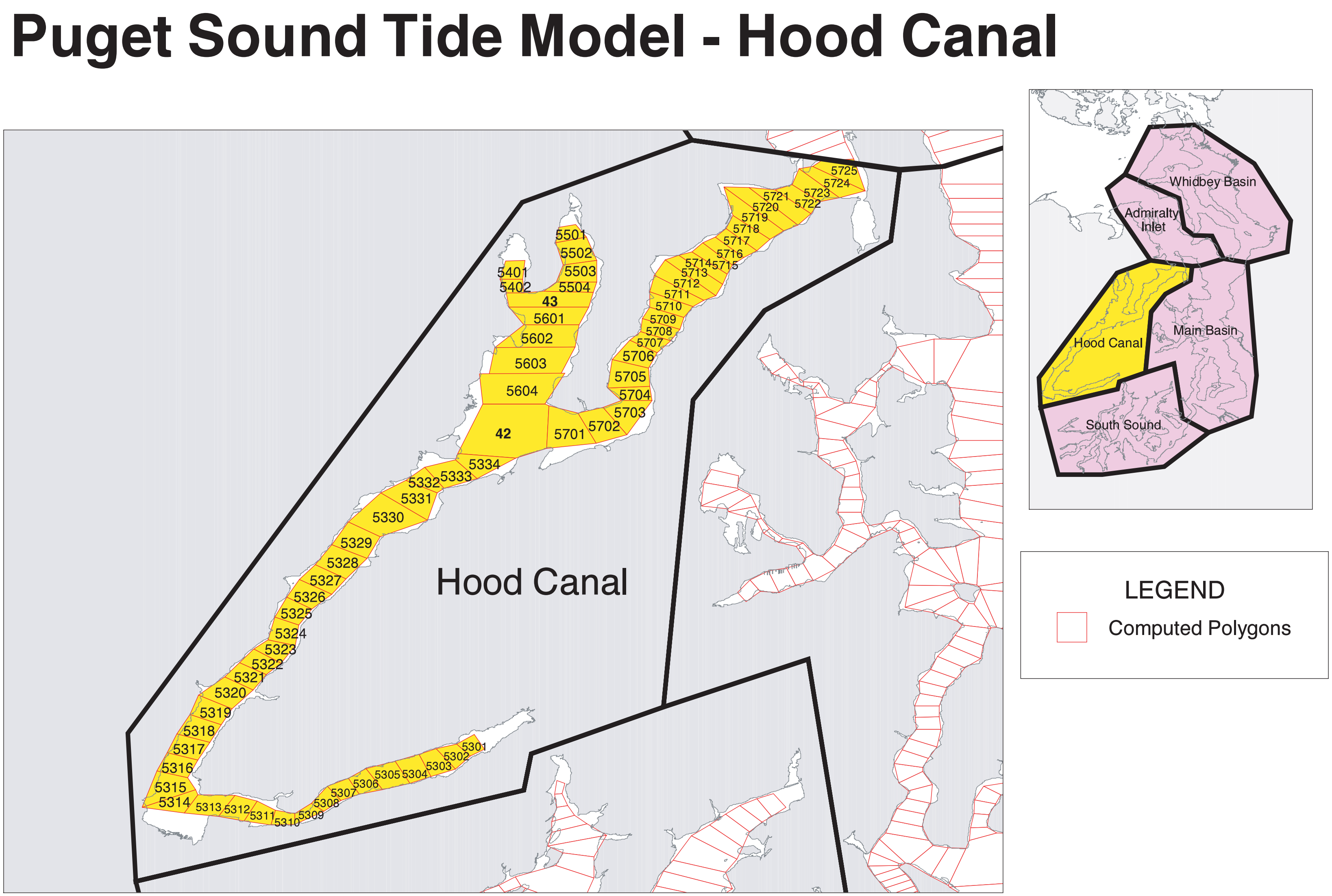


Figure 3.1c: Map of Hood Canal showing segments from the Puget Sound channel tide model (Lavelle *et al.*, 1988).

Puget Sound Tide Model - Main Basin

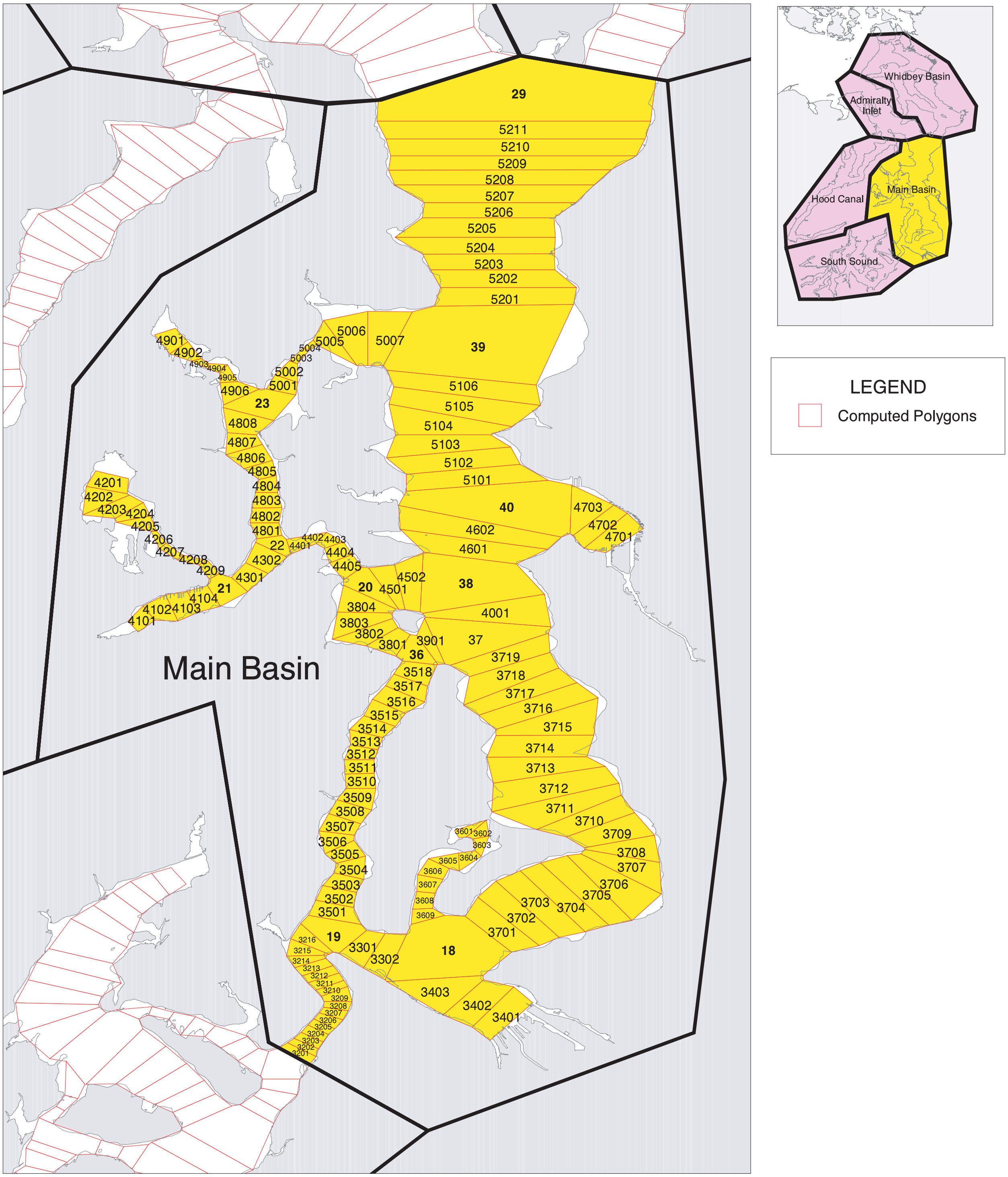
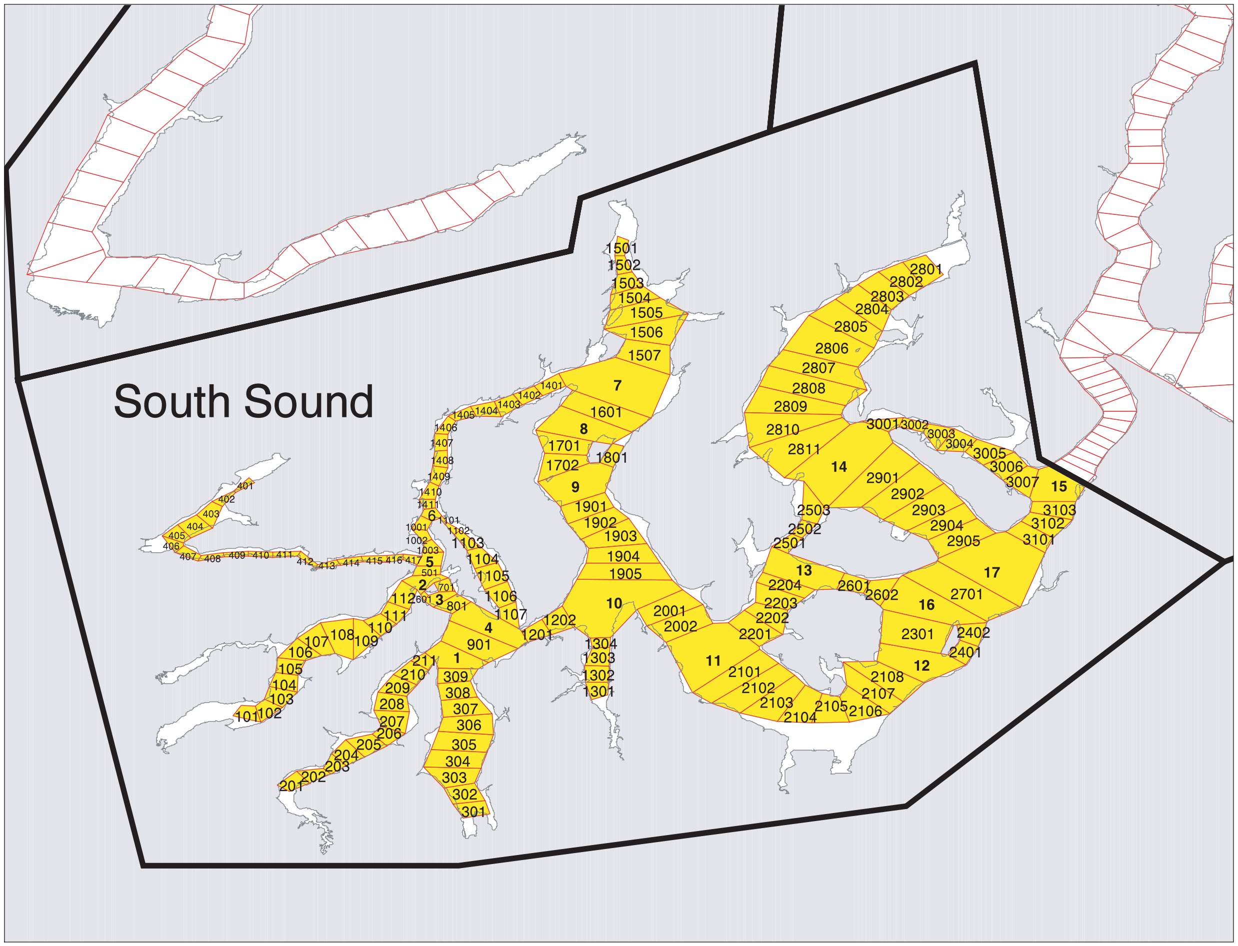
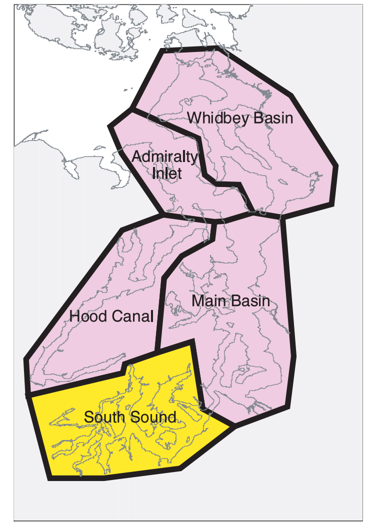


