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Estimation of Typical High Intertidal Beach-Face Slope in Puget Sound

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Estimation of Typical High Intertidal Beach-Face Slope in Puget Sound

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Contents

List of Figures iii

List of Tables iv

Abstract v

Acknowledgments vi

Introduction 1

Methods 3

- Constructing Tidal Contours 4
- Randomly Sampling Unarmored Beaches 6
- Automating Slope Estimation 7
- Verifying Samples Visually 8
    - Comparison of TCARI and VDATUM outputs to Harmonic Stations 9
    - Data Availability 9

Results 10

Discussion 15

- Known Error in Topobathymetric Models and Tidal Datum Modeling 16
- Potential Error in Construction of Tidal Datum Lines 16
- Estimation of Beach Slope on Unarmored Beaches 18
- Sub-Basin Effects 19
- Shoretype Effects 20
- Intertidal Encroachment and Endangered Species Act Consultations 21
- Potential Future Work 22

List of References 24

Appendix A: Additional Data Tables 26

Appendix B: Metadata 44

Figures

Figure 1. Conceptual diagram of how beach slope is used to estimate intertidal encroachment maintained by armoring 2

Figure 2. TCARI point distribution. 82,918 well distributed points provide a continuous estimate of HAT elevation within a nearshore zone 5

Figure 3. Distribution of final sample points among un-armored beaches by shoretype and sub-basin 7

Figure 4. Visual verification of transects 8

Figure 5. Comparison of Model Outputs to Published Tidal Datums 10

Figure 6. Histogram of slope and log-transformed slope estimates 10

Figure 7. Beach slope by sub-basin 12

Figure 8. Beach slope by beach shore form 13

Figure 9. Box and whisker plots of beach slope for each shoretype among sub-basins 13

Figure 10. Oblique aerial of a steep sloped beach sampled in the San Juan Islands 20

Tables

Table 1. Number of samples by shoretype and sub-basin 3

Table 2. Analysis of Variance Outputs 11

Table 3. Bonferroni test results showing which sub-basins differ from each other 11

Table 4. Bonferroni test results among shore type 12

Table 5. Median Beach Slope by Sub-basin and Shoretype 14

Table A-1. Comparison to tidal datum model outputs to harmonic station observations 26

Table A-2. Complete Bonferroni Test results among combinations of shoretype and sub-basin 27

Table A-3. Summary of beach sites, including sub-basin, shoretype, sub-sample count, and mean slope 30

Abstract

Many habitat service quantification methods measure the areal extent of impacts from development or restoration. This paper presents the development of two metrics that are useful for delineating habitat area affected by shoreline armoring in Puget Sound, Washington: typical unarmored beach slope and the elevation of highest astronomical tide (HAT).

To estimate typical beach slope at Puget Sound beaches, we completed a four-part GIS analysis. We constructed tidal contour lines estimating HAT and Mean Higher High Water (MHHW) using NOAA National Ocean Service's Center for Operational Oceanographic Products and Services (CO-OPS) Tidal Constituent and Residual Interpolation (TCARI) and VDATUM models. Second, we randomly identified 30 points along unarmored beach shorelines within each of five sub-basins and among four beach shoretypes (600 points total). For each random point, we developed automated slope estimates for the upper beach. Finally, we verified that each randomly selected point was located at an unarmored beach visually using aerial photography and a topobathymetric digital elevation model. We used Analysis of Variance (ANOVA) to evaluate the influences of sub-basin and shoretype on log transformed beach slope. We used Bonferroni's Test to evaluate the differences in log transformed slopes between sub-basins, shoretypes, and shoretypes within sub-basins.

The interpolated HAT elevations from the TCARI and VDATUM models correlated strongly with observed tidal elevations at all 34 available Puget Sound harmonic stations for which observed tidal elevations are available. Typical median beach slopes on unarmored shorelines were developed for four beach shoretypes within each of five sub-basins in Puget Sound. Thirty-three percent of the variation in beach slope could be explained by shoretype and marine sub-basin. Bonferroni comparison tables showed significant differences in slope between all shoretypes. Generally, accretion beaches were the flattest and transport zone beaches the steepest.

The results were used to support the determination of the area affected by shoreline armoring for use with the Puget Sound Nearshore Conservation Calculator – a tool that can be used to support Endangered Species Act consultations in Puget Sound's nearshore.

Acknowledgments

We are thankful to George Kaminsky and Hannah Drummond for early conversations about development and use of beach data. We are grateful to David Wolcott, Christina Urizar, and Sierra Davis at the National Ocean Service for their assistance in developing interpolated values for Highest Astronomical Tide in Puget Sound using Tidal Constituent and Residual Interpolation. We thank Todd Ehret from NOAA Center for Operational Oceanographic Products and Services for his assistance with explaining NOAA tidal data as they relate to HAT. A particular thanks to Bill Ehinger for his guidance on statistical analysis.

Introduction

The National Marine Fisheries Service (NMFS) consults on impacts to critical habitats of federal Endangered Species Act (ESA)-listed species. In Puget Sound, these listed ESA-listed species include threatened Hood Canal summer-run chum (*Oncorhynchus keta*) and Chinook salmon (*Oncorhynchus tshawytscha*), which are important prey for endangered Southern Resident Killer whale. Many development proposals include the construction and replacement of shoreline armoring (such as riprap, bulkheads, seawalls, etc.) This armoring commonly encroaches into the intertidal zone, thereby reducing the area of shallow beach under tidal inundation. Truncating the beach has a range of likely adverse effects on ESA-listed species, including loss of detrital food webs associated with wrack accumulation and loss of forage fish spawning habitat (Dethier, et al. 2016; Heerhartz, et al. 2014; Heerhartz, et al. 2016).

The spatial extent of marine shoreline habitats commonly references the typical elevations of tides and their physical effects[1]. A tidal datum is the average height of a specific tide over a 19-year epoch. The highest of these tidal datums is Highest Astronomical Tide (HAT)—the elevation of the highest predicted tide not incorporating atmospheric pressure and storm surge. As such, HAT is a useful reference point for regulating the intertidal zone, a reasonable upper edge of the intertidal zone. Observed Extreme High Tide may exceed HAT by several feet during storms, and so the area under tidal influence extends past the HAT line, but is not as easily or consistently defined as a reference point, and depends on weather.

NMFS designated the lateral extent of Puget Sound Chinook and Hood Canal summer-run chum critical habitat to extend up to extreme high tide. This designation is based on the "unique ecological setting and well-documented importance of the nearshore habitats" (FR 70 52666 September 2, 2005). HAT, while commonly lower than the extreme high tide, can serve as an appropriate and measurable surrogate for the extreme high tide for evaluating effects to habitat for ESA-listed Puget Sound Chinook and Hood Canal summer-run chum.

Gain or loss of habitat area is an expeditious and commonly used component in quantifying ecosystem services. For example, Habitat Equivalency Analysis, which is frequently used to determine damages under Natural Resource Damage Assessments[2], is based on the areal extent of impacts. Wetland area is a significant measure in Clean Water Act administration. To quantify the effects of development actions in Puget Sound, NMFS relies on the lateral extent of designated critical habitat to determine affected area. NMFS quantifies the gain or loss of shoreline habitat functions caused by repair, replacement or, new installation, or removal of shoreline armoring based on the area of the impact to the designated critical habitat.

Under the ESA, NMFS is required to consult on nearshore development proposals in Puget Sound. Determining the area of intertidal habitat affected by a bulkhead is an important component of this analysis as armoring can be placed at different tidal elevations and affect vastly different amounts of intertidal habitat. In general, a bulkhead cuts off access for fish

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[1] https://ecology.wa.gov/Water-Shorelines/Shoreline-coastal-management/Shoreline-coastal-planning/Shoreline-Management-Act-SMA/Shoreline-Management-Act-jurisdiction/Ordinary-high-water-mark

[2] https://darrp.noaa.gov/what-we-do/natural-resource-damage-assessment

to intertidal areas landward of the bulkhead, which we describe as intertidal encroachment (Figure 1). To determine the area of intertidal encroachment, we need to know the length of armoring along the shoreline, the elevation of HAT, the average elevation of the toe of armoring, and the typical beach slope between Mean Higher High Water (MHHW) and HAT.

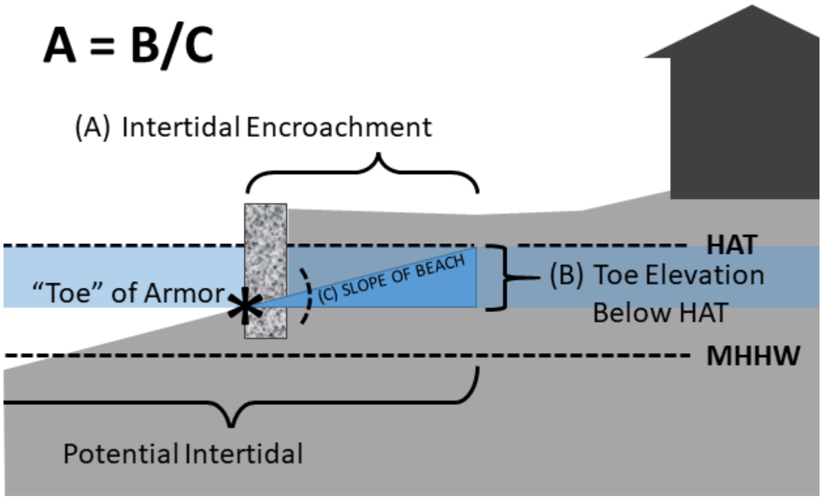

Figure 1. Conceptual diagram of how beach slope is used to estimate intertidal encroachment maintained by armoring. HAT is the highest astronomical tide. Slope is represented as a proportion of elevation gain for each unit of distance. Thus, we estimate intertidal encroachment by locating the elevation of the toe of armoring below HAT, and divide that by a typical beach slope. This effort provides a reasonable estimate of beach slope where none is otherwise available in the application.

We propose using typical beach slopes rather than attempting to measure likely site-specific slopes for several reasons. First, most proposals for consultation under the ESA don't contain information on beach slope. Second, determining the most probable slope of a beach buried under fill on a (site modified by armoring) is slow and expensive. Finally, currently available digital elevation data for Puget Sound, while useful for extensive studies like those described below, cannot offer reliable assessments at a specific site. Using typical beach slopes for a given beach type and basin addresses these challenges.

To estimate typical beach slope in Puget Sound, we completed a desktop survey of randomly selected unarmored beaches across Puget Sound using high resolution lidar elevation models and sound-wide estimates of the elevation of HAT and MHHW. This allowed us to rapidly observe a wide range of naturally occurring beach conditions, to more precisely and accurately estimate the typical area of intertidal encroachment at a given site (Figure 1).

The Puget Sound Partnership and NOAA identified five marine sub-basins for the purpose of administering their Nearshore Conservation Credit program (https://www.psp.wa.gov/pspnc.php). A recent Beach Analysis by WDFW identified four kinds of beaches based on their geomorphic context (MacLennan et al. 2017), a refinement of categories proposed by Shipman (2008), and used extensively in the Puget Sound Nearshore Ecosystem Restoration Project (USACE 2015). We anticipated that geomorphic context may systematically affect beach slope. In this way, sub-basin and shoretype are two readily available project attributes that could be used to define a typical beach slope estimate considering ecosystem processes. We also compared beach slope among sub-basins and shoretypes to determine if there was systematic interaction between these attributes that should be considered during a quantification process.

Methods

To estimate typical beach slope among Puget Sound beaches, we completed a four-part desktop analysis using ESRI ArcGIS Pro (ESRI Inc., 2022) for spatial analysis:

1. **Constructing Tidal Contours:** We constructed contour lines estimating Highest Astronomical Tide and Mean Higher High Water using a USGS high-resolution topobathymetric digital elevation model (DEM) and a series of NOAA tidal datum model outputs.
2. **Randomly Sampling Unarmored Beaches:** we randomly identified 30 points along unarmored beach shorelines within each of five (5) sub-basins and among four beach shoretypes (600 points total).
3. **Automating Slope Estimation:** At each random point, we automated construction of transects perpendicular to the shoreline at 10-meter intervals extending 50 meters on either side of the random point. This produced approximately ten (10) transects surrounding each random point depending on the shoreline curvature. At each transect, we recorded the distance between HAT and MHHW contours, and the elevation interval between HAT and MHHW, as well as sub-basin and shoretype. We calculated slope as a proportion, by dividing the elevation interval by the distance between contours ("rise over run").
4. **Verifying Samples Visually:** Automated GIS processes resulted in some transects that wrongly selected armored beach faces or beaches not exposed to wave action. We used the topobathymetric digital elevation model, aerial photography, and oblique aerial photography to inspect each randomly identified point and associated transects to verify that measurements met the intended purpose. We removed sites and samples that did not measure an unarmored beach face exposed to wave energy. The final number of samples by shoretype and sub-basin are summarized in Table 1.

Table 1. Number of samples by shoretype and sub-basin. The low number of samples in Strait of Juan de Fuca reflects that a limited extent of the sub-basin is located within the area of the topobathymetric digital elevation model.

	Shoretype				
Sub-Basins	**Accretion**	**Feeder Bluff Exceptional**	**Feeder Bluff**	**Transport zone**	**Total**
Hood Canal	26	30	30	24	**110**
North Puget Sound	27	30	28	28	**113**
South Central Puget Sound	22	29	27	25	**103**
Strait of Juan de Fuca	19	16	25	9	**69**
Whidbey	24	29	30	29	**112**
Total	**118**	**134**	**140**	**115**	**507**

Constructing Tidal Contours

While interpolation of tidal datum elevation has been complete in the past (Hess & Gill 2003), we have no currently available spatial resources to support these analyses. NOAA maintains standard tools for estimating tidal datum at any location in coastal waters (VDATUM; see Thatcher et al. 2016). Unlike the Mean Higher High Water (MHHW) datum, HAT is not included as part of the standard NOAA VDATUM library. While we could estimate the elevation of MHHW, we needed to estimate the interval between MHHW and HAT across Puget Sound.

NOAA National Ocean Service's Center for Operational Oceanographic Products and Services (CO-OPS) supported this project with a Tidal Constituent and Residual Interpolation[3] (TCARI) model-run encompassing all of Puget Sound and adjacent waters. Typically, TCARI is used to compute water level corrections for bathymetric surveys; however, it was adapted to assist with this project. TCARI uses observed water level data and datums and creates a grid over which it calculates "continuous" tidal datum relationships. The TCARI model generated for this project had 189,053 grid points with an average nearest neighbor of 82 meters, with a high degree of point clustering along shorelines. At each point TCARI calculated the increment between MHHW and HAT.

To define tidal elevation across Puget Sound, we added additional tidal datum attributes to the TCARI Points using the NOAA VDATUM software. Using VDATUM, we converted the elevation of MHHW to an absolute elevation in North American Vertical Datum of 1988 (NAVD88) for all points. We added the MHHW-HAT interval calculated using TCARI to establish an elevation for HAT. NAVD88 is the native elevation datum used for the topobathymetric model from the USGS Coastal National Elevation Database (CoNED Model; Danielson et al. 2016). The USGS Coastal National Elevation Dataset is the result of collaboration between USGS, NOAA, and USACE to develop an aligned 1-meter resolution topobathymetric dataset using best available Puget Sound data sources. These data were developed to support shoreline delineation and coastal modeling.

For the purpose of processing efficiency, we limited our analysis to a "Nearshore Zone" using the nearshore portion of the Geographic Scale Units polygon feature from the Puget Sound Nearshore Ecosystem Restoration Project geodatabase architecture (Anchor QEA, 2009)[4]. This area of analysis included uplands within 200m of the state-defined shoreline, and offshore to approximately 10m of water depth below mean tide, thereby encompassing those areas likely to be affected by shoreline development. After clipping the TCARI Point to this Nearshore Zone and to the CoNED Model extent, and discarding any points not recognized as "in water" within the VDATUM software, we were left with 82,918 well-distributed points describing MHHW and HAT tidal datum elevations across a large portion of Puget Sound, excluding only portions of the western Strait of Juan de Fuca (Figure 2).

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[3] https://tidesandcurrents.noaa.gov/hydro.html

[4] https://wagda.lib.washington.edu/data/geography/wa_state/#PSNERP

Figure 2. TCARI point distribution. 82,918 well distributed points provide a continuous estimate of HAT elevation within a nearshore zone. These points were a sub-set of a continuous grid developed by NOAA CO-OPS. Figure 2A shows the typical density of points within the nearshore zone. Figure 2B shows the position of Figure 2A, as well as the extent of the CoNED Model.

The MHHW and HAT elevations described by these point estimates (in NAVD88) were converted into a coarse resolution interpolated raster surface using Inverse Distance Weighted Interpolation[5]. The 10m square cells of this coarse raster were aligned to the CoNED Model (both in NAVD88). These coarse rasters describing the MHHW and HAT surfaces were then subtracted from the CoNED Model, using a Raster Calculator[6] to generate a set of relative surface rasters, such that the spatial position of each tidal datum becomes a new “zero” value in the new relative raster. Using these relative surface models, two contour lines were then constructed[7], to represent the estimated spatial location of MHHW and HAT across the extent of the Puget Sound shoreline. No further refinement of these contour lines was performed, but the quality of lines was evaluated during visual verification of randomly sample locations.

There are several potential sources of error embedded in these two contour lines, such that they may not represent the precise position of the tidal datum. Error could be attributed to either the TCARI model outputs, the VDATUM model outputs, or to inaccuracies or imprecision in the CoNED Model. To evaluate the accuracy of TCARI and VDATUM outputs we compared predicted MHHW and HAT elevations from the TCARI and VDATUM outputs to observed and predicted water levels at tidal harmonic station array in Puget Sound. We calculated mean differences of predicted versus measured values using all 34 available harmonic stations. No harmonic station was located more than 330 meters from a TCARI point, with an average distance of 50 meters. We also ran a regression of the predicted elevation outputs versus the observed outputs to visualize the relationship, as described in our results.

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[5] https://pro.arcgis.com/en/pro-app/2.8/tool-reference/spatial-analyst/idw.htm
[6] https://pro.arcgis.com/en/pro-app/2.8/tool-reference/spatial-analyst/raster-calculator.htm
[7] https://pro.arcgis.com/en/pro-app/2.8/tool-reference/spatial-analyst/contour-list.htm

There is also potential for error in the CoNED Model, either from lidar artifacts, interpolated gaps in coverage, or actual measurement error native to lidar. In addition, as the beach slope increases, the distance between HAT and MHHW contour lines decreases, until precise measurement may be compromised by the 1-meter resolution of the CoNED Model used to create those lines. This issue comes into focus in our discussion of our lower confidence in beaches observed with steep slopes.

