Summary

Olympic Natural Resources Center (ONRC) GIS has produced maps showing predicted tidal exposure durations for resource managers and stakeholders to use when planning when and where to spray herbicides to control *Spartina alterniflora* in Willapa Bay. The efficacy of Rodeo® (Glyphosate) and Habitat® (Imazapyr), the two primary herbicides used in the bay, drops dramatically when treatment area exposure durations drop below a certain value. We used a LIDAR based Mean Lower Lowest Water (MLLW) referenced elevation model and NOAA National Ocean Service (NOS) tide predictions to provide these spatially explicit tidal exposure duration maps. Validation and accuracy assessment is underway. One challenge we overcame is that the MLLW datum itself, used by all tide stations for which predictions are published by the NOS, varies from point to point in the bay. Another is the fact that features within the bay exert their own dynamic hydrologic effects on all aspects of tide mechanics, which makes correlation with NOS tide predictions, which are typically open-water data, very difficult. Our approach to these challenges was to obtain GPS points along the water line to detect quantifiable errors at the intersection between the water surface and the underlying terrain. Using this error data, we have refined the MLLW-referenced elevation model that is the basis of our mapping methodology. When properly validated, tidal exposure duration maps can be far superior to the use of tide tables alone. They provide a useful and elegant decision support tool to economically and effectively incorporate chemical applications into the Integrated Pest Management Strategy for Willapa Bay.

Keywords: Estuary, Invasive Species, Tides, Tidal, Intertidal, Willapa Bay, Spartina, Tidal Exposure, Mapping, Tide Prediction, Terrain Modeling, Geographic Information System
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Introduction

The Olympic Natural Resources Center (ONRC) was created by the Washington State Legislature to focus the scientific resources of the University of Washington on the priority marine issues facing coastal Washington. Interviews with hundreds of stakeholders and managers indicated that invasive species are one of the highest priority problems in Washington’s most threatened estuary — Willapa Bay.

Willapa Bay is located on the southwest Washington coast between Grays Harbor and the mouth of the Columbia River. The bay is bordered on the west by Long Beach Peninsula, and opens to the Pacific Ocean between Leadbetter Point at the north end of the peninsula, and Toke Point on the mainland to the northeast, a distance of approximately 4 miles.

The bay is roughly rectangular, oriented along a north-south line, about 6 miles wide by 24 miles long. Four moderately sized rivers drain west into the estuary. These rivers are Willapa from the northeast, the Palix and Nemah near the bay’s center, and the Naselle, from the southeast. There is a large island, Long Island, in the south-central bay, managed by the Willapa National Wildlife Refuge.

Willapa Bay is an immensely productive estuary: its commercial shellfish beds generate more oysters than any other in the state; its broad intertidal mudflats are among the top ten fueling stops for migrating birds along the Pacific Flyway; its network of sloughs supports some of the healthiest salmon and steelhead runs in the Northwest. Invasive species have altered habitat and threatened to bring an end to the diversity and productivity of Willapa Bay and the businesses it has supported for the past century and a half. Spartina alterniflora infests over one third of the intertidal mudflats of the Bay.

In the 2003 under the Comprehensive Unified Plan for Spartina Control, ONRC was charged with providing mapping and Geographic Information System (GIS) support to agencies doing work in Willapa Bay; specifically, with preparing “dry time” maps that would be used to plan herbicide treatments throughout the bay.

Dr. Kim Patten, Research Scientist at Washington State University Extension Cranberry Research Station, when comparing the two primary herbicides of use in the bay in 2002, Rodeo® (Glyphosate) and Habitat® (Imazapyr), found that dry-time was of major factor affecting kill rates. Dr. Patten’s research required that minimum times used in dry time mapping for the two chemicals are 12 and 4 hours respectively¹, and for treatment to be effective, eighteen inches of the Spartina plant’s stem must be exposed for the durations specified.

Exposure events of the appropriate duration for Glyphosate are generally restricted to the days surrounding neap tides. At other times, tide level changes are more extreme, and exposure durations that are long enough and low enough occur less frequently. Imazapyr is much less difficult to find exposure events for, and suitable days can be found at any time during the growing season.