Figure 3.1d: Map of the Main Basin showing segments from the Puget Sound channel tide model (Lavelle *et al.*, 1988).

Puget Sound Tide Model - South Sound





LEGEND

Computed Polygons

Figure 3.1e: Map of the South Sound showing segments from the Puget Sound channel tide model (Lavelle *et al.*, 1988).

Table 3.1: Indices of channel segments and junctions of the Puget Sound channel tide model. The indices have been modified from those used by Lavelle *et al.* (1988).

Name	Channel Segments	Junctions
ADMIRALTY INLET		
Admiralty Inlet	6501–6506,6301–6312,6001–6002,5801–5808	33,30,41,29
Port Townsend	6401,6104–6110	33,31
Kilisut Harbor	6201–6207	31
Oak Bay	6101–6103	41
WHIDBEY BASIN		
Deception Pass	6801–6802	34
Skagit Bay	6803–6805,6901,7001,7101–7115	34,35,32
Crescent Harbor	6705–6707	32
Penn Cove	6701–6704	
Saratoga Passage	7201–7210,7401–7411	32,24,26
Holmes Harbor	7301–7308	24
Possession Sound	7601,7701–7704,7801–7803,8001–8006, 5901–5905	26,27,28,25,29
Port Susan	7501–7515	27
Snohomish Delta	7901–7902	28
HOOD CANAL		
Hood Canal	5701–5732, 5301–5334	30,42
Quilcene Bay	5401–5402	43
Dabob Bay	5501–5504,5601–5604	43,42
MAIN BASIN		
Puget Sound Main Reach	5201–5211,5101–5106,4601–4602,4501–4502, 3801–3804,3901,4001	29,39,40,38,20,36
Port Madison	5005–5007	39
Agate Passage	5003–5004	23
Liberty Bay	4901–4906	23
Port Orchard	5001–5002,4801–4808,4301–4302	23,22,21
Rich Passage	4401–4405	20,22
Sinclair Inlet	4101–4104	21
Dyes Inlet	4201–4205	
Port Washington Narrows	4206–4209	21
Elliott Bay	4701–4703	40
Colvos Passage	3501–3518	38,19
East Passage	3701–3719	37,18
Quartermaster Harbor	3601–3609	18
Commencement Bay	3401–3403	18
Dalco Passage	3301–3302	18,19
SOUTH SOUND		
The Tacoma Narrows	3201–3216	19,15
Hale Passage	3001–3007	15,14
Carr Inlet	2801–2811,2901–2905	14,17
Off Steilacoom	3101–3103,2301,2701	15,17,16,12
Pitt Passage	2501–2503	14,13
Balch Passage	2601–2602	16,13
Drayton Passage	2201–2204	11,13
Cormorant Passage	2401–2402	16,12
Nasqually Reach	2101–2108	12,11
Dana Passage	1201–1202,901	10,4,1
Case Inlet	1501–1507,1601,1701–1702,1801,1901–1905,2001–2002	7,8,9,10,11
Pickering Passage	1401–1411	7,6
Peale Passage	1101–1107	6,4
Squaxin Passage	1001–1003,501,601,701,801	5,2,3,4
Oakland Bay	401–406	
Hammersley Inlet	407–417	5
Henderson Inlet	1301–1304	10
Budd Inlet	301–309	1
Eld Inlet	201–211	1
Totten Inlet	101–112	2

4. Computational Procedures

The FORM180 Version 1.8 program was used to compute the tidal datums from the channel model harmonic constants. Since the type of tide in Puget Sound is mixed semidiurnal or mixed diurnal, issues do not arise concerning the effects of datums of spatial transitions between mixed and diurnal tides (Mofjeld *et al.*, in review). For definiteness the logical variable 'diurnal' in the program was set to .false., in principle requiring that the mixed tidal algorithms be used exclusively.

To provide the geospatial information for the GIS database, each channel segment and junction was considered to be a polygon object defined by its vertices. This is consistent with the straight shorelines and cross-channel sections defining the segments and junctions. The centroids of the segments were also computed for plotting variations along major and side channels of Puget Sound. All locations are in digital degrees. The tidal datums, the input channel model harmonic constants, and the geospatial information were then imported into ArcView for graphical display and further analyses.

5. Results and Products

5.1 Spatial distributions of the model datums

To summarize the general variations of the tidal datums in Puget Sound, it is convenient to plot them along its main channels (Fig. 5.1) and to tabulate datum values at the ends of various sections. Relative to mean sea level (MSL), the high and low waters (Fig. 5.2) diverge from each other along the Main Axis of Puget Sound, as the tidal range increases from the main entrance to Olympia in the South Sound. However, the differences in heights between the high waters remain relatively constant, as do the height differences between the low waters. The spread is substantially greater within the low waters. Mean tide level (MTL) is slightly above MSL, decreasing from 4.5 cm at the Main Entrance to 0.1 cm at Olympia. The relationships between datums are summarized in Table 5.1–5.3. Relative to MHW, MHHW is almost constant (0.29–0.33 m) in Puget Sound with the exception of northern Admiralty Inlet. This is also true for MLW (0.79–0.83 m) relative to MLLW, and the percentage MSL/MHW ratio (61–63%).

Focusing in more detail on MHW relative to MLLW, it increases southward (Fig. 5.3 and Table 5.1) from 2.16 m at the main entrance to 4.10 m at Olympia in the South Sound. The increases in MHW per unit distance (Table 5.2) are largest in Admiralty Inlet and the Tacoma Narrows and more gradual in the Main Basin and the South Sound. MHW along a side channel connecting the Main Basin with the head of Dyes Inlet essentially follows the MHW profile in the Main Basin. The largest value (4.17 m) of MHW in the Sound occurs in Oakland Bay, at the southwestern end of the South Sound.

In Hood Canal, there is also a progressive increase in MHW from 2.76 m at its entrance to 3.23 m at the head of Lynch Cove. The strongest spatial gradients of MHW in Hood Canal occur seaward of its junction with Dabob Bay. In Whidbey Basin, MHW increases from 3.00 m at its southern entrance to a maximum of 3.17 m in southern Skagit Bay. It then decreases to values around 3.00 m in the eastern approaches to Deception Pass. Limitations of the channel tide model in the immediate vicinity of Deception Pass make the tidal datum estimates less accurate there than in the rest of the Sound. The detailed distributions of the model MHW are shown in Fig. 5.4.

5.2 Comparison of model and observed datums

The model MHW heights (Table 5.4) tend to be slightly less than those observed at 47 tide stations (Fig. 1.1) located throughout Puget Sound. At Seattle, the primary reference tide station for the Sound, the deviation for MHW is −4.0 cm and is therefore close to the average (−3.6 cm) value for the Main Basin. The average MHW deviation varies from lesser values in Admiralty Inlet (−1.1 cm) and the South Sound (−1.8 cm) to larger values in Whidbey Basin (−7.8 cm) and Hood Canal (−8.5 cm). The largest single-station deviation (−15.0 cm) occurs at a 1-month long station at the head of Lynch Cove. A discussion of the accuracy of observed tidal datums in relation to the length of the time series is given by Swanson (1974).