Finally beaches and shorelines are in constant flux. We suspect that we have achieved a relatively precise snapshot of beach condition, and that these various sources of error are likely to be randomly distributed, and thus can be overcome by sampling a large number of beaches (as we have done), and averaging the results to produce a reasonable parameter estimate. Thus, we believe that our results provide a broad-scale insight into typical beach conditions and variation.

Randomly Sampling Unarmored Beaches

To identify unarmored beaches, we used shoreline attributes from the Washington Department of Fish and Wildlife's Beach Strategy, as developed by MacLennan *et al.* (2017). We selected beach line features that were unarmored, attributed these with sub-basin designations provided by the Puget Sound Partnership, and then split these line features into four classes, based on the four "shoretype" attributes associated with beach geomorphology (feeder bluff, feeder bluff exceptional, transport, and accretion). "Feeder bluffs" generally showed some evidence of historical landslide through vegetation and topography, while with "feeder bluff exceptional" the absence of vegetation provides evidence of frequent shoreline erosion. Accretion beach are beaches, spits, forelands, or barriers with backshore features, where accumulated sediments prevent wave energy from working on shorelines. Transport zones are those beaches with no evidence of either sediment input or accumulation (see MacLennan et al 2017 for examples) .

Unarmored beaches of all types were present in all sub-basins. The presence of armoring was based on aggregated observations from multiple surveys over the last several decades, also provided by MacLennan *et al*. (ibid.). Among these unarmored beach shoreline features, we randomly located 30 points in each of the twenty classes created by the cross-tabulation of shoretype and sub-basin (a total of 600 randomly located points.)

Armoring is unevenly distributed within Puget Sound. Large stretches of beach along railroad lines and roads, particularly along the eastern shore of Puget Sound and western shore of Hood Canal are completely armored. In sub-basins with extensively armored shorelines, our randomly sampled sites are concentrated on the remaining un-armored beaches. The uneven distribution of unarmored beaches samples can be observed in Figure 3.

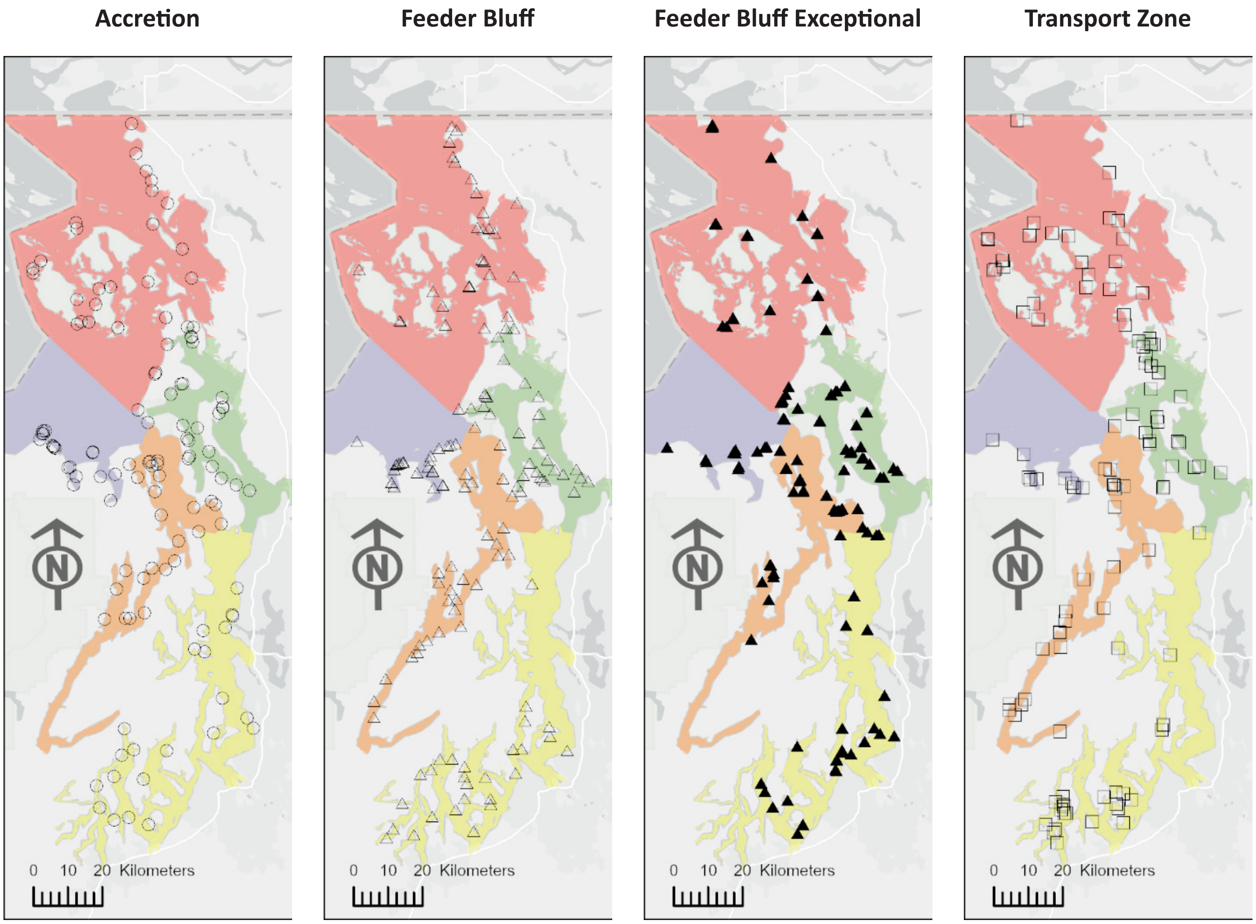

Figure 3. Distribution of final sample points among un-armored beaches by shoretype and sub-basin. The dashed line indicates the extent of the CoNED Elevation Model. Samples were distributed among sub-basins. The uneven distribution of armoring may result in an uneven distribution of sample sites. In sub-basins with few unarmored beaches, sample sites may be concentrated on the remaining un-armored beaches.

Automating Slope Estimation

We clipped a shoreline segment within 50 meters of each point, and within this segment constructed transects at 10-meter intervals perpendicular to the shoreline. This resulted in approximately five transects on either side of each point (Figure 3), although due to shoreline curvature, between eight and twelve transects were created. On each transect, we clipped the transect line at the HAT and MHHW contours and calculated the length of the resulting segments. Each resulting transect was attributed with the HAT-MHHW interval from the nearest TCARI Point. In this way, we obtained up to twelve slope estimates from each of 600 stratified and randomly selected 100-meter unarmored beach segments.

Verifying Samples Visually

We inspected locations and transects compared to our contour lines, the CoNED Model, aerial photography (ESRI, 2022), and oblique aerial photography (WDOE, 2022) to eliminate points and transects that didn't provide a reasonable estimate the slope of an unarmored, seaward beach slope (Figure 4). We eliminated samples that were not located on an unarmored beach face, not on a shoreline exposed to wave energy, or not adjacent to a viable landward building site.

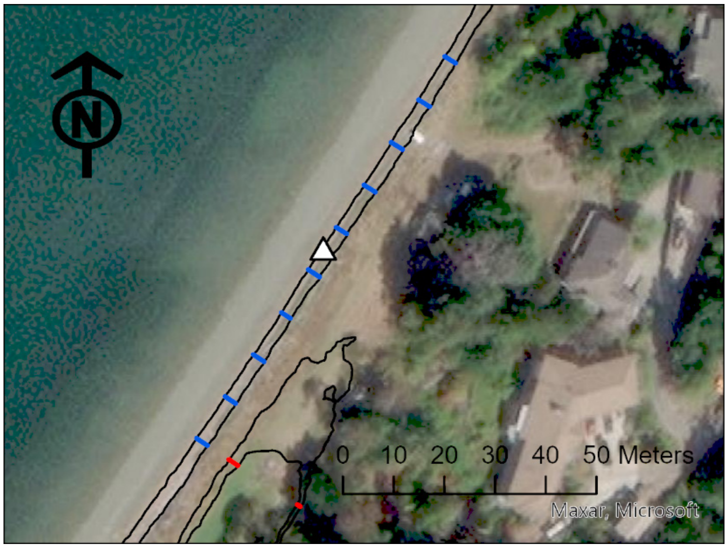

Figure 4. Visual verification of transects. In this example of an accretion shoretype, the random point is marked with a triangle, transects are arrayed at 10m intervals, five to either side. Blue transects on the seaward beach face were retained while red transects in the backshore were discarded.

We eliminated transects on low-elevation sand spits and other depositional features that were not buildable, or within backshore features not affected by wave energy, or where obvious lidar artifacts prevented accurate estimation of slope. Where backshore beach topography created intermittently inundated backshore areas, the seaward beach face alone was used for slope estimation. Where contour islands were present because of local beach topography, the continuous contour lines rather than topographic islands were used to estimate slope. Where a random point was located next to an armored shoreline, such that it was not possible to create measurement transects on both sides of the random point without intersecting armored shoreline, the transects were constructed entirely on the side of the random point away from armoring. If a randomly selected point was located at the edge of a shoretype, such that some transects were placed in an adjacent but different shoretype, additional transects were manually created to obtain a minimum of five (5) transects for each randomly sampled point.

After this visual verification, we analyzed slope estimates at 507 randomly selected points distributed among all shoretypes and sub-basins. Each slope estimate was calculated as the mean of all valid transects associated with a given point. In 79% of cases, slope was estimated using eight (8) or more viable transects. At a single narrow site, slope was estimated using three (3) transects, and the remaining point estimates were made using five (5) or more transects.

Comparison of TCARI and VDATUM outputs to Harmonic Stations

The modelled interval between HAT and MHHW using Tidal Constituent and Residual Interpolation (TCARI) was critical to slope estimation. To evaluate our methods, we compared this modeled interval to observed measurements at harmonic tidal stations in Puget Sound. This does not test the model across a wide range of shoreline circumstances, but does test whether our model tidal datum surface generally aligns with observed measurements.

Data Availability

TCARI points and derived contour lines are available by request from the authors.
Beach Strategy Data are available upon request from the WDFW ESRP program. USGS Topobathymetric models are available as part of the public USGS Science Base Catalog[8].
VDATUM software is available at the public NOAA VDATUM website[9].

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[8] https://www.sciencebase.gov/catalog/item/5d72b5dfe4b0c4f70cffa775

[9] https://vdatum.noaa.gov/

Results

The interpolated Highest Astronomical Tide (HAT) from the TCARI and VDATUM models correlated strongly with observed tidal elevations at all 34 available Puget Sound harmonic stations. Differences between observed tidal elevations and model outputs ranged between 0.001 and 0.397 feet among 32 of the stations, while Telegraph Bay and Sandy Point Anderson Island show a difference of 1.946 feet and 1.335 feet, respectively. Both stations appear to have a short period of record. When these two stations are removed, the average difference between observation and model decreased from 0.068 to 0.031 feet (Table A1) generating a regression with a high correlation ($r^2 = 0.9827$) (Figure 5).

The distribution of beach slope among all sub-basins and shoretypes was skewed, with a large proportion of beaches having a slope between 0.075 and 0.275, but with a small number of beaches with much higher slopes (Figure 6). A base-10 log transformation on slope data produced an approximately normal distribution of beach slope, supporting the use of an Analysis of Variance (ANOVA) to evaluate the influences of sub-basin and shoretype on beach slope.

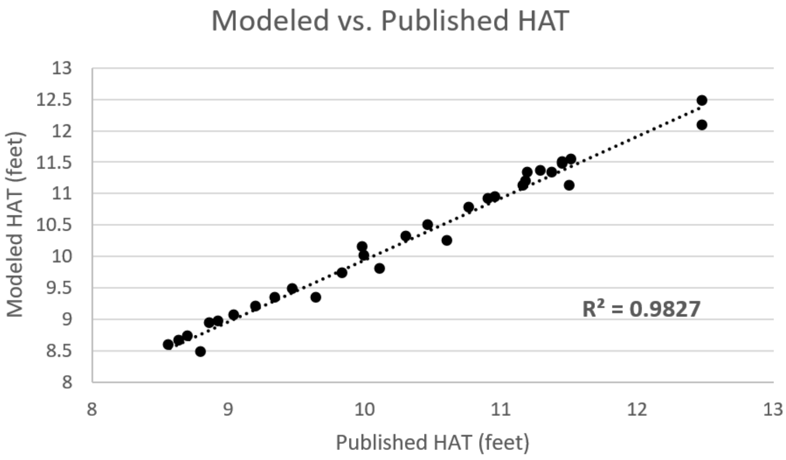

Figure 5. Comparison of Model Outputs to Published Tidal Datums. Model outputs were highly correlated to published HAT elevations at 32 tidal stations. Residual error appears to be well distributed. Two outliers at Sandy Point Anderson Island, and Telegraph Bay are not considered in this graph and calculations.

The ANOVA indicated that approximately a third of the variation in beach slope can be explained by shoretype, basin, and shoretype within basin ($n = 507$, $r^2 = 0.333$), indicating that there are likely other substantive factors affecting beach slope. The ANOVA indicated that there were significant differences in slope between shoretypes, between basins, and between shoretype within basins, such that the basin being observed affects the pattern of variation among shoretypes (Table 2).

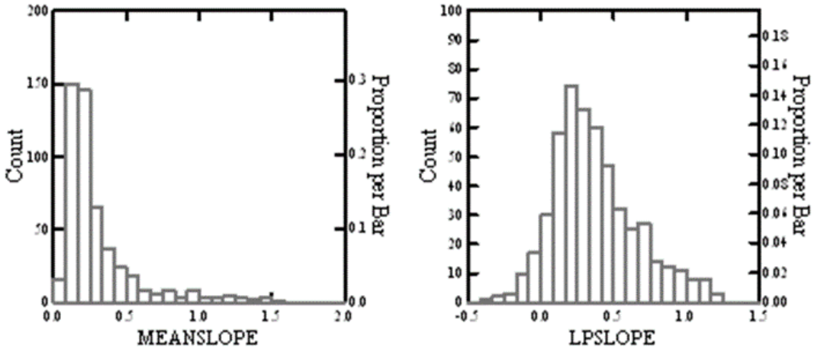

Figure 6. Histogram of slope and log-transformed slope estimates. Transformed data display an approximately normal distribution without systematic variation in residuals.

We used Bonferroni's Test (creating multiple comparison tables) to evaluate the differences

Table 2. Analysis of Variance Outputs. Thirty-three percent of variation in beach slope is explained by shoretype and marine sub-basin ($n = 507$, $r^2 = 0.333$). A significant difference in log transformed slope was observed between shoretype, sub-basin, and shoretype within sub-basin.

Source	Type III sum of squares	df	Mean Squares	F-Ratio	p-Value
Shoretype	6.261	3	2.087	35.966	0.000
Sub-basin	3.233	4	0.808	13.929	0.000
Shoretype x Sub-Basin	3.687	12	0.307	5.295	0.000
Error	28.315	488	0.058	—	—

in log transformed slopes between specific sub-basins, shoretypes, and shoretypes within sub-basins. Evaluating differences between sub-basins (not considering beach types), beach slopes in North Puget Sound were particularly unlike other basins, while other sub-basin comparisons showed greater similarity (Table 3). Beach slopes were not significantly different among Hood Canal (HC) versus South Central Puget Sound (SC) and Whidbey (WB) basins (Figure 7). All three, HC, SC, and WB, were significantly different from Strait of Juan de Fuca Basin (JdF). Both HC and WB were significantly different from North Puget Sound (NPS), and JdF and NPS were significantly different from each other. This suggests that Beach Slope could be considered more similar among HC, SC, and WB, but that typical beach slope in NPS and JdF were each different from the other basins, with NPS beaches steeper, and JdF beaches flatter.

Since it is easier to consider these results with non-log transformed slope values, we show box plots using the un-transformed slope values by basin in subsequent figures. The statistical parameters and confidence intervals in tables use log-transformed values.

Table 3. Bonferroni test results showing which sub-basins differ from each other. Difference and confidence interval values are in log transformed slope values. Low p-values (in bold) indicate that the compared sub-basins had significant differences in log transformed slope.

Marine Basin	Marine Basin	Difference	p-Value	Low 95%	High 95%
HC	**NPS**	**–0.152**	**0.000**	**–0.243**	**–0.061**
HC	SC	–0.068	0.401	–0.161	0.025
HC	**JdF**	**0.115**	**0.029**	**0.011**	**0.219**
HC	W	–0.010	1.000	–0.101	0.081
NPS	SC	0.084	0.113	–0.009	0.176
NPS	**JdF**	**0.267**	**0.000**	**0.164**	**0.371**
NPS	**W**	**0.142**	**0.000**	**0.052**	**0.233**
SC	**JdF**	**0.184**	**0.000**	**0.078**	**0.289**
SC	W	0.058	0.774	–0.034	0.151
JdF	**W**	**–0.125**	**0.012**	**–0.229**	**–0.022**

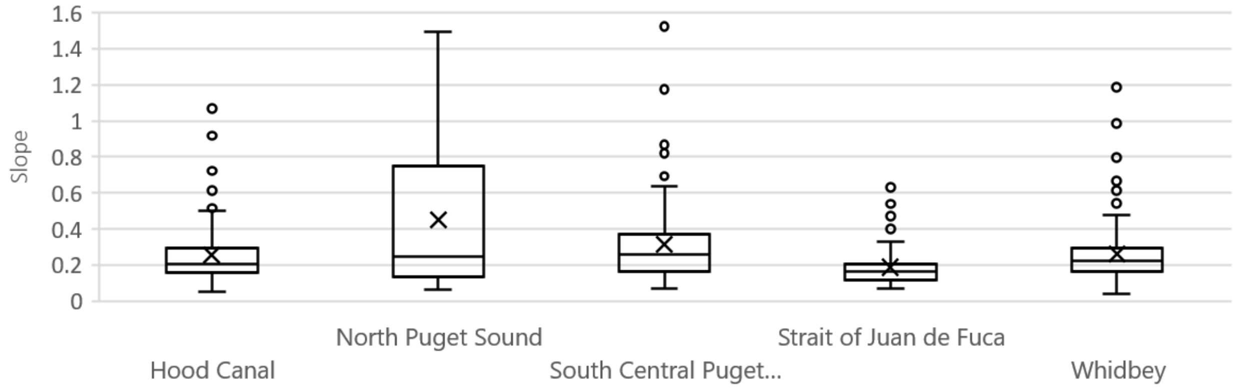

Figure 7. Beach slope by sub-basin. Box plots indicate quartile distribution of estimated beach slope, with the center line of the box being median slope. Note that beach slope, and not log-10 transformed beach slope is used in these plots to show the range and central tendencies of beach slope as observed in GIS measurements. Observations greater than 1.5 times the inter-quartile range were identified by a circle. Mean slope is marked with an X.