This paper describes the methods and the mapping procedures used to create tidal exposure duration maps, provides a sample map, and illustrates GPS-survey based preliminary validation efforts.

¹ Patten, Kim. 2002. unpublished work?
Methods

In order to produce tidal exposure duration maps, several different types of data were collected, preprocessed, and analyzed. First, base GIS data (geospatial data), including a terrain model, Spartina inventory and habitat range data, and tide prediction “station” locations, were gathered. All these data were placed in a common vertical and horizontal coordinate system. Then, numerical water level and exposure time data at these tide prediction stations were obtained from queries using tide prediction software and attached to the tide prediction station data in the GIS. Water level “surfaces” and Spartina-overlaid terrain were created and analysed. The results were used to compose displays used to create exposure duration maps. Over the last 2 years, validation efforts have been implemented to improve the accuracy of our maps.

Vertical and Horizontal Coordinate Systems

The horizontal coordinate system is State Plane (SPCS), Washington South Zone 5626 (FIPSZone 4602), North American Datum of 1983 (NAD83), with units in feet. This horizontal coordinate system was chosen as most of the agencies involved in the control and treatment of Spartina use either SPCS NAD83 or SPCS NAD27.

The vertical coordinate system, also often referred to as a datum, is for our work, Mean Lower Lowest Water (MLLW), with units in feet. This datum was chosen because NOAA CO-OPS/NOS uses MLLW for all tide prediction data. It makes much more sense to use the vertical datum of the data that is continually changing and constantly collected rather than the datum that static data is referenced to. In choosing MLLW as the vertical datum, whatever conversion work required will only need to be applied once to the terrain model, and once validated, only occasionally updated thereafter.

The choice of vertical datum presented significant technical and practical challenges. On the technical side, MLLW varies locally with respect to other vertical datums like the North American Vertical Datum of 1988 (NAVD88) or the National Geodetic Vertical Datum of 1929 (NGVD29). This condition made it necessary to interpolate a “correction grid” based on points whose MLLW datum is known relative NAVD88 within Willapa Bay. As there are only four points in the bay where such data are available, the data was very coarse, and the resultant grid did not take into consideration local hydrological effects on the MLLW datum. Of primary concern was the fact that restricted waterways, of which there are many in the bay, cause tidal variations to become more extreme. The nature of this effect causes MLLW to “drop” in relation to a fixed vertical datum like NAVD88. Thus, it became necessary to refine the correction grid using GPS points to capture the water line in critical areas. Approximately 140 useful points were captured during the past two years and error adjustments were applied. The correction grid was then applied to a LiDAR-derived terrain model referenced to NAVD88 to generate a MLLW-referenced terrain model that would be compatible with tide prediction data.

At the time this work began in 2003, none of the agencies or stakeholders in the bay were using a common reference for their tide predictions. As a matter of fact, many were using tide prediction data made available at Astoria, Oregon or Aberdeen, Washington - entirely outside the bay - because of an historical approximate fit with local expert knowledge. The value of our

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product is that it’s implementation did not necessarily require that these organizations adapt the same tide tables as long as we limited our mapping to showing what is exposed on the tideflats on a particular day and for how long. Regardless of what tidal “yardstick” was used, this aspect of tidal exposure mapping would be universally useful. The difference between the various organizations’ yardsticks would be apparent only when a decision had to be made as to what tide level such exposures occurred.

**Terrain model**

The terrain model is essential for mapping tidal exposures. Our terrain model is a grid of 30-foot cells which includes those portions of the tide flats in Willapa Bay that are of interest, and holds elevation values in feet relative MLLW. This terrain model used in analysis is actually resampled from the actual base data, which is a 10-foot grid. Areas whose elevations were between –1 and +11 feet relative MLLW represent virtually all available habitat for *Spartina alterniflora*.

As little as three years ago, no reliable intertidal elevation data with the requisite resolution and accuracy existed for Willapa Bay. At that time, the only useful data that existed was United States Geological Survey (USGS) digital elevation models (DEMs) dating from the 1940’s and 1950’s and bathymetry data, which had been collected on sporadic occasions in the bay over many years. These data were compiled into the Washington Bathymetry Mosaic dataset, which is a product of the Washington Framework Project and was the most accurate bathymetry available to us.