In terms of percentage deviations, the model MHW is only 0.8% smaller than the observed value (3.20 m) at Seattle. The small size of this difference is due to the careful tuning of the channel model and to the accuracy of the HCD method. For many purposes, the datums presented here are sufficiently accurate; one example is the construction of a digital elevation model for use in tsunami inundation studies. However, it should be noted that the model datums are unofficial products and that official datums are available from NOAA/NGS and NOAA/NOS.

5.3 Geodetic datums

The observed NGVD29 datum (Table 5.5) varies from 10–13 cm below MTL in Hood Canal to 17–22 cm below in the other major regions. Again, northern Admiralty Inlet is an exception (7 cm at Port Townsend). NAVD88 is 1.04–1.14 m below NGVD29 with the largest values in Whidbey Basin and northern Admiralty Inlet. Along the main axis of Puget Sound, NAVD88 increases from 0.37 m above MLLW at Port Townsend, through the Main Basin (0.70–0.90 m) and the South Sound (1.12–1.27 m) to 1.27 m at Olympia. It has comparable values to the Main Basin in Whidbey Basin (0.67–0.73 m) and Hood Canal (0.79–0.92 m). MSL is not reported at many of the tide gages in Table 5.5. However, the model MTL-MSL values (e.g., Table 5.1) can be used to estimate MSL relative to the NGVD29 and NAVD88.

To account for mean sea level rise and changes in the tidal regime caused by harbor development or other factors, the tidal datums are defined for particular 19-year tidal epochs that corresponds to individual nodal cycles of the moon's orbit. The tidal datums reported here are for the 1960–1978 epoch. For Puget Sound, the long-term trend in sea level is monitored by the permanent tide gage at Seattle. At that gage, the rate of sea level rise (Zervas, 2001) is 2.11 ± 0.1 mm/yr for 1898–1999 and 2.26 ± 0.30 mm/yr over the recent 50-year period 1950–1999. In the near future, NOS will adopt a new 1980–1998 epoch. When this occurs, the values of the geodetic datums relative to MLLW will change to accommodate the rise in relative MSL.

5.4 Available products

Full distributions of the tidal datums, as well as the harmonic constants, are available at the website `www.pmel.noaa.gov/tsunami/TIME/`. Also available are the geospatial data for the channels and junctions. These consist of polygon vertices for each model segment and locations of the polygon centroids. All locations are in digital degrees. For convenience and portability, comma-delimited ASCII formats are used with the segment index as the first column. A metadata file accompanies each data file, describing its contents.

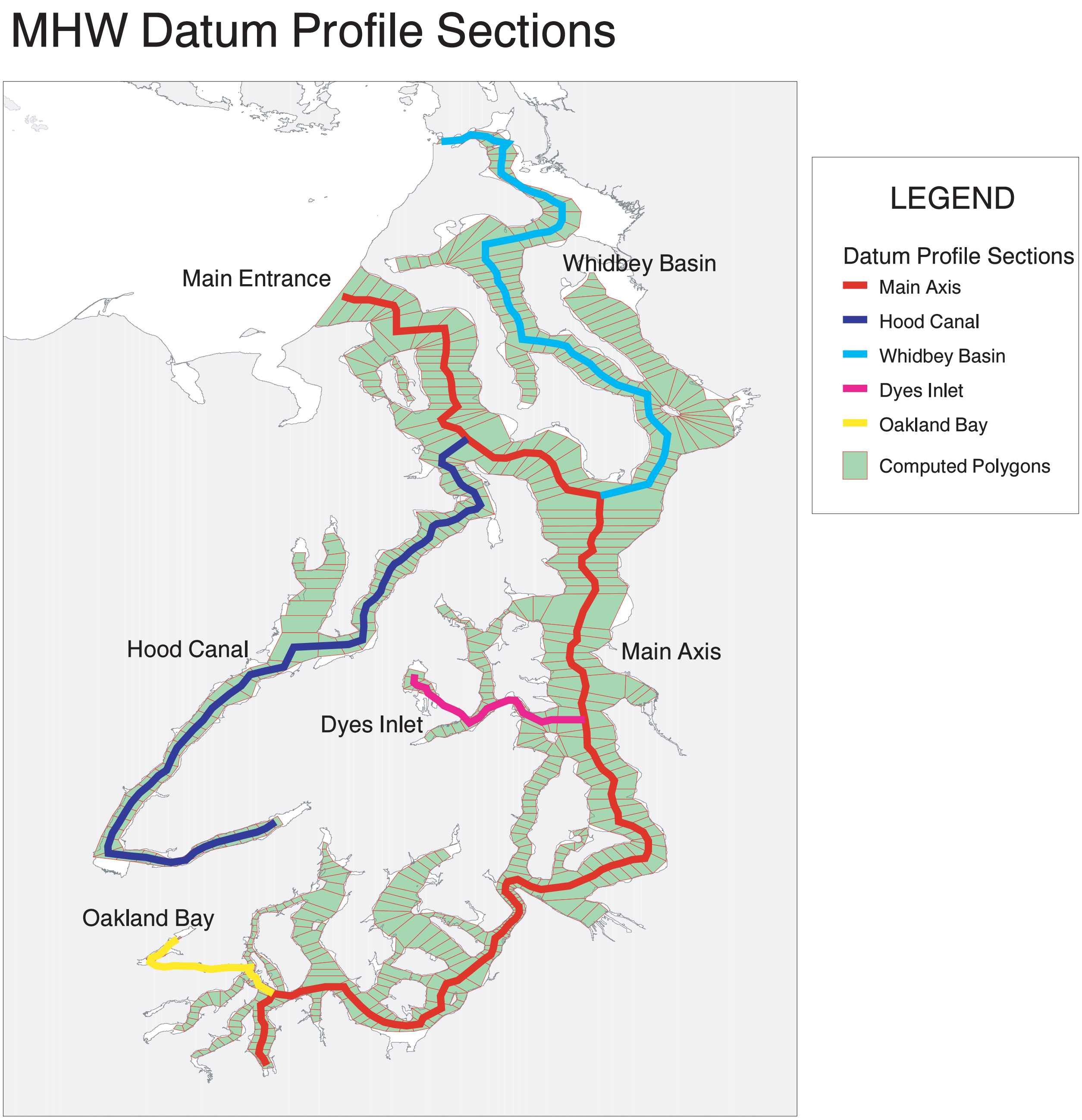


Figure 5.1: Map of Puget Sound showing sections along which profiles of harmonic constants and tidal datums will be shown.

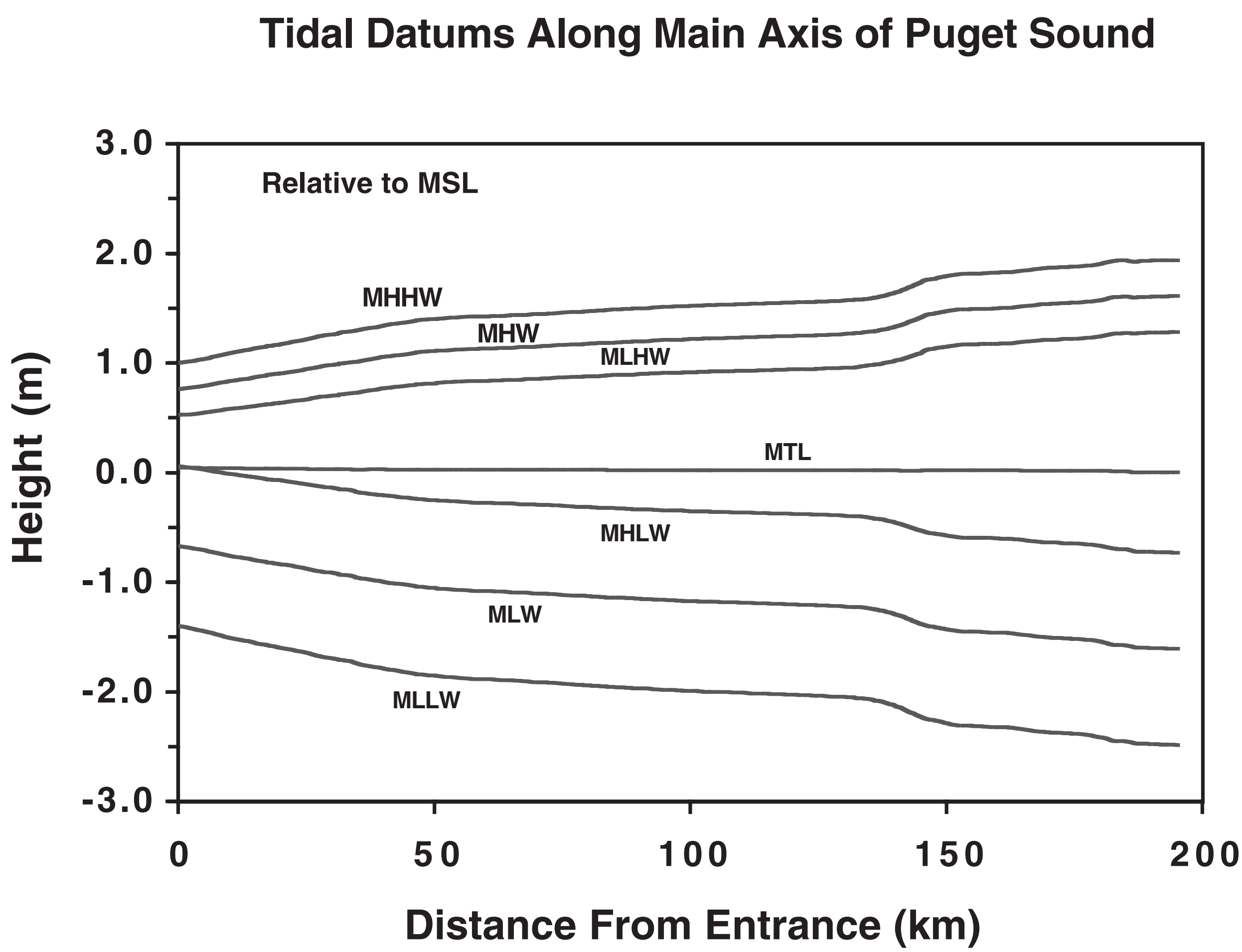


Figure 5.2: Profiles of tidal datums, relative to MSL, down the main axis of Puget Sound as computed from the harmonic constants of the Puget Sound channel tide model using the harmonic constant datum method.