Bonferroni comparison tables showed significant differences between all shoretypes (Table 4). Beach geomorphic context (shoretype) appears to have a stronger correlation with beach slope than marine sub-basin. Again, box plots of slopes by beach types are depicted in Figure 8. Accretion shoretypes have the shallowest slope, and transport shoretypes have the steepest slope.

Further use of the Bonferroni Test allows for comparison of log-transformed beach slopes for different shoretypes within sub-basins (see Appendix A for complete comparison tables). These differences are illustrated in a set of box and whisker plots (Figure 9). The pattern of relative slope among shoretypes clearly varies among basins. The potential meaning of these patterns is discussed further below.

Table 4. Bonferroni test results among shore type. Difference and confidence interval values are in log-10 transformed slope. p-values in bold suggest that all shoretypes had a significantly different slope when compared to any other shoretype.

Shoretype 1	Shoretype 2	Difference	p-value	Low 95%	High 95%
AS	FB	−0.224	**0.000**	−0.303	−0.144
AS	FBE	−0.122	**0.001**	−0.202	−0.042
AS	TZ	−0.322	**0.000**	−0.406	−0.239
FB	FBE	0.102	**0.004**	0.025	0.179
FB	TZ	−0.099	**0.013**	−0.179	−0.018
FBE	TZ	−0.200	**0.000**	−0.281	−0.119

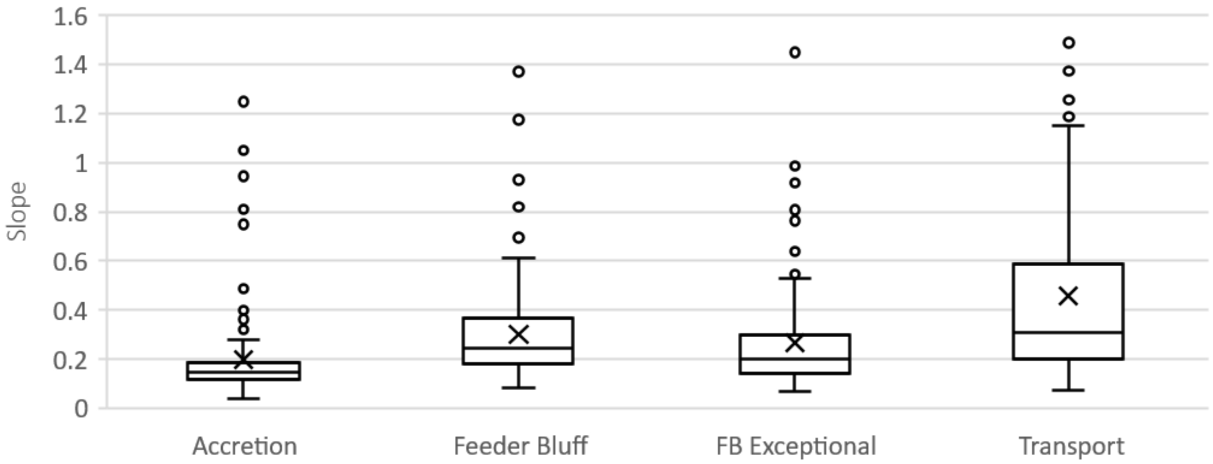

Figure 8. Beach slope by beach shore form. Box and whisker plots indicate quartile distribution of estimated beach slope. Note that beach slope, and not log-transformed beach slope is used in these plots to show the range and central tendencies of beach slope as observed in GIS measurements. Observations greater than 1.5 times the inter-quartile range are identified by a circle. Mean slope is marked with an X.

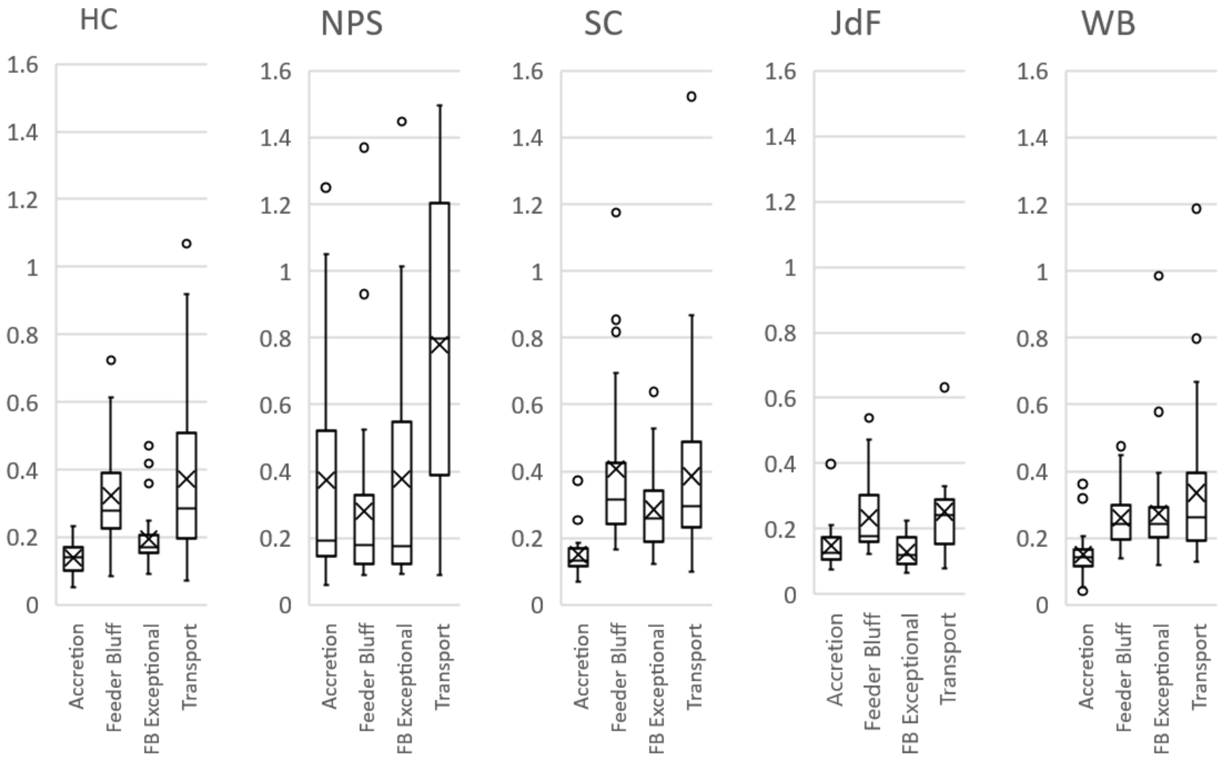

Figure 9. Box and whisker plots of beach slope for each shoretype among sub-basins. The vertical axis shows slope (height/width) with higher numbers indicating steeper beaches. Note that beach slope, and not log-10 transformed beach slope is used in these plots to show the range and central tendencies of beach slope as observed in GIS measurements. Observations greater than 1.5 times the inter-quartile range are show with a circle. Mean slope is indicated with and X. The variation of median slope among shoretypes can be observed in the center lines of the box which shows the median slope.

Because of the use of log transformation, statistical inference of significant difference references the median slope value of beaches observed by shoretype and sub-basin. As discussed above, some sub-basins have a high degree of similarity, while other sub-basins show a higher degree of difference. Because of the differences between sub-basins, and between shoretypes, and because of the interaction between sub-basin and shoretype, we present typical beach slopes using the median value by sub-basin and shoretype (Table 5).

Median beach slope provides our best estimate of typical beach slope between MHHW and HAT. The skewed distribution of slope (Figure 6) and the presence of observations that deviate strongly from the mean (circles in Figures 7,8, and 9) suggests that mean slope may not represent a typical beach compared to median. In addition, the use of log-transformed data for statistical analysis indicates significant differences among medians rather than means. While 67% of variation in slope is not explained by sub-basin and shoretype, Table 5 provides our best-available estimate of typical beach slope among sub-basins and shoretypes.

Table 5. Median Beach Slope by Sub-basin and Shoretype. Median provides the most reasonable measure of typical beach slope of a given type in a given sub-basin. Sixty-seven percent of variation is not defined by these two predictor variables, and so while these summary statistics provide best available evidence, we anticipate future improvements.

Sub-basin	**Accretion**	**Feeder Bluff**	**FB Exceptional**	**Transport**	**All**
Hood Canal	0.142	0.280	0.170	0.287	**0.202**
North Puget Sound	0.191	0.177	0.176	0.799	**0.249**
South Central Puget Sound	0.134	0.316	0.260	0.295	**0.256**
Strait of Juan de Fuca	0.126	0.177	0.120	0.240	**0.165**
Whidbey	0.143	0.243	0.241	0.262	**0.221**
All	**0.144**	**0.245**	**0.198**	**0.307**	**0.213**

Discussion

This study explored new spatial products derived from existing data to support analysis of Puget Sound shorelines. In the absence of data describing a specific site (such as beach slopes and the location of tidal datums along the beach face) these products may provide a reasonable basis for estimating a typical upper beach slope based on observations of a large number of Puget Sound beaches.

Our conclusions depend on the general validity of the CoNED Model. Because we are at this time unable to complete field validation of a subset of observed transects using high-precision survey equipment, we compared the position of contour lines, created using the CoNED Model to obvious features in aerial photography. We generally observed a high fidelity of our tidal datum lines to features observed on aerial photography, such as the edges of sea walls and tidal channel edges in natural estuaries. Many detailed shoreline features were well-delineated using tidal datum lines, with a variety of potential applications for characterizing shoreline conditions.

The frequency of tidal inundation strongly affects fish access and ecosystem services in the nearshore. Delineating habitat by elevation zones provides a reasonable basis for describing the ability of fish the access habitat, habitat area, and the presence of habitat forming processes, and thus describing the local provision of ecosystem functions, goods and services. This delineation of tidal zones provides a useful input for weighted-area-based quantitative models such as Habitat Equivalency Analysis.

TCARI and VDATUM outputs, combined with high-resolution lidar can produce Puget Sound-wide topographic contour lines that describe shoreline features observed in aerial photographs. These constructed tidelines are more precise and accurate than any existing shoreline spatial data (such as those used in the Puget Sound Nearshore Ecosystem Restoration Project[10]).

These results were primarily developed to provide decision support to ongoing NOAA regulatory efforts. To increase consistency and efficiency of regulatory consultations, interdisciplinary teams are developing tools like the Puget Sound Nearshore Habitat Conservation Calculator[11]. These tools quantify the relative impacts of coastal development and restoration on threatened and endangered species and rely on dividing shoreline landscapes into zones based on tidal data. High resolution spatial descriptions of coastal habitats provide a range of opportunities for improving these tools. However use of these contour lines require ongoing careful consideration of potential sources of error.

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[10] https://wdfw.wa.gov/species-habitats/habitat-recovery/nearshore/conservation/programs/psnerp
[11] https://www.fisheries.noaa.gov/west-coast/habitat-conservation/puget-sound-nearshore-habitat-conservation-calculator

Known Error in Topobathymetric Models and Tidal Datum Modeling

Error in input data may affect the accuracy of our derived data. Our analysis depends on the precision and accuracy of the CoNED Model. The CoNED Model used to define our shoreline datum lines summarizes elevation measurements into a one-meter-resolution grid. Elevation models derived from lidar data may include grid cells with limited density of point-cloud measurements such that surface features are not detected. The process of averaging point cloud measurements into a one-meter grid may misrepresent details of on-the-ground conditions.

There are known gaps between lidar-derived topography and sonar-derived bathymetry (Danielson and others, 2016). In the CoNED Model, the gaps between these two surfaces are interpolated, creating a presumed but artificial surface, with a potential loss of detail.

Using automated cross-section measurements in GIS we were able to rapidly obtain a large number of samples across a stratified landscape. If the error in beach slope estimation is randomly distributed, this ability to obtain a large number of samples may produce robust parameter estimates, and allow for observation of large-scale patterns. This rapid assessment of large-scale patterns can provide hypotheses that could be tested using other more precise methods such as benchmark-based surveys, RTK-GPS survey or boat-based lidar.

The risk of inaccurate measurement may increase dramatically if we attempt to use these products to describe particular locations. When observing a large number of sites, anomalies that represent error in underlying data are more likely to “cancel each other out” through averaging and statistical analysis, allowing observation of patterns and comparison of central tendencies. Thus, because of the likely presence of anomalies in underlying data, using these data to describe individual site conditions may result in erroneous conclusions.

For this reason, to average out the effect of site-specific errors, we recommend that the Conservation Calculator use the median beach slope (Table 5) rather than extracting site-specific observations from contour lines and aerial photographs to estimate beach slope.

These data, contour lines and beach slopes, should be considered as only one point of evidence. Corroboration or disagreement among several points of evidence should be considered when attempting to make determinations of site conditions, with a strong weight of evidence applied to local observations and high-precision surveys. Even as spatial data extent and quality improves, scientific evaluation of specific sites and situations should continue to contribute strongly to a weight of evidence approach.

Potential Error in Construction of Tidal Datum Lines

Use of lidar-derived data on shorelines requires consideration of how lidar interacts with the water surface. Lidar typically uses near-infrared lasers mounted on airplanes, while bathymetry uses sonar on watercraft. Lidar lasers typically bounce off the water surface. The extent of the beach surface accurately rendered by lidar depends on the elevation of tidal water surface at the time of the survey. Bathymetry is not commonly available in shallow water. For those areas below the extent of lidar, but above the extent of sonar bathymetry, the surface of the CoNED Model is an interpolation. This gap is estimated using an Empirical Bayesian Kriging algorithm (see Thatcher et al. 2016).

Our area of interest was high on the beach between MHHW and HAT, an area that is only inundated for brief periods. We presumed that the majority of the data we used for contour line construction used high-resolution lidar measurement, commonly available throughout Puget Sound, and were not constructed on interpolated data. We did not have the capability to test this presumption.

The number of "surface bounces" from a laser within each one-meter cell, in part determines the precision of a lidar DEM. These bounces generate a "point cloud" with the resulting one-meter cell elevations based on an average of those point measurements. In this way, the CoNED Model generalizes beach structure at a one-meter or greater resolution. Complex beach topography from scarps, boulders, or other irregular surfaces are poorly represented and may introduce error into cell values, and thus into our slope estimates.

The typical beach cross section in our study measured a distance of 10.86 feet (3.31 m) between HAT and MHHW. Thus, a typical slope estimate is based on comparing elevation change over four grid cells. Within an individual cell, the contour line position is estimated by the ArcGIS Pro contour algorithm. This may introduce some error into the actual position of the MHHW and HAT contour lines, based on the generalized elevations of the lidar grid surface. This error is likely to both overestimate and underestimate slope. By increasing the number of samples, we presume that this source of error would be resolved through repeated sampling to arrive at a robust parameter estimate. As with the errors in the underlying data discussed above, we expect that the errors introduced through the ArcGIS Pro contour algorithm when placing the contour lines will "cancel each other out".

Among steeper beaches, our slope estimate is based on the elevation differences between two adjacent cells or even within a single cell. This increases the potential source of error introduced through the ArcGIS Pro contour algorithm line placement. With the distance between the MHHW and HAT decreasing, the effect of line placement within a grid cell increases. This suggests that there is a greater potential for inaccuracy among measurements of steep beaches. We consider this risk later as we propose the use of median slope rather than mean slope in developing decision support tools for regulatory applications under the Endangered Species Act.

Compared to the issues presented by the resolution of available topobathymetric models (a world built of one-meter blocks) the risk of error in tidal datum modelling appears relatively low. We observed very strong correlation between published datums at harmonic stations, and VDATUM and TCARI model outputs (Figure 5 and Table A1). Potential vertical elevation error of the contour lines at the harmonic stations is at the scale of a half-inch or in some cases, a few inches with potential for both over-estimation and underestimation over the whole model domain.

The potential error of the contour lines may be larger at locations further away from harmonic stations. For example, we find it likely that model error increases in areas with strong resonance or concentration effects that are not well represented by model assumptions. Without extensive field measurement of water surface to evaluate accuracy of the contour lines away from harmonic stations, we are unable to gather evidence about this presumption. Most tidal stations are located in open water areas. A consulting biologist should be increasingly cautious in interpreting these model outputs at sites more removed from open bodies of water and located within one of the many narrowly isolated or drowned topographic features of the Puget Sound trough, where there is a greater likelihood of resonance or concentration effects.

Estimation of Beach Slope on Unarmored Beaches

We did not validate these desktop surveys with field surveys. This limits our ability to evaluate the accuracy of GIS-based methods compared to more accurate and precise field measurements. The high-resolution boat-based lidar data developed by Kaminsky (personal communications) may provide a useful method for comparing measurement methods over larger landscapes.

Only 33 percent of variation in beach slope is explained by sub-basin and shoretype over 507 sample sites (Table 2). Our survey methods revealed a wide range of beach slope from very low slope beaches most commonly associated with accretion features, and very steep beach slope most commonly found in transport zone beaches in the San Juan Islands.

In addition, our sample of un-armored beaches is not evenly distributed on the shoreline (Figure 3). Armoring is associated with development and is greater near population centers. Unarmored beach sites are therefore disproportionately located away from developed areas. Large areas of the eastern shore of Puget Sound that are almost continuously armored and therefore were not sampled.

Although we have no specific evidence, it is logical that armoring may be more common on beaches that are more prone to erosion. Observation of erosion during storms may motivate landowners to construct armoring to protect their properties. Erosion prone beaches, whether due to higher wave energy or more erodible bluff materials, could have more sediment inputs, and thus produce beaches with a flatter slope. This would result in greater armoring among beaches with a naturally flatter slope, and a greater proportion of unarmored beaches with a naturally steeper slope. While speculative, the degree to which our society preferentially constructs armoring on rapidly eroding beaches, and thereby exacerbating the degradation of sediment supply over decades of development, has not been evaluated. The relatively lower levels of armoring inside of coastal inlet landforms where erosion rates are lower and also armoring is less prevalent supports this hypothesis that armoring has a disproportionate impact of sediment input compared to its extent (Cereghino et al. 2012).

Future efforts may increase our understanding of these data by widening or comparing the width of beach between intervals other than between HAT and MHHW. For example, determining slopes between Mean Lower Low Water (MLLW) and HAT could help determine whether the general tendencies our current analysis yielded could be observed across a longer beach cross-section. Determining slopes between MLLW and MHHW would allow comparison of slopes on upper (MHHW to HAT) and lower (MLLW and MHHW) intertidal areas. While lower elevations increase the risk of using interpolation data to describe beach structure, these methods create the opportunity to generally describe beach structure at large spatial scales using many samples. These exploratory studies seem essential for stratifying beach sites as we work toward better understanding the provision of ecosystem functions, goods and services, as well as evaluating climate risk and restoration strategy.