There were profound limitations with these two data sources. Bathymetry data is referenced to MLLW but cannot be collected over the tidelands. USGS DEMs did not include elevations below zero datum, NGVD29. These conditions led to the quandary where the very gradually changing elevation tide flats, areas critical for modeling Spartina infestations and associated phenomena, were a sort of data “no man’s land.”

In 2003, NOAA CSC made available online data collected by aerial flights using a single return Infrared (IR) instrument: LiDAR (Light Detection And Ranging). This data, collected over three days in 2002, offered an opportunity for the first time to model the tide flats to a very high vertical and horizontal resolution. Because of the very gradual changes in elevation in the tide flats, differences as little as one foot in actual water level can move the water line horizontally 1000 feet or more. The availability of LiDAR data was the key to moving ahead with such elevation-sensitive endeavors such as ours.

Using NOAA CSCs’ LDART website we downloaded raw data in 5 foot horizontal resolution and elected to filter for the minimum of returns as is standard procedure for bare ground terrain modeling. Their data used SPCS NAD83 as a horizontal reference, with horizontal units in feet and NAVD88 as the vertical datum, with vertical units in centimeters.

These data were converted to ESRI grid format tiles with 5-foot cell resolution and elevation values in centimeters. The resultant tiles were merged into a single bay wide grid. The vertical values were then converted to feet.

Next, to achieve a conversion from NAVD88 to MLLW, we needed tidal benchmark stations within Willapa Bay whose MLLW datum was referenced to NAVD88 (See Figure 1)³.

³ Image courtesy of NOAA and NGS
In the case of Willapa Bay, MLLW as a datum varies widely with respect to NAVD88. Variation in the difference between the two can be greater than three feet. In the course of an effort to create a seamless elevation/bathymetry model for Puget Sound, David Finlayson et al. found that tidal swings tended to become more extreme the farther one goes up this restricted waterway. These same affects apply to Willapa Bay, which, like Puget Sound, has sloughs, islands, and estuaries, which further complicate local tidal mechanics. Because of the statistical relationship between MLLW and the diurnal tide cycle, the effect is to push MLLW “downward” in relation to its level at the mouth of the bay.

To make the conversion from NAVD88 to MLLW, we used four locations within Willapa Bay that had benchmarks whose tide gauges were referenced to an NGS (National Geodetic Survey) monument whose elevation was accurately measured. These benchmark stations were Toke Point, South Bend, Nahcotta, and Naselle River Swing Bridge.

The values representing the difference in feet between local MLLW and NAVD88 at each station were used to generate a correction grid “surface” that was then used to adjust the LIDAR-derived terrain model to MLLW (See Figure 2).
Spartina Inventory and Habitat

The ONRC, supporting agencies, and stakeholders involved in the treatment and control of Spartina in Willapa Bay have acted to assemble an accurate picture of what Spartina exists on the ground over the past several years. Our Spartina Inventory is a polygon spatial dataset with fractional ground cover densities and is used for final map displays. Regions not containing Spartina are not represented in this dataset.

The currentness of the Spartina Inventory is maintained by obtaining data from various sources such as Washington State Department of Natural Resources color-infrared aerial photographs, field observations, and helicopter and airboat GPS surveys. These data are then aggregated into this polygon dataset and are used as an overlay on our maps to indicate where Spartina currently exists.

Since the 1980s, several efforts have been made to determine how Spartina is distributed within Willapa Bay and how the favorable tidal range for the spread of Spartina is identified. In 1988, observations by Sayce indicated a preference for the middle- and upper- intertidal zones. In 1997, the Harringtons along with Cynthia Berlin modeled bay wide Spartina spread, which supported Sayce’s observations and showed potential habitat in graphic detail using remotely

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sensed imagery. In 1998, observations by Berlin\textsuperscript{6} characterized the preferred tidal range as being from 1 meter below MLLW to 0.5 meters above MHHW. These studies added considerable detail to how \textit{Spartina alterniflora} spreads in Willapa Bay.