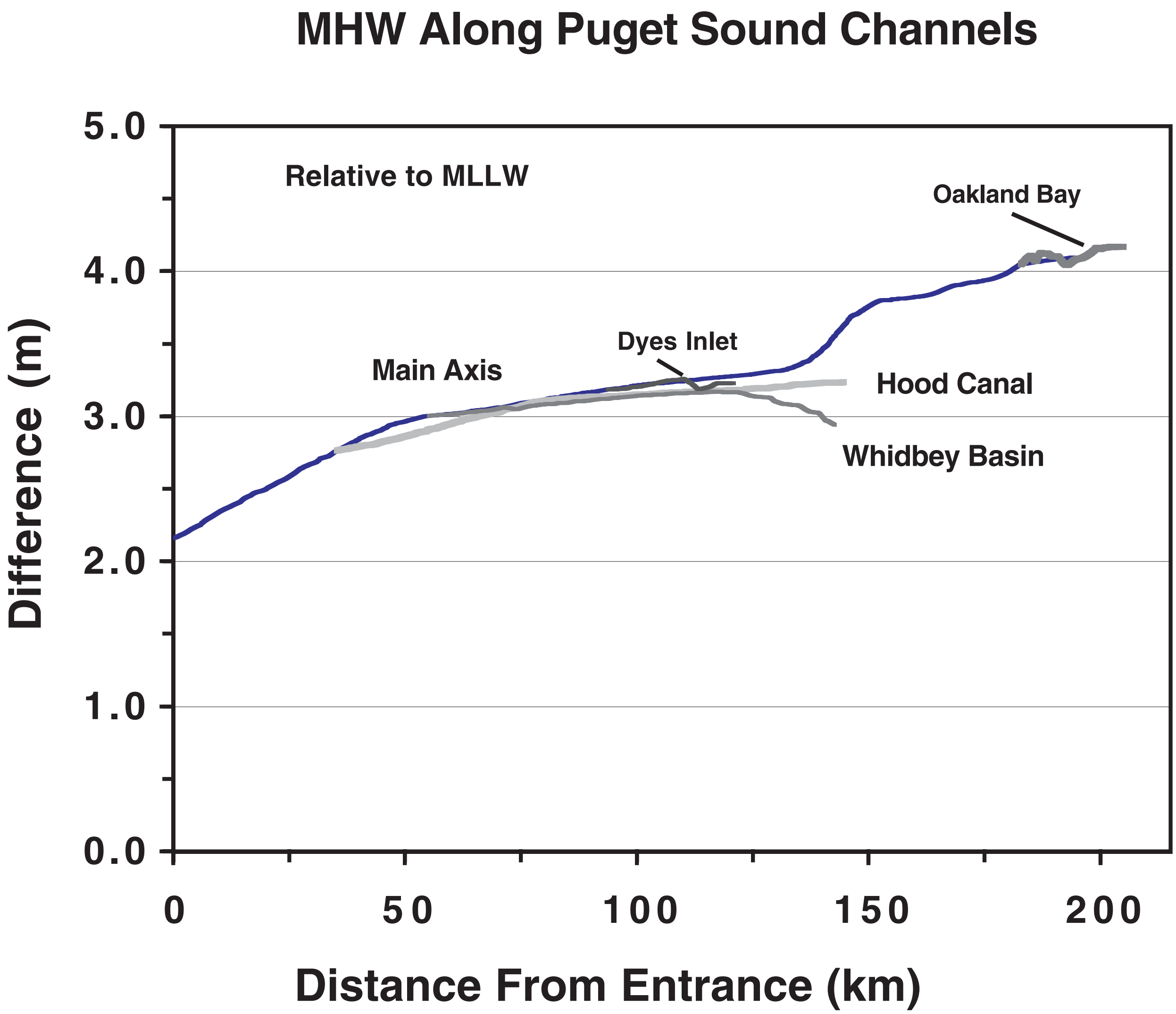


Figure 5.3: Profiles of MHW relative to MLLW the main axis of Puget Sound, Whidbey Basin and Hood Canal. Also shown are profiles of MHW from the main axis to the heads of Dyes Inlet, Main Basin, and Oakland Bay, South Sound.

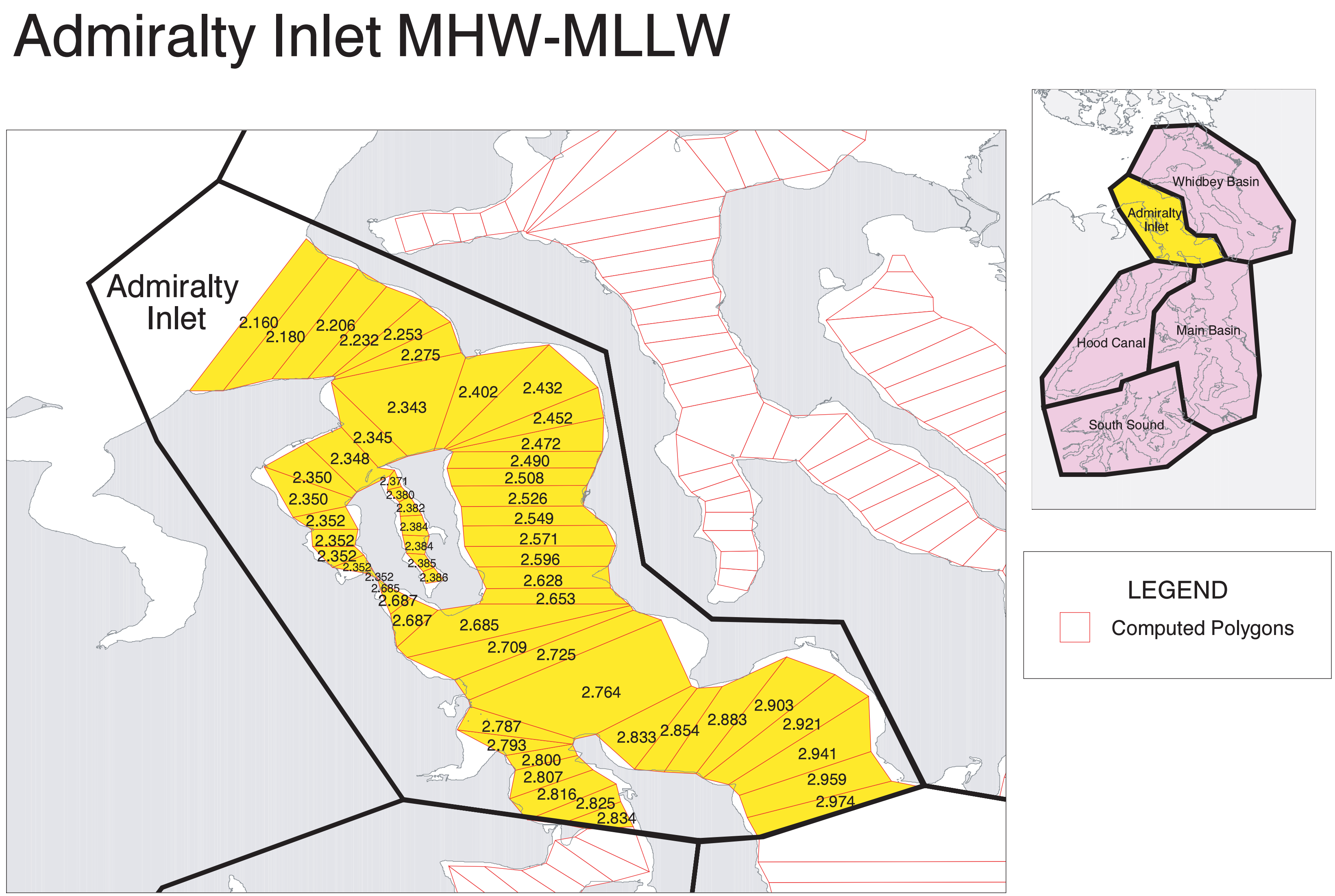


Figure 5.4a: Map of mean high water (MHW) relative to MLLW in Admiralty Inlet, Puget Sound, as computed from the harmonic constants of the Puget Sound channel tide model (Lavelle *et al.*, 1988).