Sub-Basin Effects

Sub-basin was not expected to be a strong predictor of beach slope, except where it serves as a surrogate for other factors such as fetch or shoreline surface geology that vary systematically among sub-basins. Conservation efforts at both Puget Sound Partnership and NOAA consider sub-basin or spatial location in general, as a factor in managing gains and losses in habitat services. Stratifying our sample by sub-basin allowed us to distribute beach samples across the landscape, and to determine if there is systematic variation in beach slope across that landscape.

North Puget Sound and Juan de Fuca sub-basin beaches were different from other sub-basins and from each other. Whidbey, Central Puget Sound and Hood Canal sub-basins were more similar. North Puget Sound sub-basin beaches were generally steeper in slope, particularly among transport zone beaches, which are beaches with no evidence of either local sediment input or accumulation. By contrast, Juan de Fuca sub-basin samples sites were generally flatter in slope.

North Puget Sound sample sites were located primarily among San Juan Island beaches, which may include many coarse gravel and cobble beaches. A beach shoretype, as identified by MacLennan et al. (2017) can include any unconsolidated material on a shoreline mobilized by waves, and so we presume the higher frequency of steep beaches in North Puget Sound may be caused by increased sampling of coarse shoretypes in the San Juan Islands, where beaches are frequently associated with exposed bedrock. Evaluation of beach type using the ShoreZone Inventory (Berry et al. 2001) was not considered by this preliminary work. We have a large variety of shoreline data to characterize beach management units at various scales. More extensive multi-variate analyses of beach and drift cell character are now available through a series of spatial efforts over the last two decades. It is clear that our data collection as now surpassed our ability to complete analyses that create meaning among that information. A coherent effort to assemble and observe patterns among those data, considering geomorphic drivers, physical structure, and biotic observations could support local strategies to protect and restore shoreline ecological functions under sea level rise.

Due to the limited extent of the CoNED Model, Juan de Fuca sub-basin sample sites were restricted to the eastern portion of the sub-basin. This shoreline is mostly located within Discovery and Sequim bays, which are protected from wave energy compared to the open strait. Including fetch as an explanatory variable may increase our ability to explain beach structure.

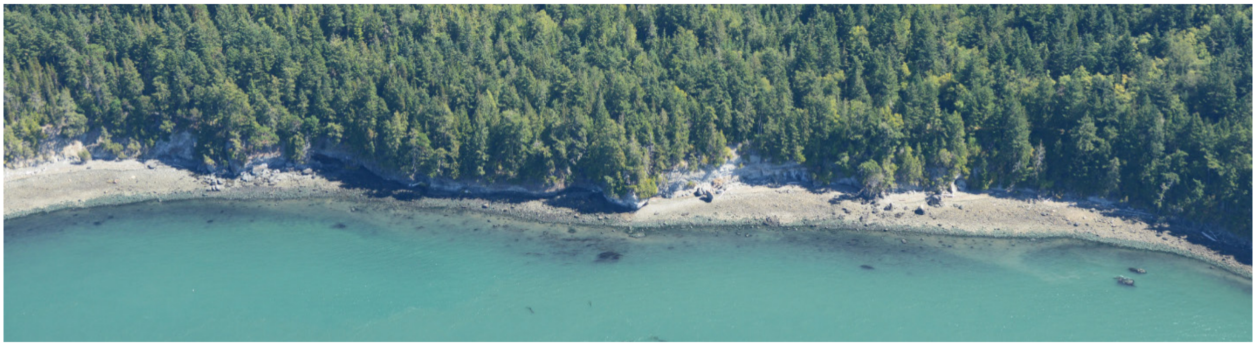

Figure 10. Oblique aerial of a steep sloped beach sampled in the San Juan Islands. The randomly selected sample location was located on a narrow coarse beach on Guemes Island.

Shoretype Effects

Generally, Accretion beaches (AC) were the flattest, Feeder Bluff Exceptional beaches (FBE) were generally significantly flatter than Feeder Bluffs beaches (FB), and transport zone (TZ) beaches were generally the steepest (Figure 5 and Table 9). However, this pattern was not consistent among all sub-basins.

For example, accretion beaches were not significantly different in slope between Hood Canal (HC), South Puget Sound (SPS), Juan de Fuca (JdF) and Whidbey Basin (WB) based on a Bonferroni analysis of shoretype and sub-basin interactions (Table A2). However, North Puget Sound (NPS) accretion beaches were significantly flatter than those found in HC, SPS, JdF, and WB. Accretion beaches occur by definition in locations where there is more sediment moving into a site than is leaving, such that sediments accumulate seaward, preventing waves from interacting with bluffs.

Conceptually a high local sediment supply could result in a reduction in beach slope. Presumably, this would explain the flattening of slope among accretion beaches compared to other beach types. By contrast, heavily armored beaches, which presumably have a reduction of sediment input, has been associated with increased slope at local scales, and coarsening of sediment at larger scales (Dethier et al. 2016). In both cases, the presence or absence of sediment inputs may affect both beach slope and texture. Including a more refined description of beach texture, such as provided in the ShoreZone Inventory (Berry et al. 2001) could be correlated with change in slope, and updrift presence of supply. Developing a coarse understanding of the relationship between sediment supply, texture and slope could allow coarse predictions of habitat change under sea level rise based on the presence or absence of armoring.

Feeder Bluff beach slope was not significantly different among all sub-basins. Feeder Bluff Exceptional beach slope only differed from Feeder Bluff beaches in a few cases (Figure 9; Table A2). Feeder Bluff Exceptional beaches in Juan de Fuca were significantly flatter than Feeder Bluff beaches in Hood canal and South Puget Sound, as well as Feeder Bluffs in Whidbey Basin. In addition, Feeder Bluff beaches in Juan de Fuca were significantly flatter than Feeder bluffs in Hood Canal, South Puget Sound and Whidbey Basin. A hypothesis for this variation could not be developed with the variables available.

The general steepness of Transport Zone beaches was largely driven by the exceptional steepness of North Puget Sound Beaches compared to all other sub-basins. No other sub-basin was significantly different (Table A2). Further, there are some cases where transport zone beaches are not significantly different than feeder bluff beaches in some sub-basins.

As only 33 percent of the variation in slope is explained by shoretype and sub-basin, other beach attributes and factors, such as offshore conditions, fetch, the character and erodability of sediment sources, or geomorphic history may better explain the variation in beach slope. A multivariate approach using a broader selection of explanatory variables could better describe the degree to which known beach conditions may be related to observed beach structural attributes.

Intertidal Encroachment and Endangered Species Act Consultations

Under the Endangered Species Act, NOAA consults with other federal agencies to determine the impacts of their actions on listed species and their designated critical habitat. In the Puget Sound, the impact of issuing a permit for shoreline development is evaluated considering adverse impacts to threatened and endangered species including Puget Sound Chinook salmon which are nearshore dependent as juveniles. NOAA evaluates any gain or loss in services from critical habitats, which includes most of Puget Sound's shoreline in the case of Chinook salmon. In the Puget Sound, development proposals often include the placement and replacement of shoreline armoring. Shoreline armoring disrupts natural shoreline processes and truncates potential intertidal habitat landward of the armoring, leaving it inaccessible to fish. The encroachment of armoring into the intertidal zone (Figure 1) reduces the habitat services that would be provided by intertidal habitats, if the armoring were not present or repaired. The larger the area of intertidal encroachment, the larger the reduction of habitat services.

Determining the area of intertidal encroachment is challenging for armoring replacement and repair. For new armoring, beach surveys are usually available. For repairing or replacing existing armoring, surveys are usually not provided and the historical intertidal zone has already been buried. At these "hydro-modified sites", the original beach slope, and distance between the toe of the armoring and HAT (which defines the extent of intertidal encroachment) would require the study of reference beaches.

Where possible, a consulting biologist would likely prefer to estimate natural beach slope by using carefully selected reference beaches that mimic the fetch, texture, and sediment supply conditions of a subject property. However, this level of information and effort is rarely available for consultations. This level of analysis would greatly increase the cost, duration, and complexity for both preparation of a Biological Assessment by the applicant and for regulatory review.

This regional study of typical beach slope offers a systematic and repeatable alternative to estimating intertidal encroachment on a beach through the study of reference beaches. At the time of this analysis, there were no other efforts to support estimation of beach slope. To assess armoring impacts efficiently, NOAA has adopted these beach slope estimates as “best available science” to calculate the area of intertidal encroachment at armoring replacement sites where there is no robust and site-specific study of beach slope. For these purposes, NOAA uses median beach slope (Table 5) as outlined in the Puget Sound Nearshore Conservation Calculator User Guide (Ehinger et al. 2023).

In general, with skewed datasets, extremely high or low observations have less influence on the median than on the mean. High slope measurements, greater than the angle of repose on some beaches, represent the greatest risk of measurement error, as discussed above. This risk of error, combined with the skewed distribution of slope measurements as well as the transformation of data for statistical analysis all suggest the use of median, rather than mean, as the more appropriate expression of central tendency (Zar, 1999).

Potential Future Work

These initial efforts demonstrate that high-resolution lidar topography, interpolated tidal datum estimates, GIS automation, and an accumulation of shoreline attributes provides a broad range of analytical opportunities to evaluate factors affecting beach structures.

Work by Kaminsky (personal communications) describes detailed beach profiles using boat-based lidar. These higher-resolution studies could be compared to airplane-based lidar data to compare their relative precision and accuracy. However, this kind of analysis may only consider general patterns, and be better suited to lower energy environments, since at high energy sites, beach structure is in constant motion.

While further analysis of beach slope may be interesting, it may have less benefit for regulatory programs than other questions with a greater potential bearing on beach conservation policy. The prioritization of future work could wisely consider:

- The degree to which we are currently unable to agree on how beach attributes describe ecosystem services over time.
- The degree to which that uncertainty affects our ability to quantify shoreline ecological functions.
- The impact those evaluations would have on policy decisions affecting shoreline development.

There are a wide range of analyses that could support more robust quantification of shoreline ecological functions. Many shoreline ecological functions are protected under state and federal law. Quantification increases consistency, efficiency, and accountability of regulation. Consistency and efficiency are increased by rapidly incorporating best available science in transparent models that support regulatory determinations. Accountability is increased by monitoring of how cumulative local, state, and federal management results in the gain or loss of shoreline ecological functions over time, thereby affecting the risk of species extinction and the condition of shoreline public trust resources. Strong inquiry necessarily integrates ecosystem science and regulatory policy. In this vein, the following questions emerged through the course of this work, in no particular order:

1. Is there correlation between the extent and configuration of shoreline armoring (reduced sediment input) and quantifiable aspects of beach structure available in remote sensing datasets?
2. Can the distribution of relative shoreline ecological function be reliably described using existing remote sensing data?
3. Which of these functions are most likely to be at risk under the combination of shoreline development, sediment input degradation, and sea level rise?
4. How are shoreline ecological functions distributed in the landscape (such as ESA critical habitats) relative to these sources of risk
5. Where are shoreline ecological functions most vulnerable to loss based on their location?
6. What are the legal attributes of scientific evidence that should be considered when organizing that evidence to develop quantification methods under the Endangered Species Act, Hydraulic Project Approval, or the Shoreline Management Act?
7. How can local models of ecosystem services, such as HEA, be used to quantify gain or loss of ecosystem functions at the scale of a municipal or county jurisdiction?
8. Is sea level rise a cumulative effect (a reasonably foreseeable future impact) or is it part of the existing "regulatory baseline", and what are the implications for the quantification of shoreline ecological functions for the purpose of regulatory decision support?
9. What is the current distribution, and the potential utility of blue-green lidar topography for the purpose of describing nearshore ecosystem functions, and the ability to extrapolate quantification of shoreline ecological functions from local sites to landscapes?

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Appendix A: Additional Data Tables

Table A1 – Comparison to tidal datum model outputs to harmonic station observations. Following TCARI and VDATUM conversions, we compared those model outputs to the observed tidal datums from 32 Puget Sound harmonic tidal stations. All elevation values are in feet (NAVD88). Two stations (9446804 and 9449988) were anomalous in the difference between predicted and observed tidal elevations. Excluding these two stations, reduced the mean difference from 0.068 to 0.031 feet.

		Observed Elevation (feet NAVD 88)		Modelled Elevation		Difference	
Station	**Station ID**	**MHHW**	**HAT**	**MHHW**	**HAT**	**MHHW**	**HAT**
Neah Bay	9443090	7.212	9.842	7.102	9.730	0.109	0.111
Sekiu, Clallam Bay	9443361	6.923	9.473	6.923	9.476	0.000	-0.003
Port Angeles	9444090	6.643	8.643	6.644	8.642	-0.002	0.000
Port Townsend	9444900	7.406	8.876	7.434	8.904	-0.028	-0.028
Foulweather Bluff	9445016	8.163	9.993	8.323	10.154	-0.161	-0.161
Bangor (Hood Canal)	9445133	8.682	10.472	8.682	10.480	0.000	-0.007
Union (Hood canal)	9445478	9.012	11.452	9.016	11.450	-0.003	0.002
Wauna	9446291	9.923	12.483	9.527	12.086	0.396	0.397
Tacoma	9446484	9.294	11.294	9.341	11.343	-0.048	-0.049
Yoman Point, Anderson Island	9446705	9.697	11.527	9.699	11.529	-0.001	-0.002
Sandy Point, Anderson Island	**9446804**	7.788	10.078	9.734	12.024	-1.946	-1.946
Budd Inlet	9446807	10.453	12.483	10.434	12.462	0.018	0.021
Seattle	9447130	9.018	10.918	9.017	10.917	0.001	0.001
Everett	9447659	9.056	11.186	9.056	11.188	0.001	-0.002
Priest Point	9447717	9.105	11.165	9.063	11.123	0.042	0.041
Tulalip Bay	9447773	9.122	11.452	9.161	11.484	-0.039	-0.032
Green Bank	9447883	9.062	11.512	9.011	11.121	0.051	0.391
Spee-Bi-Dah	9448009	9.167	11.377	9.122	11.323	0.045	0.054
Tulare Beach	9448043	8.990	11.200	9.109	11.317	-0.119	-0.117
Sneeoosh Point	9448576	9.046	10.956	9.034	10.944	0.012	0.013
Bowman Bay, Fidalgo Island	9448614	7.484	8.934	7.499	8.949	-0.015	-0.015
Turner Bay	9448657	8.815	10.765	8.816	10.765	-0.002	0.000
Swinomish	9448682	8.179	10.109	7.870	9.799	0.310	0.311
Village Point Lummi Island	9449161	8.013	10.303	8.006	10.303	0.007	0.000
Cherry Point	9449424	8.190	10.000	8.186	9.997	0.004	0.003
Point Roberts	9449639	8.506	10.606	8.135	10.238	0.371	0.368
Waldron Island	9449746	7.756	9.646	7.445	9.331	0.311	0.315
Hanbury Point (San Juan Island)	9449828	7.246	8.706	7.256	8.710	-0.011	-0.004
Kanaka Bay, San Juan Island	9449856	7.183	8.813	6.836	8.470	0.347	0.343
Friday Harbor	9449880	6.741	9.351	7.377	9.339	-0.637	0.011
Upright Head	9449911	7.303	9.213	7.277	9.187	0.026	0.026
Armitage Island	9449932	7.462	9.042	7.466	9.048	-0.004	-0.006
Richardson	9449982	7.061	8.571	7.059	8.572	0.001	-0.001
Telegraph Bay	**9449988**	5.862	7.292	7.201	8.628	-1.338	-1.335
Mean Difference (not including Sandy Point and Telegraph Bay stations)						**0.031**	**0.062**

Table A2 - Complete Bonferroni Test results among combinations of shoretype and sub-basin. Significantly different (p <0.05) comparisons are indicated with bold text.

Shoretype x Sub-basin	Shoretype x Sub-basin	Difference	p-Value	95% Confidence Interval	
				Lower	Upper
AS*Hood Canal	AS*North Puget Sound	-0.312	**0.001**	-0.556	-0.069
AS*Hood Canal	AS*South Central Puget Soun	-0.029	1.000	-0.286	0.227
AS*Hood Canal	AS*Strait of Juan de Fuca	-0.018	1.000	-0.282	0.245
AS*Hood Canal	AS*Whidbey	-0.026	1.000	-0.277	0.224
AS*Hood Canal	**FB*Hood Canal**	**-0.359**	**0.000**	**-0.596**	**-0.122**
AS*Hood Canal	FB*North Puget Sound	-0.215	0.208	-0.457	0.026
AS*Hood Canal	**FB*South Central Puget Soun**	**-0.435**	**0.000**	**-0.678**	**-0.191**
AS*Hood Canal	FB*Strait of Juan de Fuca	-0.215	0.292	-0.463	0.033
AS*Hood Canal	**FB*Whidbey**	**-0.281**	**0.003**	**-0.518**	**-0.043**
AS*Hood Canal	FBE*Hood Canal	-0.148	1.000	-0.385	0.089
AS*Hood Canal	**FBE*North Puget Sound**	**-0.298**	**0.001**	**-0.535**	**-0.061**
AS*Hood Canal	**FBE*South Central Puget Soun**	**-0.302**	**0.001**	**-0.541**	**-0.063**
AS*Hood Canal	FBE*Strait of Juan de Fuca	0.031	1.000	-0.251	0.312
AS*Hood Canal	**FBE*Whidbey**	**-0.279**	**0.004**	**-0.518**	**-0.040**
AS*Hood Canal	**TZ*Hood Canal**	**-0.378**	**0.000**	**-0.629**	**-0.127**
AS*Hood Canal	**TZ*North Puget Sound**	**-0.667**	**0.000**	**-0.909**	**-0.426**
AS*Hood Canal	**TZ*South Central Puget Soun**	**-0.392**	**0.000**	**-0.641**	**-0.144**
AS*Hood Canal	TZ*Strait of Juan de Fuca	-0.221	1.000	-0.564	0.121
AS*Hood Canal	**TZ*Whidbey**	**-0.339**	**0.000**	**-0.578**	**-0.099**
AS*North Puget Sound	**AS*South Central Puget Soun**	**0.283**	**0.009**	**0.029**	**0.537**
AS*North Puget Sound	**AS*Strait of Juan de Fuca**	**0.294**	**0.008**	**0.033**	**0.555**
AS*North Puget Sound	**AS*Whidbey**	**0.286**	**0.005**	**0.038**	**0.534**
AS*North Puget Sound	FB*Hood Canal	-0.047	1.000	-0.281	0.188
AS*North Puget Sound	FB*North Puget Sound	0.097	1.000	-0.142	0.336
AS*North Puget Sound	FB*South Central Puget Soun	-0.122	1.000	-0.363	0.119
AS*North Puget Sound	FB*Strait of Juan de Fuca	0.097	1.000	-0.148	0.343
AS*North Puget Sound	FB*Whidbey	0.032	1.000	-0.203	0.267
AS*North Puget Sound	FBE*Hood Canal	0.164	1.000	-0.071	0.399
AS*North Puget Sound	FBE*North Puget Sound	0.014	1.000	-0.221	0.249
AS*North Puget Sound	FBE*South Central Puget Soun	0.011	1.000	-0.226	0.247
AS*North Puget Sound	**FBE*Strait of Juan de Fuca**	**0.343**	**0.002**	**0.064**	**0.622**
AS*North Puget Sound	FBE*Whidbey	0.033	1.000	-0.204	0.270
AS*North Puget Sound	TZ*Hood Canal	-0.066	1.000	-0.314	0.183
AS*North Puget Sound	**TZ*North Puget Sound**	**-0.355**	**0.000**	**-0.594**	**-0.116**
AS*North Puget Sound	TZ*South Central Puget Soun	-0.080	1.000	-0.326	0.166
AS*North Puget Sound	TZ*Strait of Juan de Fuca	0.091	1.000	-0.250	0.432
AS*North Puget Sound	TZ*Whidbey	-0.026	1.000	-0.263	0.211
AS*South Central Puget Soun	AS*Strait of Juan de Fuca	0.011	1.000	-0.263	0.285
AS*South Central Puget Soun	AS*Whidbey	0.003	1.000	-0.258	0.264
AS*South Central Puget Soun	**FB*Hood Canal**	**-0.330**	**0.000**	**-0.578**	**-0.081**
AS*South Central Puget Soun	FB*North Puget Sound	-0.186	1.000	-0.438	0.066
AS*South Central Puget Soun	**FB*South Central Puget Soun**	**-0.405**	**0.000**	**-0.660**	**-0.151**
AS*South Central Puget Soun	FB*Strait of Juan de Fuca	-0.186	1.000	-0.445	0.073
AS*South Central Puget Soun	**FB*Whidbey**	**-0.251**	**0.043**	**-0.500**	**-0.003**
AS*South Central Puget Soun	FBE*Hood Canal	-0.119	1.000	-0.367	0.130
AS*South Central Puget Soun	**FBE*North Puget Sound**	**-0.269**	**0.015**	**-0.517**	**-0.020**
AS*South Central Puget Soun	**FBE*South Central Puget Soun**	**-0.273**	**0.014**	**-0.523**	**-0.022**
AS*South Central Puget Soun	FBE*Strait of Juan de Fuca	0.060	1.000	-0.231	0.351
AS*South Central Puget Soun	**FBE*Whidbey**	**-0.250**	**0.052**	**-0.500**	**0.001**
AS*South Central Puget Soun	**TZ*Hood Canal**	**-0.349**	**0.000**	**-0.610**	**-0.087**
AS*South Central Puget Soun	**TZ*North Puget Sound**	**-0.638**	**0.000**	**-0.890**	**-0.386**