Though these works were definitive, the data we had at hand allowed us to produce a reasonably accurate estimate of the actual tidal range or habitat Spartina prefers very easily. To accomplish this, our Spartina Inventory data was overlaid onto the base 10-foot MLLW-referenced terrain model. The intersection yielded cells containing valid elevation values where Spartina was present. These elevation values in these cells were captured and assembled into categories of 1/10-foot intervals between –5 and 13 feet. The number of values (cells) in each category were counted and plotted on a graph (fig 3).

We also divided the bay into areas that were designated as estuaries, sloughs, and open water. Counts were taken for each category type then summed to yield a total distribution. See Figure 3 for a graphical representation of our results.

A cursory analysis of the graph revealed that \textit{Spartina alterniflora} prefers the tidal elevations between –1 and 11 feet. There appears to be no visually significant differences between the distribution curves of Spartina in sloughs, estuaries, or open water. No considerations were made for other factors that could influence our estimates, and only visual cues were used to divide the bay into the respective categories.

\textbf{Figure 3.} Counts of cells sorted by elevation underlying \textit{Spartina alterniflora} in three types of water in Willapa Bay. Estuarine, slough, and open-water distribution curves all appear roughly similar to the total distribution curve in black. By estimation, most Spartina exists between –1 and 11 feet.

To obtain a Spartina Habitat grid, we used the results of our analysis to query the MLLW-referenced terrain model for all cells whose elevations were between –1 and 11 feet, inclusive. Using this data in the mapping process, together with the overlaying of the Spartina Inventory polygon dataset allows users, upon locating Spartina that is outside the areas where it is known to be to still be able to evaluate it for treatment. Our Spartina Habitat is a 30-foot grid.

**Tide Stations and Tide Prediction Software**

Had our mapping efforts been directed only at localized areas, the use of tide prediction data would have been greatly simplified. However, a bay wide approach was needed, as there are ongoing treatment and control efforts in widely separated areas within the bay.

Twelve tide station locations, based on NOAA CO-OPS/CSC tide stations whose prediction tables are available online, were represented as points in a GIS data layer. The location of each station is available online in Geographic Coordinate System (GCS) decimal degrees. This information was used to create this point dataset in SPCS NAD83.

Nobeltec’s Tides and Currents Pro® software was used to obtain suitable predictions for times and tides in feet relative MLLW at each of the points.

In contrast to other tide prediction software that was tested, predictions from Tides and Currents Pro® matched the prediction data NOAA provided online. This particular software has a database for West Coast U.S. that includes the NOAA stations mentioned above. In addition, this software has a number of other useful features that enabled reasonably complete coverage of Willapa Bay as well as obtain tide prediction data using various query techniques.

We needed more than the twelve stations that were available due to the aforementioned feature-driven complexities affecting tidal mechanics inside the bay. To this end, Tides and Currents Pro® allows the user to create custom stations at locations other than those provided in the West Coast database that came with it. To create our custom stations, four parameters were needed besides the locations we selected for each of these new stations. Fortunately, these four parameters are available in the “headers” of the tide prediction data files provided online by NOAA. We used these to populate the records attached to the twelve existing station points and used these existing stations to interpolate a grid for each parameter. This allowed us to obtain a reasonable value for each parameter needed to construct the custom stations. After the twelve new custom station points were created and added to the original tide station dataset, the values of the four parameters at each new point were obtained by querying the cell of the appropriate parameter grids directly underneath them. These values were then used to populate the record that is attached to each custom station. Using the information now stored in the tide station dataset, we added the same twelve custom stations to Tide and Currents® using the custom station wizard. We now had a total of twenty-four stations available to query for tide prediction data and could provide coverage of the entire bay.

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7 Correlation with NOAA online tide stations and predictions provided an accuracy assessment of the Nobeltec Tides and Currents Pro® tide predictions.
Tide Prediction Data

To properly represent what is exposed, when the exposure event takes place, and how long it lasts, we queried Tides and Currents® by determining on a given day what the minimum tide level is needed to give the minimum exposure time we required. Tides and Currents® provides a wizard where each station can be queried for events where the tide level is at or below a certain value (See Figure 4). When the query yields an event that lasts for at least the minimum required duration, that event value is used to populate the record for that station. Each tide station “exposure event” dataset contains such a water level for the appropriate duration length at minimum for each station’s record for each day queried. These values are in feet relative MLLW.