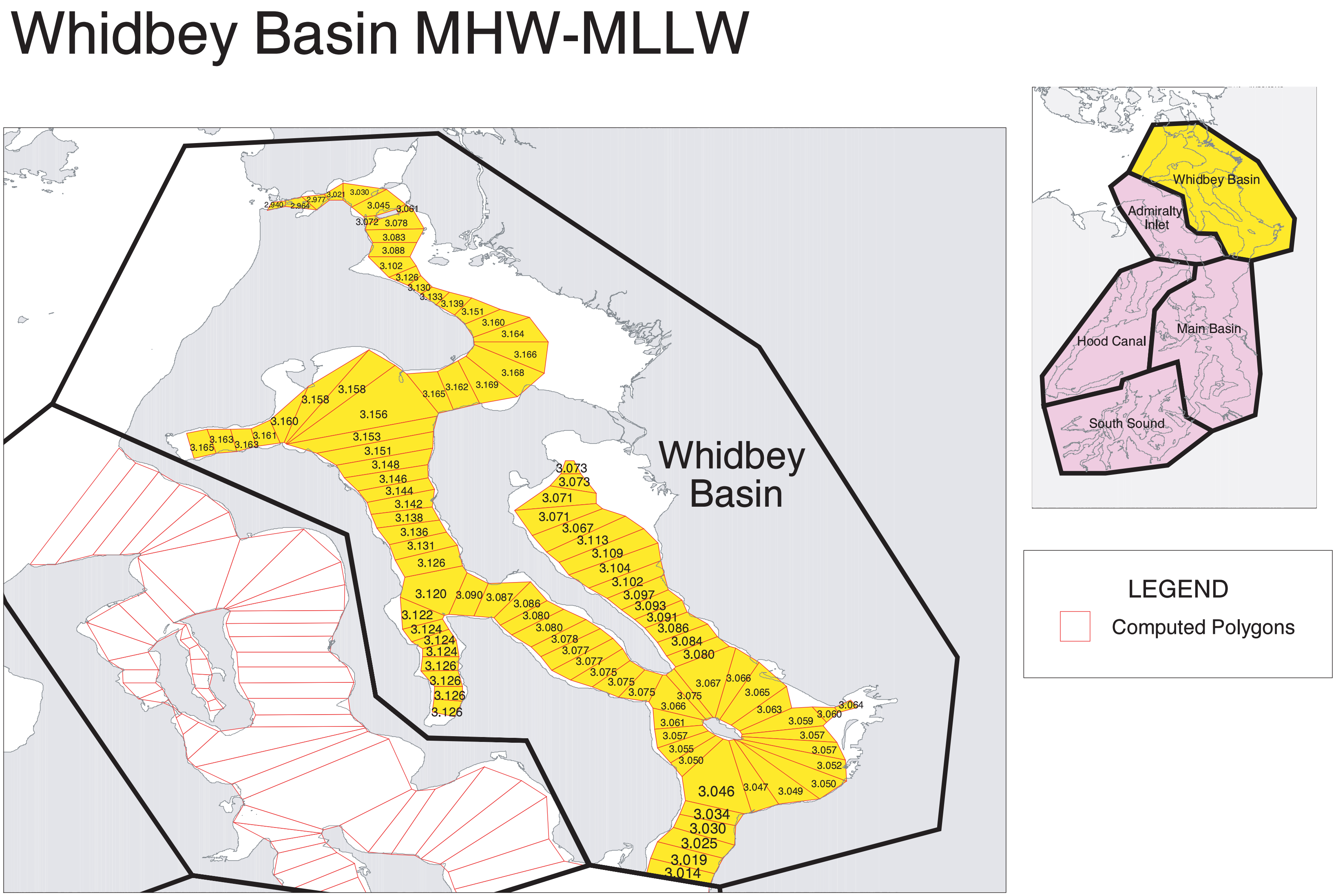


Figure 5.4b: Map of mean high water (MHW) relative to MLLW in Whidbey Basin, Puget Sound, as computed from the harmonic constants of the Puget Sound channel tide model (Lavelle *et al.*, 1988).

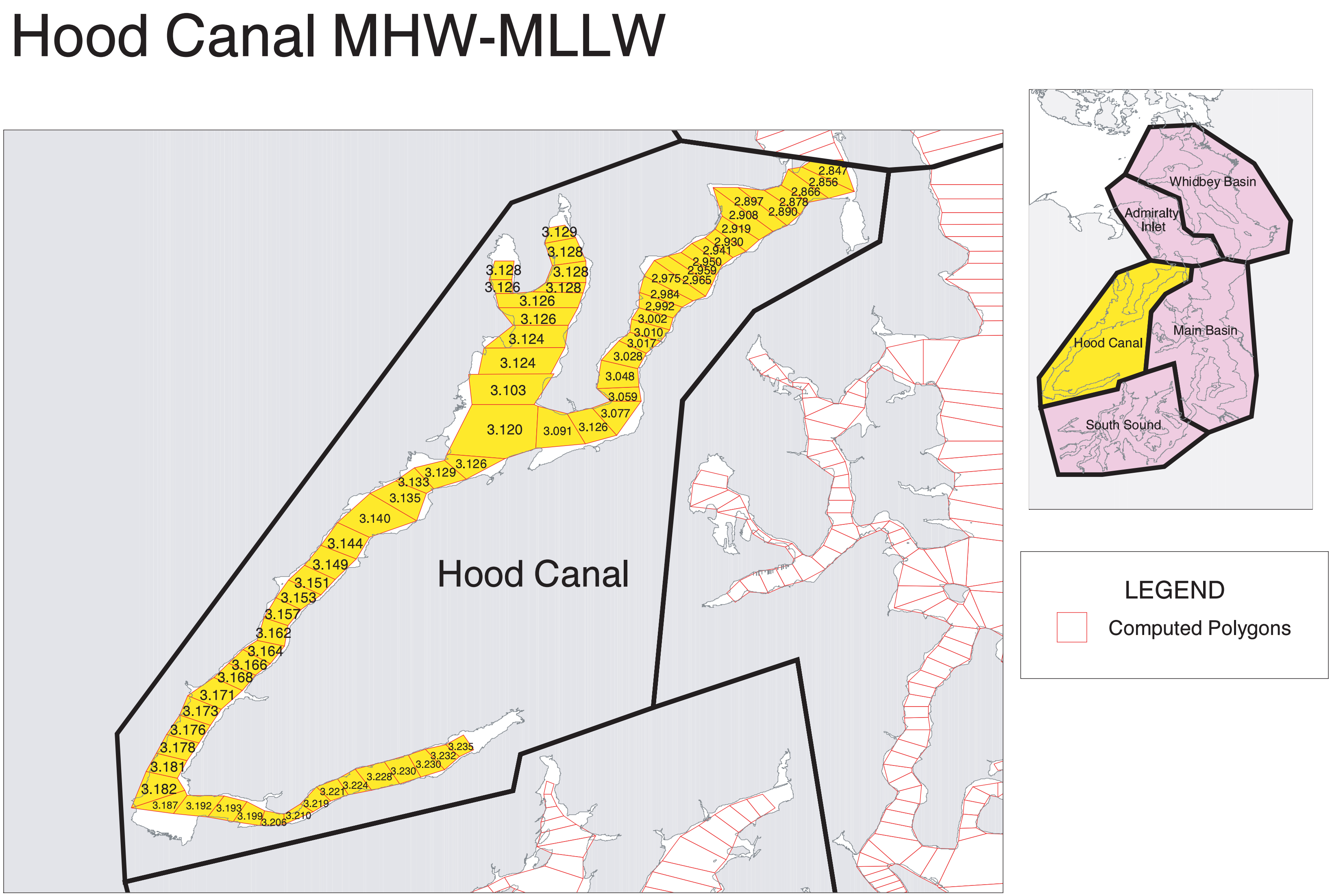


Figure 5.4c: Map of mean high water (MHW) relative to MLLW in Hood Canal, Puget Sound, as computed from the harmonic constants of the Puget Sound channel tide model (Lavelle *et al.*, 1988).

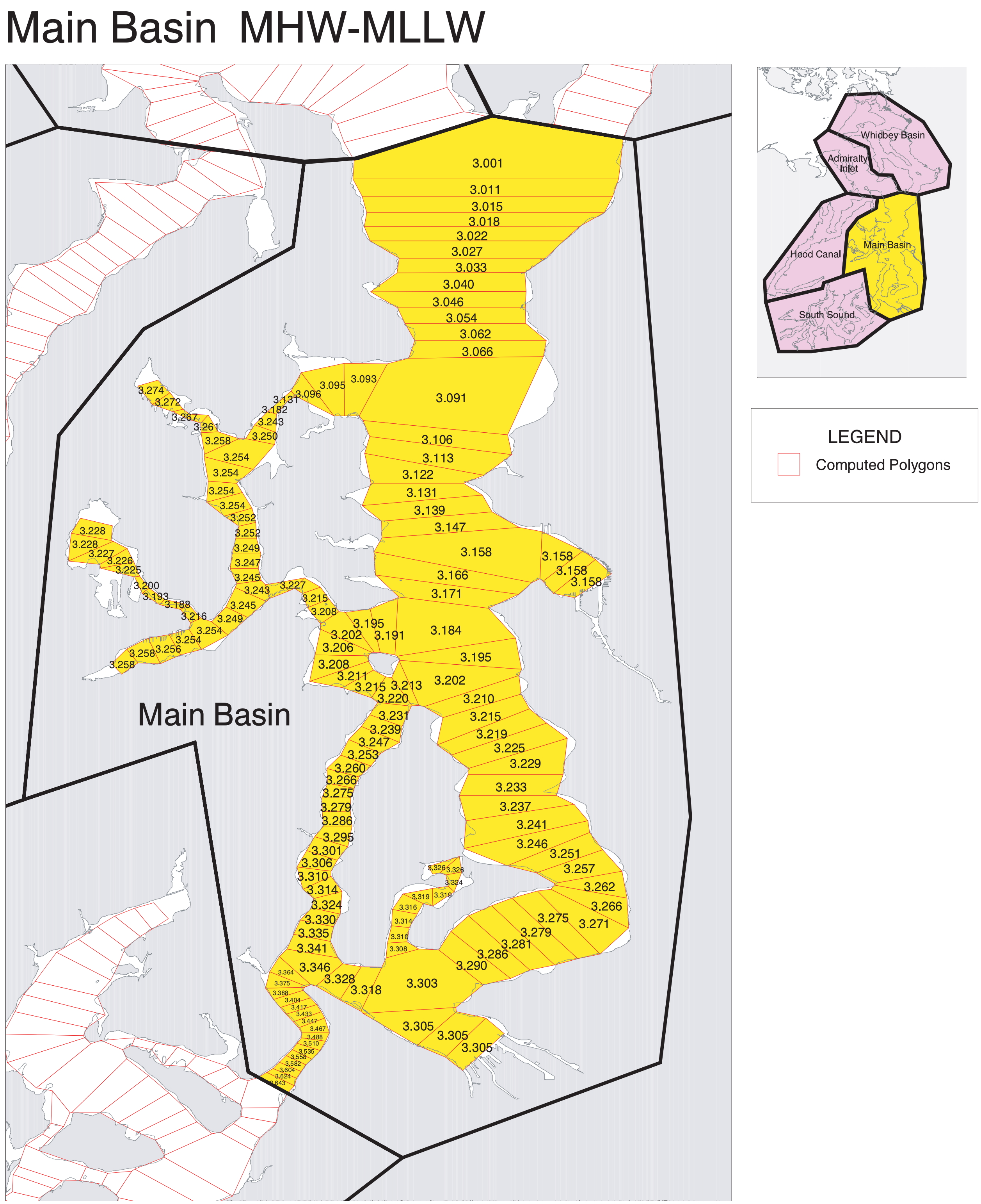


Figure 5.4d: Map of mean high water (MHW) relative to MLLW in the Main Basin, Puget Sound, as computed from the harmonic constants of the Puget Sound channel tide model (Lavelle *et al.*, 1988).