Shoretype x Sub-basin	Shoretype x Sub-basin	Difference	p-Value	95% Confidence Interval	
				Lower	Upper
AS*South Central Puget Soun	**TZ*South Central Puget Soun**	**-0.363**	**0.000**	**-0.622**	**-0.104**
AS*South Central Puget Soun	TZ*Strait of Juan de Fuca	-0.192	1.000	-0.542	0.158
AS*South Central Puget Soun	**TZ*Whidbey**	**-0.309**	**0.001**	**-0.560**	**-0.059**
AS*Strait of Juan de Fuca	AS*Whidbey	-0.008	1.000	-0.276	0.260
AS*Strait of Juan de Fuca	**FB*Hood Canal**	**-0.341**	**0.000**	**-0.596**	**-0.085**
AS*Strait of Juan de Fuca	FB*North Puget Sound	-0.197	1.000	-0.456	0.062
AS*Strait of Juan de Fuca	**FB*South Central Puget Soun**	**-0.417**	**0.000**	**-0.678**	**-0.155**
AS*Strait of Juan de Fuca	FB*Strait of Juan de Fuca	-0.197	1.000	-0.462	0.069
AS*Strait of Juan de Fuca	**FB*Whidbey**	**-0.262**	**0.035**	**-0.518**	**-0.007**
AS*Strait of Juan de Fuca	FBE*Hood Canal	-0.130	1.000	-0.386	0.126
AS*Strait of Juan de Fuca	**FBE*North Puget Sound**	**-0.280**	**0.013**	**-0.535**	**-0.024**
AS*Strait of Juan de Fuca	**FBE*South Central Puget Soun**	**-0.284**	**0.011**	**-0.541**	**-0.026**
AS*Strait of Juan de Fuca	FBE*Strait of Juan de Fuca	0.049	1.000	-0.248	0.346
AS*Strait of Juan de Fuca	**FBE*Whidbey**	**-0.261**	**0.041**	**-0.518**	**-0.003**
AS*Strait of Juan de Fuca	**TZ*Hood Canal**	**-0.360**	**0.000**	**-0.628**	**-0.092**
AS*Strait of Juan de Fuca	**TZ*North Puget Sound**	**-0.649**	**0.000**	**-0.908**	**-0.390**
AS*Strait of Juan de Fuca	**TZ*South Central Puget Soun**	**-0.374**	**0.000**	**-0.640**	**-0.109**
AS*Strait of Juan de Fuca	TZ*Strait of Juan de Fuca	-0.203	1.000	-0.559	0.152
AS*Strait of Juan de Fuca	**TZ*Whidbey**	**-0.320**	**0.001**	**-0.578**	**-0.063**
AS*Whidbey	**FB*Hood Canal**	**-0.333**	**0.000**	**-0.575**	**-0.090**
AS*Whidbey	FB*North Puget Sound	-0.189	0.942	-0.435	0.057
AS*Whidbey	**FB*South Central Puget Soun**	**-0.408**	**0.000**	**-0.657**	**-0.160**
AS*Whidbey	FB*Strait of Juan de Fuca	-0.189	1.000	-0.442	0.064
AS*Whidbey	FB*Whidbey	-0.254	0.025	-0.497	-0.012
AS*Whidbey	FBE*Hood Canal	-0.122	1.000	-0.364	0.121
AS*Whidbey	**FBE*North Puget Sound**	**-0.272**	**0.008**	**-0.514**	**-0.029**
AS*Whidbey	**FBE*South Central Puget Soun**	**-0.275**	**0.008**	**-0.520**	**-0.031**
AS*Whidbey	FBE*Strait of Juan de Fuca	0.057	1.000	-0.229	0.343
AS*Whidbey	**FBE*Whidbey**	**-0.253**	**0.031**	**-0.497**	**-0.008**
AS*Whidbey	**TZ*Hood Canal**	**-0.352**	**0.000**	**-0.607**	**-0.096**
AS*Whidbey	**TZ*North Puget Sound**	**-0.641**	**0.000**	**-0.887**	**-0.395**
AS*Whidbey	**TZ*South Central Puget Soun**	**-0.366**	**0.000**	**-0.619**	**-0.113**
AS*Whidbey	TZ*Strait of Juan de Fuca	-0.195	1.000	-0.541	0.151
AS*Whidbey	**TZ*Whidbey**	**-0.312**	**0.001**	**-0.557**	**-0.068**
FB*Hood Canal	FB*North Puget Sound	0.144	1.000	-0.089	0.376
FB*Hood Canal	FB*South Central Puget Soun	-0.076	1.000	-0.311	0.159
FB*Hood Canal	FB*Strait of Juan de Fuca	0.144	1.000	-0.096	0.384
FB*Hood Canal	FB*Whidbey	0.078	1.000	-0.150	0.307
FB*Hood Canal	FBE*Hood Canal	0.211	0.144	-0.018	0.439
FB*Hood Canal	FBE*North Puget Sound	0.061	1.000	-0.168	0.290
FB*Hood Canal	FBE*South Central Puget Soun	0.057	1.000	-0.173	0.288
FB*Hood Canal	**FBE*Strait of Juan de Fuca**	**0.390**	**0.000**	**0.116**	**0.664**
FB*Hood Canal	FBE*Whidbey	0.080	1.000	-0.151	0.310
FB*Hood Canal	TZ*Hood Canal	-0.019	1.000	-0.262	0.223
FB*Hood Canal	**TZ*North Puget Sound**	**-0.308**	**0.000**	**-0.541**	**-0.076**
FB*Hood Canal	TZ*South Central Puget Soun	-0.034	1.000	-0.273	0.206
FB*Hood Canal	TZ*Strait of Juan de Fuca	0.138	1.000	-0.199	0.474
FB*Hood Canal	TZ*Whidbey	0.020	1.000	-0.210	0.251
FB*North Puget Sound	FB*South Central Puget Soun	-0.219	0.151	-0.458	0.020
FB*North Puget Sound	FB*Strait of Juan de Fuca	0.001	1.000	-0.243	0.244
FB*North Puget Sound	FB*Whidbey	-0.065	1.000	-0.298	0.168
FB*North Puget Sound	FBE*Hood Canal	0.067	1.000	-0.165	0.300
FB*North Puget Sound	FBE*North Puget Sound	-0.083	1.000	-0.315	0.150
FB*North Puget Sound	FBE*South Central Puget Soun	-0.086	1.000	-0.321	0.148
FB*North Puget Sound	FBE*Strait of Juan de Fuca	0.246	0.226	-0.031	0.524

Shoretype x Sub-basin	Shoretype x Sub-basin	Difference	p-Value	95% Confidence Interval	
				Lower	Upper
FB*North Puget Sound	FBE*Whidbey	-0.064	1.000	-0.298	0.171
FB*North Puget Sound	TZ*Hood Canal	-0.163	1.000	-0.409	0.084
FB*North Puget Sound	**TZ*North Puget Sound**	**-0.452**	**0.000**	**-0.689**	**-0.215**
FB*North Puget Sound	TZ*South Central Puget Soun	-0.177	1.000	-0.421	0.067
FB*North Puget Sound	TZ*Strait of Juan de Fuca	-0.006	1.000	-0.345	0.333
FB*North Puget Sound	TZ*Whidbey	-0.123	1.000	-0.358	0.111
FB*South Central Puget Soun	FB*Strait of Juan de Fuca	0.220	0.205	-0.026	0.466
FB*South Central Puget Soun	FB*Whidbey	0.154	1.000	-0.081	0.389
FB*South Central Puget Soun	**FBE*Hood Canal**	**0.287**	**0.002**	**0.052**	**0.522**
FB*South Central Puget Soun	FBE*North Puget Sound	0.137	1.000	-0.098	0.372
FB*South Central Puget Soun	FBE*South Central Puget Soun	0.133	1.000	-0.104	0.370
FB*South Central Puget Soun	**FBE*Strait of Juan de Fuca**	**0.465**	**0.000**	**0.186**	**0.745**
FB*South Central Puget Soun	FBE*Whidbey	0.156	1.000	-0.081	0.392
FB*South Central Puget Soun	TZ*Hood Canal	0.057	1.000	-0.192	0.305
FB*South Central Puget Soun	TZ*North Puget Sound	-0.233	0.072	-0.471	0.006
FB*South Central Puget Soun	TZ*South Central Puget Soun	0.042	1.000	-0.203	0.288
FB*South Central Puget Soun	TZ*Strait of Juan de Fuca	0.213	1.000	-0.127	0.554
FB*South Central Puget Soun	TZ*Whidbey	0.096	1.000	-0.141	0.333
FB*Strait of Juan de Fuca	FB*Whidbey	-0.066	1.000	-0.305	0.174
FB*Strait of Juan de Fuca	FBE*Hood Canal	0.067	1.000	-0.173	0.307
FB*Strait of Juan de Fuca	FBE*North Puget Sound	-0.083	1.000	-0.323	0.157
FB*Strait of Juan de Fuca	FBE*South Central Puget Soun	-0.087	1.000	-0.329	0.155
FB*Strait of Juan de Fuca	FBE*Strait of Juan de Fuca	0.246	0.292	-0.038	0.529
FB*Strait of Juan de Fuca	FBE*Whidbey	-0.064	1.000	-0.306	0.178
FB*Strait of Juan de Fuca	TZ*Hood Canal	-0.163	1.000	-0.416	0.090
FB*Strait of Juan de Fuca	**TZ*North Puget Sound**	**-0.452**	**0.000**	**-0.696**	**-0.209**
FB*Strait of Juan de Fuca	TZ*South Central Puget Soun	-0.178	1.000	-0.428	0.073
FB*Strait of Juan de Fuca	TZ*Strait of Juan de Fuca	-0.006	1.000	-0.351	0.338
FB*Strait of Juan de Fuca	TZ*Whidbey	-0.124	1.000	-0.365	0.118
FB*Whidbey	FBE*Hood Canal	0.132	1.000	-0.096	0.361
FB*Whidbey	FBE*North Puget Sound	-0.018	1.000	-0.246	0.211
FB*Whidbey	FBE*South Central Puget Soun	-0.021	1.000	-0.252	0.209
FB*Whidbey	**FBE*Strait of Juan de Fuca**	**0.311**	**0.007**	**0.037**	**0.585**
FB*Whidbey	FBE*Whidbey	0.001	1.000	-0.229	0.232
FB*Whidbey	TZ*Hood Canal	-0.098	1.000	-0.340	0.145
FB*Whidbey	**TZ*North Puget Sound**	**-0.387**	**0.000**	**-0.620**	**-0.154**
FB*Whidbey	TZ*South Central Puget Soun	-0.112	1.000	-0.352	0.128
FB*Whidbey	TZ*Strait of Juan de Fuca	0.059	1.000	-0.277	0.396
FB*Whidbey	TZ*Whidbey	-0.058	1.000	-0.289	0.173
FBE*Hood Canal	FBE*North Puget Sound	-0.150	1.000	-0.379	0.079
FBE*Hood Canal	FBE*South Central Puget Soun	-0.154	1.000	-0.384	0.077
FBE*Hood Canal	FBE*Strait of Juan de Fuca	0.179	1.000	-0.095	0.453
FBE*Hood Canal	FBE*Whidbey	-0.131	1.000	-0.362	0.100
FBE*Hood Canal	TZ*Hood Canal	-0.230	0.102	-0.472	0.013
FBE*Hood Canal	**TZ*North Puget Sound**	**-0.519**	**0.000**	**-0.752**	**-0.287**
FBE*Hood Canal	**TZ*South Central Puget Soun**	**-0.244**	**0.038**	**-0.484**	**-0.005**
FBE*Hood Canal	TZ*Strait of Juan de Fuca	-0.073	1.000	-0.410	0.263
FBE*Hood Canal	TZ*Whidbey	-0.190	0.481	-0.421	0.040
FBE*North Puget Sound	FBE*South Central Puget Soun	-0.004	1.000	-0.234	0.227
FBE*North Puget Sound	**FBE*Strait of Juan de Fuca**	**0.329**	**0.002**	**0.055**	**0.603**
FBE*North Puget Sound	FBE*Whidbey	0.019	1.000	-0.212	0.250
FBE*North Puget Sound	TZ*Hood Canal	-0.080	1.000	-0.322	0.163
FBE*North Puget Sound	**TZ*North Puget Sound**	**-0.369**	**0.000**	**-0.602**	**-0.137**
FBE*North Puget Sound	TZ*South Central Puget Soun	-0.094	1.000	-0.334	0.145
FBE*North Puget Sound	TZ*Strait of Juan de Fuca	0.077	1.000	-0.260	0.413

Shoretype x Sub-basin	Shoretype x Sub-basin	Difference	p-Value	95% Confidence Interval	
				Lower	Upper
FBE*North Puget Sound	TZ*Whidbey	-0.041	1.000	-0.271	0.190
FBE*South Central Puget Soun	**FBE*Strait of Juan de Fuca**	**0.333**	**0.002**	**0.057**	**0.608**
FBE*South Central Puget Soun	FBE*Whidbey	0.023	1.000	-0.210	0.255
FBE*South Central Puget Soun	TZ*Hood Canal	-0.076	1.000	-0.321	0.168
FBE*South Central Puget Soun	**TZ*North Puget Sound**	**-0.366**	**0.000**	**-0.600**	**-0.131**
FBE*South Central Puget Soun	TZ*South Central Puget Soun	-0.091	1.000	-0.332	0.151
FBE*South Central Puget Soun	TZ*Strait of Juan de Fuca	0.080	1.000	-0.257	0.418
FBE*South Central Puget Soun	TZ*Whidbey	-0.037	1.000	-0.269	0.196
FBE*Strait of Juan de Fuca	**FBE*Whidbey**	**-0.310**	**0.008**	**-0.586**	**-0.034**
FBE*Strait of Juan de Fuca	**TZ*Hood Canal**	**-0.409**	**0.000**	**-0.695**	**-0.123**
FBE*Strait of Juan de Fuca	**TZ*North Puget Sound**	**-0.698**	**0.000**	**-0.976**	**-0.421**
FBE*Strait of Juan de Fuca	**TZ*South Central Puget Soun**	**-0.423**	**0.000**	**-0.707**	**-0.140**
FBE*Strait of Juan de Fuca	TZ*Strait of Juan de Fuca	-0.252	1.000	-0.621	0.117
FBE*Strait of Juan de Fuca	**TZ*Whidbey**	**-0.369**	**0.000**	**-0.645**	**-0.094**
FBE*Whidbey	TZ*Hood Canal	-0.099	1.000	-0.343	0.145
FBE*Whidbey	**TZ*North Puget Sound**	**-0.388**	**0.000**	**-0.623**	**-0.154**
FBE*Whidbey	TZ*South Central Puget Soun	-0.113	1.000	-0.355	0.128
FBE*Whidbey	TZ*Strait of Juan de Fuca	0.058	1.000	-0.280	0.396
FBE*Whidbey	TZ*Whidbey	-0.059	1.000	-0.292	0.173
TZ*Hood Canal	**TZ*North Puget Sound**	**-0.289**	**0.004**	**-0.536**	**-0.043**
TZ*Hood Canal	TZ*South Central Puget Soun	-0.014	1.000	-0.268	0.239
TZ*Hood Canal	TZ*Strait of Juan de Fuca	0.157	1.000	-0.189	0.503
TZ*Hood Canal	TZ*Whidbey	0.039	1.000	-0.205	0.284
TZ*North Puget Sound	**TZ*South Central Puget Soun**	**0.275**	**0.008**	**0.031**	**0.519**
TZ*North Puget Sound	**TZ*Strait of Juan de Fuca**	**0.446**	**0.000**	**0.107**	**0.785**
TZ*North Puget Sound	**TZ*Whidbey**	**0.329**	**0.000**	**0.094**	**0.563**
TZ*South Central Puget Soun	TZ*Strait of Juan de Fuca	0.171	1.000	-0.173	0.515
TZ*South Central Puget Soun	TZ*Whidbey	0.054	1.000	-0.188	0.296
TZ*Strait of Juan de Fuca	TZ*Whidbey	-0.117	1.000	-0.455	0.221

Table A3 – Summary of beach sites, including sub-basin, shoretype, sub-sample count, and mean slope.