Figure 4. Nobeltec’s Tides & Currents Pro® with Event Query Wizard. The user selects the station, event type (in this case less than or equal to a specific tide level), and value. The results in the search results window can be saved directly to an open spreadsheet file.

Each station’s query results are assembled into a single file containing a record for each of the twenty-four stations and with tide level, start time, and duration length (See Table 1).
Mapping Procedures

The tidal exposure table is joined to the Feature Attribute Table (FAT) of the tide station point dataset. These are then used as mass points to interpolate a grid in ESRI ArcView 3.2® from the water level field (Lev0706 in table 1 above) using default spline-method interpolation settings that are available with the Spatial Analyst® extension. This grid represents a water “surface”, above which, exposure time for that day will be long enough.

All processing with grids was done at 30-foot resolution. The Spartina Habitat grid is used to generate a grid whose cells can hold estimated or actual stem heights of the plant. This grid is then overlaid onto the terrain model to simulate the actual conditions on the ground where Spartina could occur, in terms of elevation. Since both the water surface and the Spartina Habitat are referenced to MLLW, a simple query of which cells in the Spartina Habitat are eighteen inches above the water surface reveal what will be exposed for the minimum desired duration.8

The Spartina Habitat grid was used to generate a series of new grids whose cells contain the Spartina stem heights to be modeled. During treatment seasons, field observations indicated a range of probable stem heights to be encountered was from ½ to 7 feet. Our stem height grids covered this range in ½-foot increments. These grids were overlaid onto the MLLW-referenced terrain model to generate fourteen new stem height terrain models (See Figure 5). These grids are retained for use in an automated query process to generate maps.

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8 As with any tide prediction, water levels can be affected by a number of meteorological and hydrological effects. The same caveats relevant to tide predictions also apply to exposure mapping.
Using an automated process, each of the fourteen models of Spartina with stem heights from ½ to 7 feet on the tide flats is queried as to whether the Spartina is 18” above the water’s surface. The result of each query is a grid with cells in the query grid having a value of either 1, indicating that the cell is 18” above the “surface” or 0, indicating it does not (See Figure 6).

**Figure 5. Modeling “real world” conditions using GIS.**

Using an automated process, each of the fourteen models of Spartina with stem heights from ½ to 7 feet on the tide flats is queried as to whether the Spartina is 18” above the water’s surface. The result of each query is a grid with cells in the query grid having a value of either 1, indicating that the cell is 18” above the “surface” or 0, indicating it does not (See Figure 6).

**Figure 6. Automated Query Process.**
These query grids are summed together to create a new grid (See Figure 7). All stem heights can be analyzed using this automated process. The way in which the data is displayed on the map determines what stem height applies to a particular exposure map.

In July 2003, exposures were mapped for the Willapa Bay-Grays Harbor Oyster Growers Association in the Nemah area as a pilot project. Observers in the field used GPS equipment to relay stem heights at various locations allowing us much greater accuracy in modeling Spartina. This method is far superior to the method described above, eliminating the need for multiple queries, and it has the added advantage of having an immediate data currentness in terms of a biological agent that changes rapidly. We retain the ability to model Spartina more accurately using this method; the multiple query method is very flexible and may be useful for generating alternative management scenarios for different stem heights during different seasons of treatment when such on-the-spot surveys of plant heights are not feasible.

**Display of analysis results**

The organization and the summing of the query grids allowed us to pack the maximum amount of data into a minimum amount of space (See Figure 8). The decision to model every plant height between ½ and 7 feet inclusive was because often we did not know exactly what the plants’ heights would be at the time a mapping request would be made. Map turn-around requests have been one or two days to two weeks, often without specific data on plant height, only a best guess. The data maximization scheme we used makes it a very flexible process and allows us to model different plant heights for a tide event using the same single dataset. To accommodate the aforementioned obstacles and still generate a useful product, all one needs to do is to select from a set of preset legends used to display these data to change what plant height is mapped (See Map 1).
Figure 8. Stem Height Data Packing and Mapping Region Correspondence. A specific stem height, 5.5 feet, is shown being mapped by assembling cells into regions. Displaying the different cell values using the same color creates these regions. Had plant heights of 4.0 feet or lower been included in this graphic the cells from those queries would have had 0 values in this area. This would not have affected how the regions in this example are displayed.