South Sound MHW-MLLW

Figure 5.4e: Map of mean high water (MHW) relative to MLLW in the South Sound, Puget Sound, as computed from the harmonic constants of the Puget Sound channel tide model (Lavelle *et al.*, 1988).

Table 5.1: Model datum levels relative to various reference levels at the ends of major sections of Puget Sound and in two side channels.

		Datum				
	Index	**MHW**	**MHHW**	**MTL**	**MSL**	**MLW**
	Reference Level:	***MLLW***	***MHW***	***MSL***	***MLLW***	***MLLW***
		(m)	**(m)**	**(cm)**	**(m)**	**(m)**
MAIN AXIS OF PUGET SOUND						
Main Entrance	6506	2.16	0.24	4.5	1.40	0.73
N. Main Basin	29	3.00	0.29	2.6	1.88	0.80
N. Tacoma Narrows	19	3.35	0.30	2.2	2.07	0.83
S. Tacoma Narrows	15	3.68	0.32	2.1	2.25	0.85
Head of Budd Inlet	0301	4.10	0.33	0.1	2.49	0.88
WHIDBEY BASIN						
S. Entrance	29	3.00	0.29	2.6	1.88	0.80
S. Saratoga Passage	26	3.07	0.30	2.5	1.91	0.81
S. Skagit Bay	32	3.17	0.30	2.5	1.96	0.82
Similk Bay	6804	3.02	0.31	2.8	1.89	0.81
Head of Lynch Cove	5301	3.23	0.30	0.4	2.03	0.83
HOOD CANAL						
Canal Entrance	30	2.76	0.28	2.6	1.75	0.79
Dabob Bay Entrance	42	3.12	0.30	1.7	1.95	0.82
Head of Lynch Cove	5301	3.23	0.30	0.4	2.03	0.83
RICH PASSAGE THROUGH DYES INLET						
E. Rich Passage	20	3.20	0.30	2.3	1.99	0.82
S. Port Wash. Narrows	21	3.25	0.31	2.3	2.02	0.82
Head of Dyes Inlet	4201	3.23	0.31	3.1	2.00	0.82
SQUAXIN CHANNEL THROUGH OAKLAND BAY						
E. Squaxin Inlet Entrance	04	4.05	0.33	1.4	2.45	0.88
E. Hammersley Inlet Entrance	05	4.12	0.34	1.2	2.49	0.89
Head of Oakland Bay	0401	4.17	0.35	1.0	2.52	0.89

Table 5.2: Net changes and spatial gradients of model MHW relative to MLLW along the same sections of Puget Sound as shown in Table 5.1.

	Length (km)	Net Change (m)	Gradient (cm/km)	Net Change Indices	Gradient Indices
MAIN AXIS OF PUGET SOUND					
Admiralty Inlet	55.2	0.84	1.66	6506-29	6506-5803
Main Basin	79.3	0.34	0.41	29-19	29-18
The Narrows	11.6	0.34	2.92	19-15	19-15
South Sound	49.3	0.41	0.70	15-0301	17-0301
Total	195.3	1.94			
WHIDBEY BASIN					
Possession Sound	21.0	0.06	0.31	29-26	29-26
Saratoga Passage	33.2	0.09	0.27	26-32	26-32
Skagit Bay	24.3	−0.08	−0.32	32-35	32-35
Deception Pass and Similk Bay	9.0	−0.14	−1.54	35-6801	35-6801
Total	87.5	−0.06			
HOOD CANAL					
Northern	48.1	0.36	0.74	30-42	30-42
Southern	61.1	0.12	0.19	42-5301	42-5301
Total	109.2	0.47			
GREATER RICH PASSAGE—DYES INLET					
Greater Rich Passage	16.6	0.05	0.47	20-21	20-21
Port Wash. Nrws and Dyes Inlet	10.6	−0.02	−0.24	21-4201	21-4201
Total	27.2	0.03			
GREATER SQUAXIN PASSAGE—OAKLAND BAY					
Squaxin Passage	5.8	0.07	1.25	04-05	04-05
Hammers. Inlet and Oakland Bay	16.3	0.05	0.29	05-0401	05-0401
Total	22.1	0.12			

Table 5.3: Ratio (%) of model MSL at the ends of major sections in Puget Sound. Both model datums are relative to MLLW.

	Index	MSL/MHW (%)
MAIN AXIS		
Main Entrance	6506	65
N. Main Basin	29	63
N. Tacoma Narrows	19	62
S. Tacoma Narrows	15	61
Head of Budd Inlet	0301	61
WHIDBEY BASIN		
S. Entrance	29	63
S. Saratoga Passage	26	62
S. Skagit Bay	32	62
Similk Bay	6804	63
HOOD CANAL		
Canal Entrance	30	63
Dabob Bay Ent.	42	63
Head of Lynch Cove	5301	63

Table 5.4: Differences (cm) between model and observed datums at tide stations (Fig. 1.1) in Puget Sound. All datums are relative to MLLW. Also shown are the averages for the major regions of the Sound. The model values are taken from the segment adjacent to the tide station or an average of values when the tide station lies on the boundary between segments. In computing the observed datums the control for all stations was Seattle, except that Friday Harbor was the control for Sneeoosh Point and Port Townsend for Clam Bay. The observed datums are taken from the NOAA/NOS/CO-OPS Website `http://www.co-ops.nos.noaa.gov/bench_mark.shtml?region=wa`.

Model Index	Station ID	Tide Station Name	Model — Observed Differences					
			MHHW (cm)	MHW (cm)	MTL (cm)	MLW (cm)	MLLW (cm)	Length
ADMIRALTY INLET								
31,6401	9444900	Port Townsend	2.6	−1.3	−2.2	−2.9	0.0	12 yrs
30	9447827	Double Bluff	−2.3	2.2	−1.7	−5.9	0.0	1 mo
5806	9445526	Hansville	−1.0	−4.3	−4.8	−5.0	0.0	13 mos
		Average:	−0.3	−1.1	−2.9	−4.6	0.0	
WHIDBEY BASIN								
35	9448576	Sneeoosh Point, Skagit Bay	1.0	−2.1	−1.0	0.1	0.0	90 days
6705	9447952	U.S. Navy Pier, Crescent Harbor	−8.9	−11.9	−7.7	−3.5	0.0	1 mo
7411	9447856	Sandy Point, Saratoga Passage	−5.6	−8.9	−6.9	−4.8	0.0	1 mo
7301	9447855	Holly Harbor Farms, Holmes Harbor	−6.0	−8.9	−6.2	−3.5	0.0	1 mo
8003	9447659	Everett, Possession Sound	−3.7	−7.2	−5.6	−4.4	0.0	10 mos
5902,5903	9447814	Glendale, Possession Sound	−3.5	−7.8	−6.4	−4.9	0.0	1 mo
		Average:	−4.5	−7.8	−5.6	−3.5	0.0	
HOOD CANAL								
5730	9445016	Foulweather Bluff	−1.1	−4.0	−5.0	−5.9	0.0	2 mos
5718	9445088	Lofall	−5.5	−7.4	−7.4	−7.3	0.0	1 mo
5401	9445272	Quilcene, Dabob Bay	−4.7	−6.5	−7.0	−7.6	0.0	3 mos
5601	9445246	Whitney Point, Dabob Bay	−9.5	−10.1	−10.1	−9.7	0.0	1 mo
5708	9445133	Bangor Wharf	−8.9	−10.6	−9.4	−8.0	0.0	10 mos
5701	9445296	Seabeck, Seabeck Bay	−11.3	−12.1	−11.0	−10.0	0.0	1 mo
5330	9445326	Triton Head	−2.9	−6.0	−6.0	−6.2	0.0	43 days
5324	9445388	Ayock Point	−0.3	−1.3	−6.0	−10.6	0.0	1 mo
5312,5313	9445478	Union	−11.4	−11.7	−10.4	−9.1	0.0	5 mos
5301,5302	9445441	Lynch Cove Dock	−15.4	−15.0	−12.8	−10.6	0.0	1 mo
		Average:	−7.1	−8.5	−8.5	−8.5	0.0	
MAIN BASIN								
5206,5207	9447427	Edmonds	−0.1	−3.6	−4.1	−4.7	0.0	3 mos
5205	9445639	Kingston	−1.5	−5.1	−5.1	−5.2	0.0	1 mo
39	9445683	Point Jefferson	8.6	5.2	0.9	−3.3	0.0	3 mos
5106	9447265	Meadow Point	−0.4	−3.9	−4.3	−4.4	0.0	3 mos
4901,4902	9445719	Poulsbo, Liberty Bay	0.1	−3.7	−4.1	−4.5	0.0	42 mos
4806,4807	9445832	Brownsville, Port Orchard	−4.3	−8.4	−7.3	−6.2	0.0	1 mo
21,4104	9445958	Bremerton, Sinclair Inlet	−2.7	−7.0	−5.6	−4.2	0.0	7 mos
20	9445938	Clam Bay, Rich Passage	1.1	−2.9	−3.4	−4.0	0.0	16 mos
4701	9447130	Seattle, Elliott Bay	−0.2	−4.0	−4.3	−4.7	0.0	19 yrs
37	9446025	Point Vashon	−1.0	−4.7	−4.9	−5.2	0.0	1 mo
3708,3709	9446248	Des Moines, East Passage	1.0	−2.4	−3.7	−4.8	0.0	1 mo
3601	9446254	Burton, Quartermaster Harbor	−4.0	−7.0	−5.9	−4.9	0.0	1 mo
3401	9446484	Tacoma, Commencement Bay	0.8	−3.4	−3.8	−4.2	0.0	19 mos
3401	9446545	Tacoma, Commencement Bay	0.3	−3.6	−4.0	−4.5	0.0	9 mos
3301,3302	9446375	Tahlequah, Dalco Passage	0.6	−3.3	−3.7	−4.3	0.0	28 days
3205	9446486	Tacoma Narrows Bridge	3.8	−0.5	−2.4	−4.0	0.0	1 mo
		Average:	0.1	−3.6	−4.1	−4.6	0.0	