Site	Sub-basin	Code	Shoretype	Sample Count	Mean Slope
1	Strait of Juan de Fuca	AS	Accretion	10	0.1182041423
2	Whidbey	AS	Accretion	8	0.1249962114
3	Hood Canal	AS	Accretion	8	0.2339278265
5	Hood Canal	AS	Accretion	10	0.1753994054
6	Hood Canal	AS	Accretion	10	0.1941975043
7	Hood Canal	AS	Accretion	9	0.2175615663
9	Hood Canal	AS	Accretion	8	0.1508948985
10	Hood Canal	AS	Accretion	7	0.1054292099
11	Hood Canal	AS	Accretion	8	0.08465736977
12	Hood Canal	AS	Accretion	10	0.1925575799
13	Hood Canal	AS	Accretion	8	0.1209007777
14	Hood Canal	AS	Accretion	11	0.1578143111
17	Hood Canal	AS	Accretion	7	0.1664720978
18	Hood Canal	AS	Accretion	9	0.13292046

19	Hood Canal	AS	Accretion	7	0.1677126899
20	Hood Canal	AS	Accretion	11	0.1879505993
21	Hood Canal	AS	Accretion	10	0.1260380352
22	Hood Canal	AS	Accretion	11	0.06431614139
23	Hood Canal	AS	Accretion	9	0.07117615992
24	Hood Canal	AS	Accretion	10	0.1080399626
25	Hood Canal	AS	Accretion	7	0.164412523
26	Hood Canal	AS	Accretion	10	0.1251798531
27	Hood Canal	AS	Accretion	10	0.1549205565
28	Hood Canal	AS	Accretion	9	0.09418556053
29	Hood Canal	AS	Accretion	10	0.1570615537
30	Hood Canal	AS	Accretion	10	0.0515582923
31	Hood Canal	AS	Accretion	10	0.1142924523
32	Hood Canal	AS	Accretion	9	0.08458237418
35	North Puget Sound	AS	Accretion	10	0.8201885511
36	North Puget Sound	AS	Accretion	10	0.3560993347
37	North Puget Sound	AS	Accretion	10	0.5203794018
38	North Puget Sound	AS	Accretion	10	1.249552991
39	North Puget Sound	AS	Accretion	7	0.2439816173
40	North Puget Sound	AS	Accretion	6	0.4860460686
41	North Puget Sound	AS	Accretion	10	0.1713470108
42	North Puget Sound	AS	Accretion	8	0.1912660489
43	North Puget Sound	AS	Accretion	9	0.2766258963
44	North Puget Sound	AS	Accretion	10	0.1822224372
45	North Puget Sound	AS	Accretion	9	0.1694286901
46	North Puget Sound	AS	Accretion	7	0.1454846515
48	North Puget Sound	AS	Accretion	9	0.06036958722
49	North Puget Sound	AS	Accretion	8	0.3609202688
50	North Puget Sound	AS	Accretion	7	0.7493387216
51	North Puget Sound	AS	Accretion	9	0.9432196695
52	North Puget Sound	AS	Accretion	10	0.1749962672
53	North Puget Sound	AS	Accretion	10	1.049165526
55	North Puget Sound	AS	Accretion	10	0.1668222642
56	North Puget Sound	AS	Accretion	7	0.809799473
57	North Puget Sound	AS	Accretion	10	0.136217
58	North Puget Sound	AS	Accretion	10	0.1265338419
59	North Puget Sound	AS	Accretion	9	0.1220410653
60	North Puget Sound	AS	Accretion	10	0.1034645734
61	North Puget Sound	AS	Accretion	10	0.125419986

62	North Puget Sound	AS	Accretion	10	0.2205451186
64	South Central Puget Sound	AS	Accretion	11	0.2544113265
65	South Central Puget Sound	AS	Accretion	7	0.1033254096
66	South Central Puget Sound	AS	Accretion	11	0.3721672928
68	South Central Puget Sound	AS	Accretion	6	0.07034445159
72	South Central Puget Sound	AS	Accretion	12	0.09430537645
73	South Central Puget Sound	AS	Accretion	10	0.2677771589
74	South Central Puget Sound	AS	Accretion	7	0.1310152675
76	South Central Puget Sound	AS	Accretion	8	0.1672691643
77	South Central Puget Sound	AS	Accretion	11	0.1233977601
78	South Central Puget Sound	AS	Accretion	7	0.147147924
79	South Central Puget Sound	AS	Accretion	6	0.07512692796
80	South Central Puget Sound	AS	Accretion	9	0.07740624285
81	South Central Puget Sound	AS	Accretion	7	0.1222058306
82	South Central Puget Sound	AS	Accretion	7	0.1320819346
83	South Central Puget Sound	AS	Accretion	9	0.1687918086
84	South Central Puget Sound	AS	Accretion	10	0.1872752227
85	South Central Puget Sound	AS	Accretion	7	0.137602067
86	South Central Puget Sound	AS	Accretion	9	0.1636559819
87	South Central Puget Sound	AS	Accretion	10	0.1414958422
88	South Central Puget Sound	AS	Accretion	7	0.1350510372
89	South Central Puget Sound	AS	Accretion	10	0.1239070891
91	South Central Puget Sound	AS	Accretion	10	0.1246059337
93	Strait of Juan de Fuca	AS	Accretion	11	0.2095650237
95	Strait of Juan de Fuca	AS	Accretion	5	0.1169681891
96	Strait of Juan de Fuca	AS	Accretion	10	0.1648351259
97	Strait of Juan de Fuca	AS	Accretion	10	0.1934400011
98	Strait of Juan de Fuca	AS	Accretion	10	0.2116238983
99	Strait of Juan de Fuca	AS	Accretion	10	0.1076354108
100	Strait of Juan de Fuca	AS	Accretion	11	0.08988835963
101	Strait of Juan de Fuca	AS	Accretion	10	0.1034560348
102	Strait of Juan de Fuca	AS	Accretion	10	0.1082272961
103	Strait of Juan de Fuca	AS	Accretion	10	0.1791903682
104	Strait of Juan de Fuca	AS	Accretion	10	0.1634363108
106	Strait of Juan de Fuca	AS	Accretion	10	0.3986332857
109	Strait of Juan de Fuca	AS	Accretion	9	0.09691320334
112	Strait of Juan de Fuca	AS	Accretion	10	0.1402555325
113	Strait of Juan de Fuca	AS	Accretion	9	0.07984234661
114	Strait of Juan de Fuca	AS	Accretion	8	0.07606003286

115	Strait of Juan de Fuca	AS	Accretion	10	0.1332827455
116	Strait of Juan de Fuca	AS	Accretion	10	0.1128506134
119	North Puget Sound	AS	Accretion	3	0.1469480355
123	Whidbey	AS	Accretion	10	0.04092332787
125	Whidbey	AS	Accretion	10	0.0511068788
127	Whidbey	AS	Accretion	10	0.1422356617
128	Whidbey	AS	Accretion	8	0.1442820382
129	Whidbey	AS	Accretion	5	0.1408803014
131	Whidbey	AS	Accretion	8	0.1494897499
132	Whidbey	AS	Accretion	11	0.1147397939
133	Whidbey	AS	Accretion	8	0.1586080708
134	Whidbey	AS	Accretion	8	0.3622409721
135	Whidbey	AS	Accretion	6	0.1443082157
136	Whidbey	AS	Accretion	9	0.2066149245
137	Whidbey	AS	Accretion	9	0.1309877842
138	Whidbey	AS	Accretion	8	0.1449697654
139	Whidbey	AS	Accretion	11	0.1656394919
141	Whidbey	AS	Accretion	6	0.1754994256
142	Whidbey	AS	Accretion	8	0.1729795281
143	Whidbey	AS	Accretion	9	0.1303191268
145	Whidbey	AS	Accretion	10	0.3195882173
147	Whidbey	AS	Accretion	10	0.1205868951
148	Whidbey	AS	Accretion	10	0.106274577
149	Whidbey	AS	Accretion	10	0.1620033669
151	Whidbey	AS	Accretion	7	0.1045741787
152	Whidbey	AS	Accretion	10	0.1163989561
153	Hood Canal	FB	Feeder Bluff	10	0.2330400301
154	Hood Canal	FB	Feeder Bluff	9	0.2284690086
155	Hood Canal	FB	Feeder Bluff	10	0.2138986061
156	Hood Canal	FB	Feeder Bluff	10	0.3509775751
157	Hood Canal	FB	Feeder Bluff	10	0.387226223
158	Hood Canal	FB	Feeder Bluff	10	0.2500609837
159	Hood Canal	FB	Feeder Bluff	10	0.2765206619
160	Hood Canal	FB	Feeder Bluff	10	0.2890195574
161	Hood Canal	FB	Feeder Bluff	6	0.328400757
162	Hood Canal	FB	Feeder Bluff	10	0.5163091815
163	Hood Canal	FB	Feeder Bluff	9	0.1988050217
164	Hood Canal	FB	Feeder Bluff	10	0.2126639393
165	Hood Canal	FB	Feeder Bluff	10	0.2171231818

166	Hood Canal	FB	Feeder Bluff	10	0.7232788812
167	Hood Canal	FB	Feeder Bluff	10	0.2711300976
168	Hood Canal	FB	Feeder Bluff	8	0.4585341087
169	Hood Canal	FB	Feeder Bluff	10	0.3390644822
170	Hood Canal	FB	Feeder Bluff	10	0.1982600069
171	Hood Canal	FB	Feeder Bluff	10	0.3765861697
172	Hood Canal	FB	Feeder Bluff	10	0.6140045657
173	Hood Canal	FB	Feeder Bluff	9	0.2284415749
174	Hood Canal	FB	Feeder Bluff	6	0.3342404182
175	Hood Canal	FB	Feeder Bluff	8	0.402719069
176	Hood Canal	FB	Feeder Bluff	7	0.2329576006
177	Hood Canal	FB	Feeder Bluff	10	0.4825211775
178	Hood Canal	FB	Feeder Bluff	7	0.4999002841
179	Hood Canal	FB	Feeder Bluff	10	0.2829976796
180	Hood Canal	FB	Feeder Bluff	10	0.2752079108
181	Hood Canal	FB	Feeder Bluff	9	0.192837583
182	Hood Canal	FB	Feeder Bluff	10	0.08372560938
183	North Puget Sound	FB	Feeder Bluff	5	0.08975426746
184	North Puget Sound	FB	Feeder Bluff	12	0.1560064927
185	North Puget Sound	FB	Feeder Bluff	10	0.4453217075
186	North Puget Sound	FB	Feeder Bluff	10	1.369841019
187	North Puget Sound	FB	Feeder Bluff	10	0.9309234064
188	North Puget Sound	FB	Feeder Bluff	6	0.3275822638
189	North Puget Sound	FB	Feeder Bluff	10	0.3945723749
190	North Puget Sound	FB	Feeder Bluff	11	0.327939796
191	North Puget Sound	FB	Feeder Bluff	9	0.143880797
192	North Puget Sound	FB	Feeder Bluff	10	0.1216953497
193	North Puget Sound	FB	Feeder Bluff	10	0.1746729866
194	North Puget Sound	FB	Feeder Bluff	10	0.1559618622
195	North Puget Sound	FB	Feeder Bluff	6	0.5249611702
196	North Puget Sound	FB	Feeder Bluff	10	0.3889630615
197	North Puget Sound	FB	Feeder Bluff	11	0.3117089981
198	North Puget Sound	FB	Feeder Bluff	10	0.1878776134
200	North Puget Sound	FB	Feeder Bluff	10	0.1029285067
201	North Puget Sound	FB	Feeder Bluff	11	0.1881608962
202	North Puget Sound	FB	Feeder Bluff	8	0.1250000352
203	North Puget Sound	FB	Feeder Bluff	10	0.180287246
204	North Puget Sound	FB	Feeder Bluff	10	0.216973584
205	North Puget Sound	FB	Feeder Bluff	10	0.1214207002

206	North Puget Sound	FB	Feeder Bluff	9	0.1088308408
207	North Puget Sound	FB	Feeder Bluff	6	0.1017546781
208	North Puget Sound	FB	Feeder Bluff	10	0.1264041705
209	North Puget Sound	FB	Feeder Bluff	10	0.1468148972
210	North Puget Sound	FB	Feeder Bluff	10	0.1140892516
212	North Puget Sound	FB	Feeder Bluff	5	0.3075895053
213	South Central Puget Sound	FB	Feeder Bluff	10	0.4023251924
214	South Central Puget Sound	FB	Feeder Bluff	6	0.2205647682
215	South Central Puget Sound	FB	Feeder Bluff	10	0.333472099
216	South Central Puget Sound	FB	Feeder Bluff	10	0.6942165967
217	South Central Puget Sound	FB	Feeder Bluff	9	0.818790899
218	South Central Puget Sound	FB	Feeder Bluff	10	0.2447730446
219	South Central Puget Sound	FB	Feeder Bluff	8	0.1820075226
220	South Central Puget Sound	FB	Feeder Bluff	11	1.174974952
221	South Central Puget Sound	FB	Feeder Bluff	10	0.287100493
223	South Central Puget Sound	FB	Feeder Bluff	12	0.4011797077
224	South Central Puget Sound	FB	Feeder Bluff	8	0.4200361774
225	South Central Puget Sound	FB	Feeder Bluff	10	0.2558979395
226	South Central Puget Sound	FB	Feeder Bluff	9	0.3159479979
227	South Central Puget Sound	FB	Feeder Bluff	8	0.4880448838
228	South Central Puget Sound	FB	Feeder Bluff	10	0.8207702847
229	South Central Puget Sound	FB	Feeder Bluff	8	0.2676519835
230	South Central Puget Sound	FB	Feeder Bluff	10	0.2822308254
231	South Central Puget Sound	FB	Feeder Bluff	9	0.2920213175
232	South Central Puget Sound	FB	Feeder Bluff	10	0.1661307054
233	South Central Puget Sound	FB	Feeder Bluff	10	0.4269011772
234	South Central Puget Sound	FB	Feeder Bluff	8	0.2125607875
236	South Central Puget Sound	FB	Feeder Bluff	10	0.3691173794
237	South Central Puget Sound	FB	Feeder Bluff	10	0.2028101014
238	South Central Puget Sound	FB	Feeder Bluff	10	0.2371179259
239	South Central Puget Sound	FB	Feeder Bluff	7	0.2412680794
240	South Central Puget Sound	FB	Feeder Bluff	6	0.8540254939
242	South Central Puget Sound	FB	Feeder Bluff	11	0.3721438526
243	Strait of Juan de Fuca	FB	Feeder Bluff	8	0.2040354786
244	Strait of Juan de Fuca	FB	Feeder Bluff	7	0.4102030292
245	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.3115221089
246	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.1677568425
247	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.2191640601
248	Strait of Juan de Fuca	FB	Feeder Bluff	7	0.167457935

249	Strait of Juan de Fuca	FB	Feeder Bluff	8	0.5390341885
250	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.1773144335
251	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.1460574666
252	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.1681548037
253	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.1480245631
254	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.4184412345
255	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.1774740756
256	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.1765952124
257	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.1477419846
258	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.2941791129
259	Strait of Juan de Fuca	FB	Feeder Bluff	11	0.1651248951
260	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.123292335
261	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.318774052
262	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.2011853011
264	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.1459271064
265	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.1572131327
266	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.1736347644
267	Strait of Juan de Fuca	FB	Feeder Bluff	10	0.2044464786
269	Strait of Juan de Fuca	FB	Feeder Bluff	6	0.4728360692
273	Whidbey	FB	Feeder Bluff	10	0.1378288917
274	Whidbey	FB	Feeder Bluff	10	0.4490128777
275	Whidbey	FB	Feeder Bluff	10	0.2227965871
276	Whidbey	FB	Feeder Bluff	10	0.2065366159
277	Whidbey	FB	Feeder Bluff	10	0.3508109649
278	Whidbey	FB	Feeder Bluff	9	0.2710574391
279	Whidbey	FB	Feeder Bluff	6	0.1907098599
280	Whidbey	FB	Feeder Bluff	9	0.2678918867
281	Whidbey	FB	Feeder Bluff	7	0.3086644847
282	Whidbey	FB	Feeder Bluff	5	0.4224960664
283	Whidbey	FB	Feeder Bluff	10	0.2673513878
284	Whidbey	FB	Feeder Bluff	5	0.2526203889
285	Whidbey	FB	Feeder Bluff	11	0.205542906
286	Whidbey	FB	Feeder Bluff	10	0.1720783294
287	Whidbey	FB	Feeder Bluff	10	0.2405342398
288	Whidbey	FB	Feeder Bluff	10	0.2488405363
289	Whidbey	FB	Feeder Bluff	8	0.1933077107
290	Whidbey	FB	Feeder Bluff	10	0.1982124545
291	Whidbey	FB	Feeder Bluff	10	0.37893688
292	Whidbey	FB	Feeder Bluff	9	0.1668590897

293	Whidbey	FB	Feeder Bluff	7	0.2782263452
294	Whidbey	FB	Feeder Bluff	10	0.2458019462
295	Whidbey	FB	Feeder Bluff	10	0.4748212703
296	Whidbey	FB	Feeder Bluff	10	0.1784760506
297	Whidbey	FB	Feeder Bluff	7	0.3688766807
298	Whidbey	FB	Feeder Bluff	10	0.2151639277
299	Whidbey	FB	Feeder Bluff	9	0.2124459582
300	Whidbey	FB	Feeder Bluff	7	0.1550965774
301	Whidbey	FB	Feeder Bluff	9	0.2317288964
302	Whidbey	FB	Feeder Bluff	10	0.294751434
303	Hood Canal	FBE	FB Exceptional	7	0.3593804808
304	Hood Canal	FBE	FB Exceptional	10	0.2034947108
305	Hood Canal	FBE	FB Exceptional	10	0.175474884
306	Hood Canal	FBE	FB Exceptional	6	0.2200336799
307	Hood Canal	FBE	FB Exceptional	11	0.1771843986
308	Hood Canal	FBE	FB Exceptional	7	0.1674715009
309	Hood Canal	FBE	FB Exceptional	10	0.2324994866
310	Hood Canal	FBE	FB Exceptional	10	0.1797351739
311	Hood Canal	FBE	FB Exceptional	9	0.1628185158
312	Hood Canal	FBE	FB Exceptional	6	0.1354681331
313	Hood Canal	FBE	FB Exceptional	10	0.2502771404
314	Hood Canal	FBE	FB Exceptional	8	0.1107004009
315	Hood Canal	FBE	FB Exceptional	10	0.1414598565
316	Hood Canal	FBE	FB Exceptional	7	0.2209954962
317	Hood Canal	FBE	FB Exceptional	5	0.4176990984
318	Hood Canal	FBE	FB Exceptional	11	0.4709830014
319	Hood Canal	FBE	FB Exceptional	9	0.1559377938
320	Hood Canal	FBE	FB Exceptional	10	0.2021190095
321	Hood Canal	FBE	FB Exceptional	10	0.1650032734
322	Hood Canal	FBE	FB Exceptional	9	0.1603012226
323	Hood Canal	FBE	FB Exceptional	10	0.08995643964
324	Hood Canal	FBE	FB Exceptional	6	0.173328477
325	Hood Canal	FBE	FB Exceptional	10	0.2023534765
326	Hood Canal	FBE	FB Exceptional	9	0.1653384047
327	Hood Canal	FBE	FB Exceptional	10	0.1416369203
328	Hood Canal	FBE	FB Exceptional	8	0.1411870699
329	Hood Canal	FBE	FB Exceptional	6	0.1639453931
330	Hood Canal	FBE	FB Exceptional	10	0.1745339781
331	Hood Canal	FBE	FB Exceptional	10	0.1347353435