A specific stem height, 5.5 feet, is shown being mapped by assembling cells into regions. Displaying the different cell values using the same color creates these regions. In this example, no Spartina whose stem height is 4.0 feet or less would be exposed long enough.
Map 1. Sample Exposure Map, Nemah area of Willapa Bay showing 4- and 6-hour exposure areas.
Validation

The water line is the intersection of the water’s surface and the underlying terrain, both of which can be modeled and compared. GPS points were captured along the water line to compare with elevations from the modeled water surface and elevations from the terrain model. Any difference between the two is considered an error.

The GPS Survey produced a point dataset from which “snapshots” of the water’s surface at the time the water line point data was captured could be created once corrections derived from a comparison of actual and predicted tide levels for at least one station in the bay were applied.

An advantage of our GPS survey data is that it has currentness that is not significantly affected by substrate buildup, erosion, or other events that may have historically changed the terrain in Willapa Bay and can be conducted in a few days of good weather.

An alternative method, the use of orthophotography products to obtain water line data at specific times, would in all likelihood be useful as well, but this is a much less flexible process. Currentness issues may crop up because deliveries are often delayed by at least one year due to labor-intensive processing. In addition, orthophoto flights are very expensive and it is not practical to have such a flight done specifically for this purpose. Thus, in the case of Willapa Bay, one would have to wait for the next cycle of the current three-year cycle in which flights are performed.

GPS Survey

We performed two GPS surveys, one in September 2003 and another in May 2004, giving a total of 140 “water line validation points” with which to work. Criteria used in the GPS Survey were as follows.

1. The surface surrounding any GPS point was free of features and relatively smooth. This ensured that co-registration error between the LiDAR derived MLLW referenced elevation model and a GPS point was obviated. Elevations of nearby features, if not excluded, could be accidentally sampled, introducing false errors.

2. No point was in a Spartina-infested area. Biomechanical changes to the substrate caused by Spartina nearby capturing sediment can change the actual elevation in that location by a foot or more in some instances. The LiDAR data was from the spring of 2002, and any intervening and erosional changes need to be obviated as much as possible.

3. The water’s edge was fairly well defined and easy to see, to prevent problems posed by capturing shallow, isolated water pools standing on level tide flats. This condition ensured that at the least, a very small slope exists.

4. Every point was in an area that fit the above three criteria for at least twenty feet in every direction. This eliminated sharp changes in elevations, which would cause amplification of any co-registration error and introduce resolution error.

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9 Need reference about substrate build-up.
5. GPS equipment had an accuracy of 3 feet or better. Our Trimble ProXR® GPS met this criterion.

6. The time was recorded to an accuracy of 1 minute or better. Our Trimble ProXR® GPS met this criterion.

7. Temporary erosional features such as small drainage sloughs were not nearby. Criterion 7 is similar to Criterion 2 in that time-sensitive erosional changes are addressed.

Historical Tide Data

Historical tide data is critical for implementing validation efforts and applying resulting corrections to the MLLW-referenced terrain model.

Only one station – Toke Point Water Level Tide Station (WLTS) – has such historical tide data within the needed time span and at desired time intervals. It is noteworthy that this station not only provides preliminary\(^{10}\) and verified actual A1 (acoustic) water level data in six-minute intervals, it also provides predictive water level data for those same intervals. The key is that there is a “residual” difference between the actual and predicted values for any particular date and time. This residual was applied as a global correction to all other sites’ predicted tide levels, allowing us to “work backwards” from the predicted tide levels to derive an approximation of what would have been the actual tide levels at that date and time for each of the other twenty-three stations.

Water Surface Modeling

To be clear, queries on the MLLW referenced elevation model using GPS points are not time sensitive. The queries on the water surfaces are, since a point taken at 0854 on 10/23, for example, must query a water surface that matches what the actual water surface should be like on that day and time. This means a longitudinal (time-series) set of “snapshots” of the water at each six-minute interval in the time span(s) GPS points were collected must be created.