Table 5.4: (Continued)

Model Index	Station ID	Tide Station Name	MHHW (cm)	MHW (cm)	MTL (cm)	MLW (cm)	MLLW (cm)	Length
			Model — Observed Differences					
SOUTH SOUND								
1501	9446281	Allyn, Case Inlet	2.7	−1.7	−3.4	−5.1	0.0	9 mos
2807,2808	9446451	Green Point, Carr Inlet	2.7	−1.3	−2.9	−4.6	0.0	1 mo
14	9446491	Arletta, Hale Passage	7.3	2.7	−0.5	−3.6	0.0	1 mo
2810	9446500	Home, Carr Inlet	4.3	0.4	−1.8	−3.9	0.0	1 mo
9,1702	9446583	Ballow, Case Inlet	5.2	1.2	−1.7	−4.6	0.0	1 mo
2602	9446705	Yoman Point, Anderson Island	3.1	−1.3	−2.5	−3.5	0.0	7 mos
2701	9446714	Steilacoom, Nisqually Reach	1.5	−3.0	−3.9	−5.0	0.0	16 days
11	9446671	Devils Head, Drayton Passage	−8.0	−7.2	−7.5	−7.8	0.0	26 days
1	9446800	Dofflemyer Point	1.2	−3.7	−5.2	−6.4	0.0	66 days
2107	9446828	Dupont Wharf, Nisqually Reach	3.9	−0.1	−2.1	−3.8	0.0	35 days
305	9446807	Budd Inlet, South Of Gull Harbor	−0.2	−4.3	−5.2	−6.1	0.0	6 mos
301	9446969	Olympia, Budd Inlet	−1.4	−3.2	−4.4	−5.6	0.0	1 yr
		Average:	1.9	−1.8	−3.4	−5.0	0.0	

Table 5.5: Observed heights of tidal datums and the geodetic datums NAVD29 and NAVD88, all relative to MLLW, in Puget Sound. The heights are averages over individual benchmark values for each tide gage that were taken from the websites of the National Geodetic Survey (`www.ngs.noaa.gov`) and the CO-OPS Program (`www.co-ops.nos.noaa.gov`) of the National Ocean Survey.

Station ID	Name	Latitude	Longitude	MHHW (m)	MHW (m)	MTL (m)	NGVD 29 (m)	MLW (m)	NAVD 88 (m)	MLLW (m)
ADMIRALTY INLET										
9444900	Port Townsend	48 06.9N	122 45.0W	2.58	2.36	1.57	1.50	0.78	0.37	0.00
WHIDBEY BASIN										
9447952	Crescent Harbor	48 17.1N	122 37.0W	3.55	3.28	2.07	1.87	0.85	0.73	0.00
9447725	Ebey Slough	48 02.7N	122 12.7W	3.30	3.04	1.91	2.12	0.77	0.99	0.00
9447659	Everett	47 58.8N	122 13.4W	3.39	3.12	1.99	1.82	0.85	0.70	0.00
9447814	Glendale	47 56.4N	122 21.4W	3.36	3.11	1.98	1.79	0.86	0.67	0.00
HOOD CANAL										
9445246	Dabob Bay	47 45.7N	122 51.0W	3.52	3.23	2.07	1.96	0.91	0.87	0.00
9445133	Bangor Wharf	47 44.9N	122 43.6W	3.39	3.12	2.00	1.87	0.89	0.79	0.00
9445389	Ayock Point	47 30.5N	124 03.2W	3.47	3.18	2.05	1.96	0.93	0.88	0.00
9445479	Union	47 21.5N	124 05.9W	3.61	3.31	2.11	1.98	0.91	0.92	0.00
MAIN BASIN										
9447427	Edmonds	47 48.8N	122 23.0W	3.33	3.07	1.96	1.79	0.85	0.70	0.00
9447130	Seattle	47 36.3N	122 20.3W	3.46	3.20	2.03	1.86	0.86	0.77	0.00
9445938	Clam Bay	47 34.5N	122 32.6W	3.49	3.23	2.05	1.87	0.86	0.81	0.00
9445958	Bremerton	47 33.7N	122 37.4W	3.58	3.31	2.09	1.89	0.87	0.82	0.00
9446254	Burton	47 23.7N	122 27.8W	3.67	3.40	2.14	1.95	0.89	0.89	0.00
9446484	Tacoma	47 16.0N	122 24.8W	3.60	3.34	2.10	1.89	0.87	0.83	0.00
9446545	Tacoma	47 15.3N	122 25.9W	3.61	3.34	2.11	1.93	0.87	0.86	0.00
SOUTH SOUND										
9446281	Allyn	47 23.0N	122 49.4W	4.32	4.03	2.48	2.29	0.92	1.22	0.00
9446714	Steilacoom	47 10.4N	122 36.2W	4.11	3.83	2.37	2.17	0.91	1.12	0.00
9446828	Dupont	47 07.1N	122 40.0W	4.12	3.83	2.37	2.17	0.90	1.12	0.00
9446969	Olympia	47 03.1N	122 54.2W	4.44	4.13	2.53	2.31	0.93	1.27	0.00

6. Discussion

The model tidal datums reported here come directly from the application of the HCD method to the harmonic constants from the channel tide model of Lavelle *et al.* (1988). As such, no improvements have been made to the model datums, e.g., by adjusting them to match the observed values. Therefore, inherent in the model datums are any limitations that exist in the HCD method and the channel tide model. A comparison of these with the observations then provides a quantitative assessment of their effects on the datums. The comparison shows that the model datums relative to MLLW tend to slightly underestimate the observed datums, with the largest deviations in Hood Canal.

The accuracy of the model datums can be improved by adjusting them to the observations using a GIS system. The result would be a set of datum distributions that are consistent with both observations and linear tidal dynamics. Additional modeling is also needed to resolve local tidal variations in points of land, where high tidal currents affect the local datums, and over tidal flats that are not included in the channel tide channel.

Since the tidal datums represent 19-year averages, they do not reflect shorter-term variations in water levels. These include oceanic and meteorological fluctuations over synoptic to seasonal time scales. Especially high water events occur during strong El Niños. Mofjeld (1992) provides a description of the subtidal water level fluctuations that occur in Puget Sound and the Strait of Juan de Fuca, and Wood (1976) describes extreme high and low water events that occur in response to perigean spring tides. More commonly, there are substantial fortnightly, monthly, and seasonal variations in Puget Sound tides that are described by Mofjeld and Larsen (1984). For specific periods of time, tidal observations and predictions are available on-line at the NOAA/NOS website `www.co-ops.nos.noaa.gov`.

7. Summary

The distributions of tidal datums in Puget Sound have been estimated by applying the harmonic constant datum (HCD) method to harmonic constants from the channel tide model of Lavelle *et al.* (1988). These distributions consist of gridded alongchannel datums at high spatial resolution, relative to mean lower low water (MLLW). Of particular interest is mean high water (MHW), because it provides the elevation differences between the reference levels for land elevation and water depth that are needed to construct digital elevation models.

Focusing on the model distribution of MHW, it increases along the main axis of Puget Sound from 2.16 m at the north end of Admiralty Inlet to a maximum of 4.17 m at the head of Oakland Bay, a side channel in the South Sound region. It does so in stages, with larger increases per km in Admiralty Inlet and the Tacoma Narrows and more gradual increases through the Main Basin and the South Sound. The MHW increases with alongchannel distance in Hood Canal and Whidbey Basin closely follow the increase along the main axis, except for a 3.17 m maximum in Whidbey Basin and a decrease toward Deception Pass.

The model datums relative to MLLW are slightly less than those estimated from observations at tide gages. At Seattle, the primary reference gage for the region, the model MHW is 4.0 cm less than the observed values. This is close to the average (3.6 cm) for the Main Basin. Elsewhere in the Sound, the average underestimates are 1.1 cm for Admiralty Inlet, 7.8 cm for Whidbey Basin, 8.5 cm for Hood Canal, and 1.8 cm for the South Sound. The detailed comparison for the individual tide stations and for the other tidal datums is provided in Section 5. The model datums can be improved by adjusting their distributions to match the observed values and by doing more detailed studies near points of land and tidal flat areas. This is left to future work.