332	Hood Canal	FBE	FB Exceptional	9	0.1571153957
333	North Puget Sound	FBE	FB Exceptional	10	0.5613351685
334	North Puget Sound	FBE	FB Exceptional	10	0.7639028039
335	North Puget Sound	FBE	FB Exceptional	10	0.9184375595
336	North Puget Sound	FBE	FB Exceptional	10	0.8066840677
337	North Puget Sound	FBE	FB Exceptional	11	1.013462779
338	North Puget Sound	FBE	FB Exceptional	10	0.09254332337
339	North Puget Sound	FBE	FB Exceptional	9	0.4289682632
340	North Puget Sound	FBE	FB Exceptional	9	0.2490795668
341	North Puget Sound	FBE	FB Exceptional	9	0.1719572509
342	North Puget Sound	FBE	FB Exceptional	10	0.1236003735
343	North Puget Sound	FBE	FB Exceptional	10	0.1324780618
344	North Puget Sound	FBE	FB Exceptional	8	0.3493878763
345	North Puget Sound	FBE	FB Exceptional	10	0.1415005673
346	North Puget Sound	FBE	FB Exceptional	8	0.1179811507
347	North Puget Sound	FBE	FB Exceptional	7	0.1119049406
348	North Puget Sound	FBE	FB Exceptional	9	0.1319545992
349	North Puget Sound	FBE	FB Exceptional	9	0.1276468928
350	North Puget Sound	FBE	FB Exceptional	7	0.3105512204
351	North Puget Sound	FBE	FB Exceptional	10	0.5152498876
352	North Puget Sound	FBE	FB Exceptional	10	1.448958301
353	North Puget Sound	FBE	FB Exceptional	9	0.5190809106
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358	North Puget Sound	FBE	FB Exceptional	9	0.1793333476
359	North Puget Sound	FBE	FB Exceptional	8	0.1132700177
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363	South Central Puget Sound	FBE	FB Exceptional	5	0.2493918547
364	South Central Puget Sound	FBE	FB Exceptional	8	0.4648644155
365	South Central Puget Sound	FBE	FB Exceptional	10	0.3035751491
366	South Central Puget Sound	FBE	FB Exceptional	10	0.4512672157
367	South Central Puget Sound	FBE	FB Exceptional	7	0.2596361451
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369	South Central Puget Sound	FBE	FB Exceptional	11	0.1940322118
370	South Central Puget Sound	FBE	FB Exceptional	10	0.3284509852

371	South Central Puget Sound	FBE	FB Exceptional	10	0.3111936015
372	South Central Puget Sound	FBE	FB Exceptional	11	0.6388476881
373	South Central Puget Sound	FBE	FB Exceptional	10	0.3585505768
375	South Central Puget Sound	FBE	FB Exceptional	11	0.2974089171
376	South Central Puget Sound	FBE	FB Exceptional	9	0.3154129817
377	South Central Puget Sound	FBE	FB Exceptional	10	0.2653413976
378	South Central Puget Sound	FBE	FB Exceptional	11	0.1542716637
379	South Central Puget Sound	FBE	FB Exceptional	8	0.1655441633
380	South Central Puget Sound	FBE	FB Exceptional	10	0.489018702
381	South Central Puget Sound	FBE	FB Exceptional	8	0.2035149536
382	South Central Puget Sound	FBE	FB Exceptional	6	0.1948565935
383	South Central Puget Sound	FBE	FB Exceptional	10	0.2182297616
384	South Central Puget Sound	FBE	FB Exceptional	9	0.2561606775
385	South Central Puget Sound	FBE	FB Exceptional	5	0.1870623646
386	South Central Puget Sound	FBE	FB Exceptional	10	0.527161044
387	South Central Puget Sound	FBE	FB Exceptional	7	0.3850073869
388	South Central Puget Sound	FBE	FB Exceptional	6	0.1468351959
389	South Central Puget Sound	FBE	FB Exceptional	10	0.1231131634
390	South Central Puget Sound	FBE	FB Exceptional	10	0.1481388424
391	South Central Puget Sound	FBE	FB Exceptional	10	0.235188655
392	South Central Puget Sound	FBE	FB Exceptional	10	0.1223820348
393	Strait of Juan de Fuca	FBE	FB Exceptional	10	0.1111688046
394	Strait of Juan de Fuca	FBE	FB Exceptional	8	0.1296060406
395	Strait of Juan de Fuca	FBE	FB Exceptional	5	0.09542649516
396	Strait of Juan de Fuca	FBE	FB Exceptional	9	0.09813854741
397	Strait of Juan de Fuca	FBE	FB Exceptional	10	0.09297926748
398	Strait of Juan de Fuca	FBE	FB Exceptional	8	0.13200499
400	Strait of Juan de Fuca	FBE	FB Exceptional	10	0.1800579868
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409	Strait of Juan de Fuca	FBE	FB Exceptional	10	0.1923170923
410	Strait of Juan de Fuca	FBE	FB Exceptional	6	0.1833206865
414	Strait of Juan de Fuca	FBE	FB Exceptional	10	0.1616423921
415	Strait of Juan de Fuca	FBE	FB Exceptional	10	0.2251233115
417	Strait of Juan de Fuca	FBE	FB Exceptional	10	0.07286081031
420	Strait of Juan de Fuca	FBE	FB Exceptional	8	0.07039522182
421	Strait of Juan de Fuca	FBE	FB Exceptional	11	0.06678974691
422	Strait of Juan de Fuca	FBE	FB Exceptional	10	0.1069314053
423	Whidbey	FBE	FB Exceptional	9	0.1883060977
424	Whidbey	FBE	FB Exceptional	9	0.2412297232

425	Whidbey	FBE	FB Exceptional	9	0.345921209
426	Whidbey	FBE	FB Exceptional	7	0.2748840998
427	Whidbey	FBE	FB Exceptional	7	0.2471749636
428	Whidbey	FBE	FB Exceptional	10	0.1717976832
429	Whidbey	FBE	FB Exceptional	8	0.223550465
431	Whidbey	FBE	FB Exceptional	10	0.1205938501
432	Whidbey	FBE	FB Exceptional	10	0.1295362425
433	Whidbey	FBE	FB Exceptional	10	0.222280442
434	Whidbey	FBE	FB Exceptional	8	0.221918505
435	Whidbey	FBE	FB Exceptional	6	0.2146068012
436	Whidbey	FBE	FB Exceptional	6	0.3955130038
437	Whidbey	FBE	FB Exceptional	9	0.249727061
438	Whidbey	FBE	FB Exceptional	9	0.2197281916
439	Whidbey	FBE	FB Exceptional	10	0.5773566906
440	Whidbey	FBE	FB Exceptional	10	0.2397288357
441	Whidbey	FBE	FB Exceptional	9	0.2452418053
442	Whidbey	FBE	FB Exceptional	10	0.1302889939
443	Whidbey	FBE	FB Exceptional	9	0.1780043426
444	Whidbey	FBE	FB Exceptional	10	0.9857310755
445	Whidbey	FBE	FB Exceptional	10	0.3128465927
446	Whidbey	FBE	FB Exceptional	10	0.2940316157
447	Whidbey	FBE	FB Exceptional	9	0.1670564942
448	Whidbey	FBE	FB Exceptional	10	0.2414332465
449	Whidbey	FBE	FB Exceptional	10	0.3156473838
450	Whidbey	FBE	FB Exceptional	9	0.2530404923
451	Whidbey	FBE	FB Exceptional	8	0.2416692884
452	Whidbey	FBE	FB Exceptional	5	0.2909888354
455	Hood Canal	TZ	Transport	10	0.1936600222
457	Hood Canal	TZ	Transport	6	0.213060938
458	Hood Canal	TZ	Transport	10	0.9184088698
459	Hood Canal	TZ	Transport	8	0.2831168317
460	Hood Canal	TZ	Transport	10	0.466283009
461	Hood Canal	TZ	Transport	10	0.2803173229
462	Hood Canal	TZ	Transport	7	0.5375478132
463	Hood Canal	TZ	Transport	6	0.1915827591
464	Hood Canal	TZ	Transport	9	0.3161980248
465	Hood Canal	TZ	Transport	10	0.2184089511
467	Hood Canal	TZ	Transport	7	0.635261991
468	Hood Canal	TZ	Transport	6	0.3740686332

469	Hood Canal	TZ	Transport	10	0.2082613727
471	Hood Canal	TZ	Transport	7	0.1601064409
472	Hood Canal	TZ	Transport	9	0.1337964439
473	Hood Canal	TZ	Transport	10	0.2478834034
474	Hood Canal	TZ	Transport	10	1.068940075
475	Hood Canal	TZ	Transport	8	0.4070007338
476	Hood Canal	TZ	Transport	10	0.5230579806
477	Hood Canal	TZ	Transport	10	0.6195603216
478	Hood Canal	TZ	Transport	10	0.4135590167
480	Hood Canal	TZ	Transport	8	0.290118382
481	Hood Canal	TZ	Transport	10	0.1914109451
482	Hood Canal	TZ	Transport	10	0.07249732227
483	North Puget Sound	TZ	Transport	10	0.9281588733
485	North Puget Sound	TZ	Transport	7	0.3819390927
486	North Puget Sound	TZ	Transport	10	1.256479368
487	North Puget Sound	TZ	Transport	8	0.4685711739
488	North Puget Sound	TZ	Transport	10	0.5804861333
489	North Puget Sound	TZ	Transport	7	0.1685182721
490	North Puget Sound	TZ	Transport	10	1.256762067
491	North Puget Sound	TZ	Transport	9	0.4071211764
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493	North Puget Sound	TZ	Transport	5	1.151457881
494	North Puget Sound	TZ	Transport	9	0.8527541785
495	North Puget Sound	TZ	Transport	9	0.2427126818
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497	North Puget Sound	TZ	Transport	11	1.487785373
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499	North Puget Sound	TZ	Transport	9	0.7449823371
500	North Puget Sound	TZ	Transport	10	1.272207465
501	North Puget Sound	TZ	Transport	10	0.2041029572
502	North Puget Sound	TZ	Transport	5	1.372945621
503	North Puget Sound	TZ	Transport	5	0.9384036377
504	North Puget Sound	TZ	Transport	9	1.084171391
505	North Puget Sound	TZ	Transport	10	1.144512408
506	North Puget Sound	TZ	Transport	6	1.219779577
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509	North Puget Sound	TZ	Transport	7	0.5858213782
510	North Puget Sound	TZ	Transport	10	0.09028091081
511	North Puget Sound	TZ	Transport	7	0.1000290641

512	North Puget Sound	TZ	Transport	10	0.6682239341
513	South Central Puget Sound	TZ	Transport	9	0.2946918964
514	South Central Puget Sound	TZ	Transport	6	0.3066444197
515	South Central Puget Sound	TZ	Transport	5	0.3626715888
516	South Central Puget Sound	TZ	Transport	7	0.1428151794
517	South Central Puget Sound	TZ	Transport	8	0.8667072932
518	South Central Puget Sound	TZ	Transport	8	0.2469370018
520	South Central Puget Sound	TZ	Transport	7	0.2434691308
521	South Central Puget Sound	TZ	Transport	12	0.3161365621
522	South Central Puget Sound	TZ	Transport	6	0.5492975244
523	South Central Puget Sound	TZ	Transport	10	0.3163646701
524	South Central Puget Sound	TZ	Transport	7	0.2943947472
525	South Central Puget Sound	TZ	Transport	10	0.2494368594
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527	South Central Puget Sound	TZ	Transport	10	0.2604763229
528	South Central Puget Sound	TZ	Transport	8	1.522569825
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531	South Central Puget Sound	TZ	Transport	10	0.4052986936
532	South Central Puget Sound	TZ	Transport	7	0.4649655065
533	South Central Puget Sound	TZ	Transport	9	0.198159243
536	South Central Puget Sound	TZ	Transport	9	0.5146594898
537	South Central Puget Sound	TZ	Transport	6	0.212170701
538	South Central Puget Sound	TZ	Transport	5	0.2331005327
540	South Central Puget Sound	TZ	Transport	10	0.5766108408
541	South Central Puget Sound	TZ	Transport	7	0.09803299467
542	South Central Puget Sound	TZ	Transport	6	0.1561168645
543	Strait of Juan de Fuca	TZ	Transport	9	0.1860323186
544	Strait of Juan de Fuca	TZ	Transport	6	0.2424173819
546	Strait of Juan de Fuca	TZ	Transport	10	0.2403985976
547	Strait of Juan de Fuca	TZ	Transport	10	0.3306311465
548	Strait of Juan de Fuca	TZ	Transport	5	0.2493352423
549	Strait of Juan de Fuca	TZ	Transport	6	0.1868146158
550	Strait of Juan de Fuca	TZ	Transport	10	0.6319609844
551	Strait of Juan de Fuca	TZ	Transport	10	0.1227491152
556	Strait of Juan de Fuca	TZ	Transport	10	0.07916553835
573	Whidbey	TZ	Transport	5	0.47388031
574	Whidbey	TZ	Transport	7	0.3322382733
575	Whidbey	TZ	Transport	10	0.1308159981
576	Whidbey	TZ	Transport	10	0.1474507311

577	Whidbey	TZ	Transport	10	0.2617647097
578	Whidbey	TZ	Transport	8	0.2138331887
579	Whidbey	TZ	Transport	9	0.2029956678
580	Whidbey	TZ	Transport	8	0.1621774834
581	Whidbey	TZ	Transport	11	0.3132921766
582	Whidbey	TZ	Transport	10	0.5430687622
583	Whidbey	TZ	Transport	9	0.4214736719
584	Whidbey	TZ	Transport	9	0.2961387542
585	Whidbey	TZ	Transport	10	0.1980638445
586	Whidbey	TZ	Transport	6	0.2725558324
587	Whidbey	TZ	Transport	6	0.2634038259
588	Whidbey	TZ	Transport	10	0.2004713862
589	Whidbey	TZ	Transport	8	0.3381019644
590	Whidbey	TZ	Transport	11	0.2026879985
591	Whidbey	TZ	Transport	7	0.1896520348
592	Whidbey	TZ	Transport	10	0.1974092895
593	Whidbey	TZ	Transport	10	0.1480306112
594	Whidbey	TZ	Transport	6	0.1617111126
595	Whidbey	TZ	Transport	9	0.1788268135
596	Whidbey	TZ	Transport	10	0.667026575
597	Whidbey	TZ	Transport	11	0.7970003925
598	Whidbey	TZ	Transport	8	0.6119950207
599	Whidbey	TZ	Transport	11	1.18710448
600	Whidbey	TZ	Transport	7	0.2360398848
602	Whidbey	TZ	Transport	9	0.3724959817

Appendix B: Metadata

Title	TCARI_Points_FINAL
Tags/Topics/Keywords	shoreline, tidal datum, elevation, Puget Sound, Salish Sea, tides
Summary	TCARI_Points_FINAL is a set of points located in the Puget Sound Nearshore (excluding the western Strait of Juan de Fuca. Each point includes the predicted elevation of four tidal datums including Highest Astronomical Tide. Tidal datum elevations were calculated using the NOAA VDATUM tool, and the increment between Mean Higher High Water and Highest Astronomical Tide derived from a Tidal Constituent and Residual Interpolation (TCARI) model run provided by NOAA CO-OPS. The definition of local tidal elevation was necessary to estimate upper beach slope, and define those areas regulated as intertidal habitat by the National Marine Fisheries Service under the Endangered Species Act. These data were used to derive three contour lines describing HAT, MHHW, and MLLW tide lines.
Description	**Purpose:** These data were developed to support estimation of beach slope. Local estimates of tidal datum were used to construct contour lines to support a desktop survey of the distance between HAT and MHHW. This water surface modeling exercise provides local estimates of HAT and MHHW across the entire Puget Sound shoreline. Prior to this exercise, there was no mechanism for the sound-wide estimation of HAT—the HAT datum elevation was only available at 32 physical tidal station locations, where tidal data is continuously monitored. **Data Description:** These data include 82,918 points located within the Puget Sound nearshore, between the high tide line out to 10m of water depth. At each point is attributed with the estimated elevation for four tidal datums: 1) highest Astronomical Tide (HAT), 2) mean higher high water (MHHW), mean high water (MHW), and mean lower low water (MLLW). All data are presented in both meters and feet relative to the North American Vertical Datum of 1988. **Source Data:** TCARI Model Outputs – Personal communications. Sierra Davis and David Wollcott, National Ocean Service, Center for Operational Oceanographic Products and Services (CO-OPS), August 3, 2021. PSNERP Geodatabase – the fd_GSU polygon set was used to define an area of study within the Puget Sound nearshore. https://wagda.lib.washington.edu/data/geography/wa_state/#PSNERP NOAA VDATUM reference data – the VDATUM tool was used to convert a 0 elevation relative to MHHW to NAVD88 for the purpose of converting the modeled increment of HAT above MHHW to a absolution elevation relative to NAVD88. https://vdatum.noaa.gov/

Methods:

1. NOAA CO-OPS provided TCARI model outputs for all of Puget Sound and adjacent waters describing the increment between MHHW and HAT.
2. A study area was defined using the Puget Sound Nearshore Ecosystem Restoration Proejct Database to include the wet nearshore zone, seaward of the high water line out to approximately 10m of water depth (fd_GSU where ZU<2), and within the extent of the USGS CoNED topobathymetric dataset.
3. Points were clipped to within the study area, and exported as ASCII file, including a unique identifier, XY coordinates, and the interval between HAT and MHHW as identified by the TCARI study.
4. Using the NOAA VDATUM conversion tool, the NAVD88 elevation was calculated for each point in the TCARI_points data set. The elevation of HAT in NAVD88 was calculated by adding the TCARI interval between MHHW and HAT to the MHHW elevation for each TCARI point.
5. Data were imported to GIS, and visually examined for discrepancies in what should be a continuously variation in tidal elevation.