Because the residual values from Toke Point change over time, we created a table in which each 6-minute interval in the span of time in which the GPS points were collected had a corresponding residual value. We accomplished this by determining the difference between the A1 and predicted water levels at Toke Point for each appropriate interval.

The second step was to create a spreadsheet in which each tide prediction station had a record. A field for each six-minute interval was added and populated by querying that station in T&C for the tide level at that same interval. The table containing the residuals from Toke Point data was then applied (this number can be either negative or positive) to each station’s data for the appropriate interval and a corrected “actual” value was then derived for that same interval. We created a set of mass points by joining this spreadsheet containing these “actual” tide levels for each time interval to the records for the twenty-four tide station points.

Next, we used an automated process to interpolate grids for each time interval of interest. With these simulated “snapshots” of the water surfaces for each GPS point at the time it was shot now available, all data needed to evaluate for error was at hand: The GPS points with time stamps, the longitudinal series of snapshots of the water surface corresponding to the same time stamps, and the MLLW referenced terrain model.

\(^{10}\) Data from this station typically takes about a month or two to be checked and verified. Usually, there is little difference between the verified and unverified data and due to currentness issues we must use what is available at the time rather than attempt to be rigorous about the quality of the data.
Comparing Terrain and Water Surfaces

To complete the process, the appropriate surfaces within the longitudinal set were then queried with their corresponding GPS points to obtain a water level at the time that point was shot. An Avenue script was written to automate this very repetitive query process. Three fields were added to the GPS point dataset: one for the query on the surface “snapshot”, one for the query on the MLLW referenced terrain model, and one for the difference between the two. This last field stores the error value needed to complete the correction process.

The script then populated the two fields for each GPS point as it proceeded from one point to the next. Then, the differences between the two columns (holding the values from queries on the MLLW referenced elevation model and the appropriate water surface respectively) were then used to populate the error field.

Generating a Correction Surface

In order to improve the existing MLLW referenced terrain model, a correction surface interpolated from the error points was be applied to the model by summing them together. This created a second-generation terrain model with more reliable values. This was accomplished by using the GPS points, now with error values, as mass points to interpolate a grid using the default IDW interpolation method provided in ESRI ArcView® Spatial Analyst® extension.

Determining the Effectiveness of Corrections

We did visual a comparison of an xy scatter plot obtained by plotting the original errors to another scatter plot of errors after the correction (See Figure 9). We obtained the new set of errors by querying on the corrected grid and comparing these values to the ones we already obtained from the same set of water surface “snapshots”.

These “error clouds” on the xy scatter plots in Figure 9 are not true error clouds in that the x-axis values are the same for both: this axis is the elevation value obtained by querying each point’s corresponding water surface. This value does not change. The errors for both are plotted on the y-axis and vary as the underlying elevation model is “above”, “below” or “at” the water level represented by the water surface.

These “error clouds” help to give some sort of qualitative picture of any bias and the magnitude of that bias. This could be done by determining the proximity of the mean vectors of the “before” and “after” clouds to the origin. The size of the cloud is also a clue as to the nature of the error. Ideally, the mean vector of the “after” cloud should be located at the origin and the cloud should collapse in the vertical direction to a line of points along the x-axis. Such ideal conditions represent the best possible outcome of any validation process. These conditions are not expected to be achievable.
Figure 9 shows two error clouds for 2003 validation, the original, which had a majority of errors ranging from –0.5 feet to –3 feet, and the queries on the revised grid, whose errors ranged from +1 foot to –1 foot. This “flattening” reflects the effectiveness in correction by demonstrating a reduction in error distribution width. The mean error was –1.343 feet for queries on the original grid and –0.102 feet for the queries on the revised grid, bringing this mean much closer to the ideal of being distributed equally about 0 feet.

Another way of visualizing the results of the validation is to map the GPS points using graduated symbols on the absolute value of the error at each point. Though the direction (sign) of the error is important, this provides another way of visualizing the effectiveness of the applied corrections.
Map 2: Example of 2003 validation results displayed on a map.
The symbols are 2 part symbols. The central point is color coded to show the absolute value of the original error, and the outer, using the same color symbology, shows the absolute value of the error after correction was applied.

Note the missing points in the south and west side of Willapa Bay. These points were reshot in 2004 to complete coverage of the bay.
Sources


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