8. Acknowledgments

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9. Appendix: Tidal harmonic constants in Puget Sound

Tables A.1–A.5 give representative values of observed harmonic constants in Puget Sound, as well as various amplitude ratios and phase differences. The channel tide model provides high-resolution profiles of the harmonic constants (Figs. A.1–A.2) along the main axis of Puget Sound that give a general overview of how the harmonic constants vary within the Sound. There are substantial increases in the semidiurnal (M2, N2, and S2) amplitudes and phase lags from the northward end of Admiralty Inlet to the southern reaches of Puget Sound. The increases are greatest in the high-current channels (Admiralty Inlet and the Tacoma Narrows) separating the major basins of Puget Sound and less within the basins themselves.

The physical reasons for the distributions of the tides in Puget Sound are discussed by Mofjeld and Larsen (1984), Lavelle *et al.* (1988), and in previous publications listed in these publications. Briefly, the semidiurnal tides form a set of partially reflecting waves in the Sound with greatest reflection between a given basin and the channel leading to the next landward basin. The interaction of the flow and hydraulic head through the channel and the landward basin's storage capacity, as measured by its surface area, lead to the increases in the tidal amplitude. The phase lag is increased as well, due to friction acting on the tidal flow. Whidbey Basin and Hood Canal act to increase the effective length of Puget Sound as seen by the tides.

In contrast, the diurnal tides (O1, P1, and K1) experience much more modest increases (Figs. A.1–A.2 and Tables A.1–A.5) in amplitude and phase lag through the Sound. This is because the diurnal tides have twice the period of oscillation, as compared with the semidiurnal tides, and therefore have twice the time for the exchange between basins to occur as the tide rises and falls at the entrance to Puget Sound.

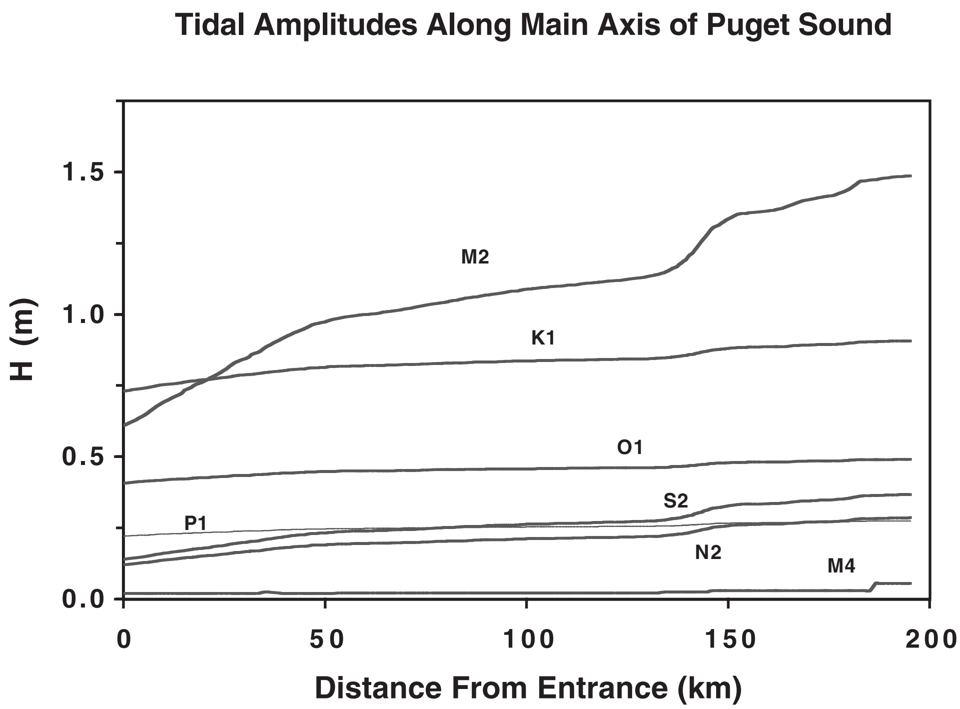

Figure A.1: Profiles of O1, K1, M2 and M4 tidal amplitudes down the main axis of Puget Sound, from the Puget Sound channel tide model (Lavelle *et al.,* 1988).

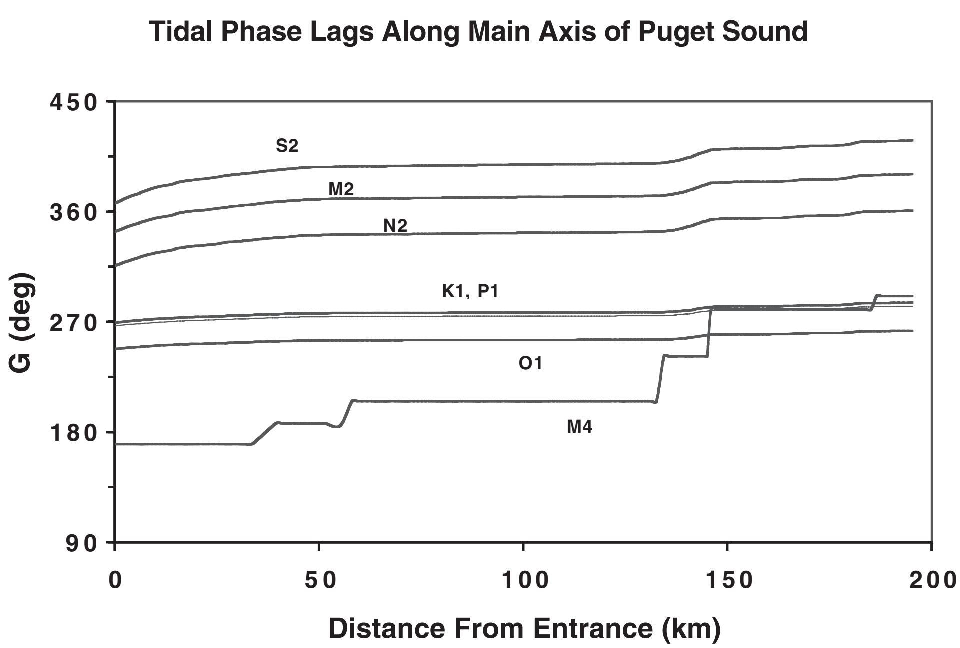

Figure A.2: Profiles of O1, K1, M2 and M4 tidal phase lags down the main axis of Puget Sound, from the Puget Sound channel tide model (Lavelle *et al.,* 1988).

Table A.1: Observed tidal harmonic constants at selected tide stations in Puget Sound. Values for Port Townsend, Seattle and Tacoma are taken from the NOAA/NOS/CO-OPS Website (`www.co-ops.nos.noaa.gov`). The values for Olympia are provided by the NOAA/National Ocean Survey (data archives).

ID	**9444900**		**9447130**		**9446484**		**9446969**	
Name	**Port Townsend**		**Seattle**		**Tacoma**		**Olympia**	
Lat.	**48° 06.9′N**		**47° 36.3′N**		**47° 16.0′N**		**47° 03.1′N**	
Long.	**122° 45.0′W**		**122° 20.3′W**		**122° 24.8′W**		**122° 54.2′W**	
Constit.	**H (m)**	**G (°)**	**H (m)**	**G (°)**	**H (m)**	**G (°)**	**H (m)**	**G (°)**
O1	0.450	249.9	0.458	255.4	0.459	255.1	0.463	265.1
P1	0.239	268.4	0.252	274.5	0.255	277.2	0.248	287.6
K1	0.764	270.8	0.831	277.3	0.838	277.9	0.849	288.7
N2	0.142	321.8	0.212	340.2	0.225	341.2	0.281	4.3
M2	0.684	350.5	1.070	11.4	1.139	11.8	1.464	29.9
S2	0.168	13.0	0.258	37.9	0.282	37.8	0.348	62.4
M4	0.038	59.7	0.021	194.9	0.019	207.7	0.055	291.0
M6	0.000	0.0	0.009	301.9	0.005	292.0	0.032	142.1

Table A.2: Percentage changes in the observed amplitudes H of the major tidal constituents and M4 at selected tide stations, relative to the corresponding values at Port Townsend near the main entrance to Puget Sound. The amplitudes are taken from Table A.1.

Constit.	**Seattle (%)**	**Tacoma (%)**	**Olympia (%)**
O1	1.8	2.0	2.9
P1	5.4	6.7	3.8
K1	8.8	9.7	11.1
N2	49.3	58.5	97.9
M2	56.4	66.5	114.0
S2	53.6	67.9	107.1
M4	−44.7	−50.0	44.7

Table A.3: Differences in the observed phase lags G of the major tidal constituents and M4 at selected tide stations, relative to the corresponding values at Port Townsend near the main entrance to Puget Sound. The phase lags are taken from Table A.1.

Constit.	**Seattle** (°)	**Tacoma** (°)	**Olympia** (°)
O1	5.5	5.2	15.2
P1	6.1	8.8	19.2
K1	6.5	7.1	17.9
N2	18.4	19.4	42.5
M2	20.9	21.3	39.4
S2	24.9	24.8	49.4
M4	135.2	148.0	231.3

Table A.4: Ratios of observed amplitudes H for the major tidal constituents at selected tide stations in Puget Sound. The amplitudes are taken from Table A.1.

	Port Townsend	**Seattle**	**Tacoma**	**Olympia**
O1/K1	0.589	0.551	0.548	0.545
P1/K1	0.313	0.303	0.304	0.292
N2/M2	0.208	0.198	0.198	0.192
S2/M2	0.246	0.241	0.248	0.238

Table A.5: Differences in the observed phase lags G of the major tidal constituents at selected tide stations, relative to the corresponding values at Port Townsend near the main entrance to Puget Sound. The phase lags are taken from Table A.1.

	Port Townsend (°)	**Seattle** (°)	**Tacoma** (°)	**Olympia** (°)
K1-O1	20.9	21.9	22.8	23.6
K1-P1	2.4	2.8	0.7	1.1
M2-N2	28.7	31.2	30.6	25.6
S2-M2	22.5	26.5	26.0	32.5

10. References

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