Fields:

OBJECTID_1 – the original object ID of data provided by

Shape - Point

Long – longitude of each point in decimal degrees

Lat – latitude of each point in decimal degrees

OBJECTID – the object ID used to link VDATUM outputs back to original point data.

MLLW_NAVD88m – the local elevation of mean lower low water in decimal meters relative to North American Vertical Datum of 1988.

MHW_NAVD88m – the local elevation of mean lower low water in decimal meters relative to North American Vertical Datum of 1988.

MHHW_NAVD88m – the local elevation of mean lower low water in decimal meters relative to North American Vertical Datum of 1988.

HAT_NAVD88m – the local elevation of mean lower low water in decimal meters relative to North American Vertical Datum of 1988.

MLLW_NAVD88ft – the local elevation of mean lower low water in decimal meters relative to North American Vertical Datum of 1988.

MHW_NAVD88ft

MHHW_NAVD88ft – the local elevation of mean lower low water in decimal meters relative to North American Vertical Datum of 1988.

	HAT_NAVD88ft – the local elevation of mean lower low water in decimal meters relative to North American Vertical Datum of 1988. TCARI_error – an error metric retained from the TCARI Model Run.
Credits.	**Data Steward:** Paul R. Cereghino, Marine Habitat Specialist, NOAA/NMFS/OHC/RC paul.r.cereghino@noaa.gov, 206-948-6360 **Citation:** Cereghino, P., J. Ory, P. Pope, S. Ehinger, M. Bhuthimethee, K. Wykoff. 2022. Estimation of typical high intertidal beach face slope in Puget Sound. Draft manuscript. Produced by the National Marine Fisheries Service, Lacey, WA.
Use Limitations	**Legal Status:** These data are an unpublished federal agency analytical work product. They are part of the administrative record of NMFS, West Coast Region, Protected Resources Division. **Technical Limitations:** These are model estimates of tidal datum. They are interpolated and extrapolated from observed tidal observations at approximately 32 harmonic stations in Puget Sound. These estimates do not consider the effects of air pressure or storm surge. They may not reflect actual dynamics of tidal harmonics or amplification. Thus they should not be used to predict a specific tide on a specific day or location, but serve to provide an approximation of typical high water elevations. Because of the interaction of atmospheric pressure, wind and tides, the highest astronomical tide (HAT) is lower than observed extreme high tides. Thus HAT does not reflect the highest influences of tides on shorelines or describe the extend of tides during storm events. Elevation precision (in six significant figures) is much higher than the potential error. An error analysis was conducted, comparing the point estimates to 32 harmonic stations (where actual water level is monitored and which is used to establish all model inputs). Nearby points were within an average of one-half-inch of observed tidal datums.
Extent	Top: 49.002065 dd Bottom: 47.043861 dd Left: -124.745052 dd Right: -122.200009 dd

	Geographic Coordinate System: WGS 1984
Scale Range	TCARI_Points_Final provides a high resolution estimate of tidal datums within the nearshore within the data extent. Points are 10s to 100s of meters apart, with change in tidal datum between points in at the scale of millimeter.

Name: Contour_HAT, Contour_MHHW, Contour MLLW

Title	Contour_HAT
Keywords	shoreline, tidal datum, highest astronomical tide, HAT, elevation, Puget Sound, Salish Sea, tides, contour, interpolation, tideline, ordinary high water
Summary	This tidal contour line provides an estimate of the position of Highest Astronomical Tide (HAT) over most of Puget Sound using the best available digital elevation models and the outputs of a Tidal Constituent and Residual Interpolation and the interpolation of the observed elevation of Mean Higher High Water among existing harmonic tidal stations.
Description	**Purpose:** These data were developed to support estimation of beach slope between Highest Astrononmical Tide (HAT) and Mean Higher High Water (MHHW). This rendering of the position of HAT was used to randomly sample beach cross sections, to calculate typical upper beach slope. **Data Description:** This line shows a contour line based on CoNED Topobathymetric model that matches the local modeled elevation of highest astronomical tide. HAT varies across Puget Sound, and so the contour is not level, but rather slopes consistent with a hypothetical surface that represents the highest astronomical tide. The surface varies from the NAVD88 planar surface by a few millimeters over every few hundred meters. **Source Data:** TCARI_Points_FINAL – These data were derived as part of this same project, and are distributed as a package. These points describe the tidal datum elevations across Puget Sound in NAVD88. PSNERP Geodatabase – the fd_GSU polygon set was used to define an area of study within the Puget Sound nearshore. https://wagda.lib.washington.edu/data/geography/wa_state/#PSNERP

	USGS CoNED Topobathymetry – this best available topobathymetric elevation model was used in conjunction with TCARI_Points_FINAL to construct the contour line. https://www.sciencebase.gov/catalog/item/5d72b5dfe4b0c4f70cffa775 **Methods:** 1. Using the TCARI_Points_FINAL a coarse raster of a 10m grid was constructed using IDW interpolation, but registered to the CoNED Model. 2. The coarse raster values (equal to HAT in meters) were subtracted from the CoNED model, creating a relative elevation surface. 3. The relative elevation surface was used to construct a contour line at the zero elevation (the elevation of HAT in NAVD88). 4. All lines less than 10m in length were removed to reduce file size, and focus attention on significant landscape features. **Fields:** OBJECTID_1 – the original object ID of data provided by Shape – Polyline Shape Length – The feature length in meters
Credits.	**Data Steward:** Paul R. Cereghino, Marine Habitat Specialist, NOAA/NMFS/OHC/RC paul.r.cereghino@noaa.gov, 206-948-6360 **Citation:** Cereghino, P., J. Ory, P. Pope, S. Ehinger, M. Bhuthimethee, K. Wykoff. 2022. Estimation of typical high intertidal beach face slope in Puget Sound. Draft manuscript. Produced by the National Marine Fisheries Service, Lacey, WA.
Use Limitations	**Legal Status:** These data are an unpublished federal agency analytical work product. They are part of the administrative record of NMFS, West Coast Region, Protected Resources Division. **Technical Limitations:** These contour lines were developed for the purpose of estimating median beach slope at a large number of sample sites. Methods were designed to use a large sample size to arrive at a median parameter estimate to minimizes known error. While the lines provide useful and interesting estimates of shoreline contours, any error in the Digital Elevation Model will transfer to the position of the line. Thus, the contour lines are only as accurate as the DEM.

	The DEM includes known errors and artifacts. Therefore, the lines should not be used to reliably represent tidal elevation at a specific site. Finally, intertidal systems shift in elevation as sediments are reworked by waves. These data provide a snapshot of beach conditions, which are expected to change over time.
Extent	Top: 5,427,772.500000 m Bottom: 5,207,185.358023 m Left: 484,875.500000 Right: 567.170.618123 m NAD 1983 (2011) UTM Zone 10N (from CoNED Model), Transverse Mercator
Scale Range	Contour lines are derived from a one-meter resolution DEM and are best viewed at a small scale. Local DEM precision depends on the quality of underlying data. See technical limitation above.

Title	Contour_MHHW
Keywords	shoreline, tidal datum, mean higher high water, MHHW, elevation, Puget Sound, Salish Sea, tides, contour, interpolation, tideline, ordinary high water
Summary	This tidal contour line provides an estimate of the position of Mean Higher High Water (MHHW) over most of Puget Sound using the best available digital elevation models and the interpolation of the observed elevation of Mean Higher High Water among existing harmonic tidal stations.
Description	Purpose: These data were developed to support estimation of beach slope between Highest Astronomical Tide (HAT) and Mean Higher High Water (MHHW). This rendering of the position of MHHW was used to randomly sample beach cross sections, to calculate typical upper beach slope. Data Description: This line shows a contour line based on CoNED Topobathymetric model that matches the local modeled elevation of highest astronomical tide. MHHW varies across Puget Sound, and so the

contour is not level, but rather slopes consistent with a hypothetical surface that represents the highest astronomical tide. The surface varies from the NAVD88 planar surface by a few millimeters over every few hundred meters.

Source Data:

TCARI_Points_FINAL – These data were derived as part of this same project, and are distributed as a package. These points describe the tidal datum elevations across Puget Sound in NAVD88.

PSNERP Geodatabase – the fd_GSU polygon set was used to define an area of study within the Puget Sound nearshore. https://wagda.lib.washington.edu/data/geography/wa_state/#PSNERP

USGS CoNED Topobathymetry – this best available topobathymetric elevation model was used in conjunction with TCARI_Points_FINAL to construct the contour line. https://www.sciencebase.gov/catalog/item/5d72b5dfe4b0c4f70cffa775

Methods:

1. Using the TCARI_Points_FINAL a coarse raster of a 10m grid was constructed using IDW interpolation, but registered to the CoNED Model.
2. The coarse raster values (equal to MHHW in meters) were subtracted from the CoNED model, creating a relative elevation surface.
3. This relative elevation surface was used to construct a contour line at the zero elevation (the elevation of MHHW in NAVD88 in meters).
4. All lines less than 10m in length were removed to reduce file size, and focus attention on significant landscape features.

Fields:

OBJECTID_1 – the original object ID of data provided by

Shape – Polyline

Shape Length – The feature length in meters

Credits.

Data Steward:

Paul R. Cereghino, Marine Habitat Specialist, NOAA/NMFS/OHC/RC

paul.r.cereghino@noaa.gov, 206-948-6360

Citation:

Cereghino, P., J. Ory, P. Pope, S. Ehinger, M. Bhuthimethee, K. Wykoff. 2022. Estimation of typical high intertidal beach face slope in Puget Sound. Draft manuscript. Produced by the National Marine Fisheries Service, Lacey, WA.

Use Limitations	**Legal Status:** These data are an unpublished federal agency analytical work product. They are part of the administrative record of NMFS, West Coast Region, Protected Resources Division. **Technical Limitations:** These contour lines were developed for the purpose of estimating median beach slope at a large number of sample sites. Methods were designed to use a large sample size to arrive at a median parameter estimate to minimizes known error. While the lines provide useful and interesting estimates of shoreline contours, any error in the Digital Elevation Model will transfer to the position of the line. Thus, the contour lines are only as accurate as the DEM. The DEM includes known errors and artifacts. Therefore, the lines should not be used to reliably represent tidal elevation at a specific site. Finally, intertidal systems shift in elevation as sediments are reworked by waves. These data provide a snapshot of beach conditions, which are expected to change over time.
Extent	Top: 5,427,772.500000 m Bottom: 5,207,191.942339 m Left: 484,875.500000 Right: 567.133.962579 m NAD 1983 (2011) UTM Zone 10N (from CoNED Model), Transverse Mercator
Scale Range	Contour lines are derived from a one-meter resolution DEM and are best viewed at a small scale. Local DEM precision depends on the quality of underlying data. See technical limitation above.

Title	Contour_MLLW
Keywords	shoreline, tidal datum, mean lower low water, MLLW, elevation, Puget Sound, Salish Sea, tides, contour, interpolation, tideline, ordinary high water
Summary	This tidal contour line provides an estimate of the position of Mean Lower Low Water (MLLW) over most of Puget Sound using the best available digital elevation models and the interpolation of the observed elevation of Mean Lower Low Water among existing harmonic tidal stations.

Description	**Purpose:** These data were developed to accompany related data developed to estimate of beach slope between Highest Astronomical Tide (HAT) and Mean Higher High Water (MHHW). This rendering of the position of MLLW was used to generally describe the beach environment. **Data Description:** This line shows a contour based on CoNED Topobathymetric model that matches the local modeled elevation of Highest Astronomical Tide. MLLW varies across Puget Sound, and so the contour is not level, but rather slopes consistent with a hypothetical surface that represents the highest astronomical tide. The surface varies from the NAVD88 planar surface by a few millimeters over every few hundred meters. **Source Data:** TCARI_Points_FINAL – These data were derived as part of this same project, and are distributed as a package. These points describe the tidal datum elevations across Puget Sound in NAVD88. PSNERP Geodatabase – the fd_GSU polygon set was used to define an area of study within the Puget Sound nearshore. https://wagda.lib.washington.edu/data/geography/wa_state/#PSNERP USGS CoNED Topobathymetry – this best available topobathymetric elevation model was used in conjunction with TCARI_Points_FINAL to construct the contour line. https://www.sciencebase.gov/catalog/item/5d72b5dfe4b0c4f70cffa775 **Methods:** 1. Using the TCARI_Points_FINAL a coarse raster of a 10m grid was constructed using IDW interpolation, but registered to the CoNED Model. 2. The coarse raster values (equal to MLLW in meters) were subtracted from the CoNED model, creating a relative elevation surface. 3. This relative elevation surface was used to construct a contour line at the zero elevation (the elevation of MLLW in NAVD88 in meters). 4. All lines less than 10m in length were removed to reduce file size, and focus attention on significant landscape features. **Fields:** OBJECTID_1 – the original object ID of data provided by Shape – Polyline Shape Length – The feature length in meters
Credits.	**Data Steward:**

	Paul R. Cereghino, Marine Habitat Specialist, NOAA/NMFS/OHC/RC paul.r.cereghino@noaa.gov, 206-948-6360 **Citation:** Cereghino, P., J. Ory, P. Pope, S. Ehinger, M. Bhuthimethee, K. Wykoff. 2022. Estimation of typical high intertidal beach face slope in Puget Sound. Draft manuscript. Prepared by the National Marine Fisheries Service, Lacey, WA.
Use Limitations	**Legal Status:** These data are an unpublished federal agency analytical work product. They are part of the administrative record of NMFS, West Coast Region, Protected Resources Division. **Technical Limitations:** These contour lines were developed for the purpose of estimating median beach slope at a large number of sample sites. Methods were designed to use a large sample size to arrive at a median parameter estimate to minimizes known error. While the lines provide useful and interesting estimates of shoreline contours, any error in the Digital Elevation Model will transfer to the position of the line. Thus the contour lines are only as accurate as the DEM. The DEM includes known errors and artifacts. Therefore the lines should not be used to reliably represent tidal elevation at a specific site. The MLLW contour was likely located in an area where the subtidal surface was interpolated between upland LIDAR and bathymetry. Thus the MLLW contour should only be considered an estimate based on interpolation, and detail features are not reliably represented. Finally, intertidal systems shift in elevation as sediments are reworked by waves. These data provide a snapshot of beach conditions, which are expected to change over time.
Extent	Top: 5,427,719.028902 m Bottom: 5,209,994.041252 m Left: 484,875.500000 Right: 564,910.831189 m NAD 1983 (2011) UTM Zone 10N (from CoNED Model), Transverse Mercator
Scale Range	Contour lines are derived from a one-meter resolution DEM and are best viewed at a small scale. Local DEM precision depends on the quality of underlying data. See technical limitation above.

Title	Beach_Slope_Ref_Line
Keywords	Sub-basin, shoretype, beach type, typical beach slope, shoreline, tidal datum, mean lower low water, MLLW, mean higher high water, MHHW, highest astronomical tide, HAT, elevation, Puget Sound, Salish Sea,
Summary	This state-developed shoreline has been attributed with attributes necessary for using the NOAA Nearshore Habitat Conservation Calculator. The line includes shoretype and the marine sub-basin as developed for conservation offsets by the Puget Sound Partnership. The line also defines the interpolated elevation in NAVD88 meters and feed for HAT, MHHW, and MLLW. It provides a median beach slope, as calculated for sub-basin and shoretype.
Description	**Purpose:** Referencing this line gives you the data necessary for a user of the NOAA Nearshore Conservation Calculator to determine a typical upper beach slope in the absence of a local study of beach structure. Typical upper beach slope, combined with the elevation of the toe of shoreline armoring can be used to estimate the extent of intertidal encroachment of that armor. **Data Description:** Data from multiple sources have been attributed to a line created by Coastal Geologic Service (MacLennan et al 2017). This line is consistent with previous shoreline analysis by ShoreZone (Berry et al 2001) and the Nearshore Project (Simenstad et al. 2011). Fields include local HAT, MHHW and MLLW elevations in NAVD88 meters and feet, sub-basin as designated by Puget Sound Partnership offset programs, and beach shoretype as defined in MacLennan et al (2017). **Source Data:** MacLennan et al 2017 – The best available beach analysis, available from the ESRP program. TCARI_Points_Final – distributed with this product, describing local tidal datum elevation using NOAA VDATUM and a Tidal Constituent and Residual Analysis (TCARI). Nearshore_MarineBasins_wm – served by Puget Sound partnership, https://services7.arcgis.com/iAd79FjHxHKsLP0y/arcgis/rest/services/Nearshore_Credits_Marine_Basins/FeatureServer **Methods:** 1. TCARI_Points_Final was used to create interpolated raster files with 10m cells describing HAT, MHHW, and MLLW. 2. Elevation was rounded to three decimal places, and values combined into a single raster with multiple fields 3. The raster was converted to Polygons retaining values as fields.

	4. Identity was used to attribute the MacLennan et al 2017 shoreline with the tidal datum polygons, and Nearshore_MarineBasins_wm polygons. 5. Unnecessary fields were removed for distribution. **Fields:** OBJECTID_1 – the original object ID of data provided by Shape – Polyline Shape Length – The feature length in meters
Credits.	**Data Steward:** Paul R. Cereghino, Marine Habitat Specialist, NOAA/NMFS/OHC/RC paul.r.cereghino@noaa.gov, 206-948-6360 **Citation:** Cereghino, P., J. Ory, P. Pope, S. Ehinger, M. Bhuthimethee, K. Wykoff. 2022. Estimation of typical high intertidal beach face slope in Puget Sound. Draft manuscript. Prepared by the National Marine Fisheries Service, Lacey, WA.
Use Limitations	**Legal Status:** These data are an unpublished federal agency analytical work product. They are part of the administrative record of NMFS, West Coast Region, Protected Resources Division. **Technical Limitations:** The DNR Shoreline is a simplified representation of the ordinary high water mark, but does not consistently align with either elevation models or aerial photos. The line is used as a vehicle for delivering attributes most likely to describe local conditions to support local regulatory coordination. Edges between shoretypes are artificial boundaries on features with continuous variation. Interpretation of line attributes requires geomorphic judgement.
Extent	Top: Bottom: Left: Right: NAD 1983 (2011) UTM Zone 10N (from CoNED Model), Transverse Mercator
Scale Range	These data are best viewed at a neighborhood to county scale.

U.S. Secretary of Commerce
Gina M. Raimondo

Under Secretary of Commerce for
Oceans and Atmosphere
Dr. Richard W. Spinrad

Assistant Administrator for Fisheries
Janet Coit

June 2023

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