Lummi Intertidal Baseline Inventory

Appendix H:
GIS Analysis

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Executive Summary

Environmental gradients such as tidal elevation, salinity, wave energy, and substrates help determine community structure and taxonomic abundance. To quantify these gradients, Geographic Information System (GIS) software was used to spatially analyze data obtained from the 2008 LiDAR flight (Appendix G), the Intertidal Biota Inventory (Appendix A), the Finfish Survey (Appendix C), and the Lummi Water Resources Division Water Quality Database. Data layers were developed that represent beach elevations, low-salinity values, average wind-fetch distances, beach slopes, and the average particle sizes of substrates.

In this appendix, the methods used to construct the data layers are presented along with the resulting maps. The results are discussed for each layer. The data layers created were used as inputs for the statistical analysis of community characteristic results from the Intertidal Biota Survey (Appendix I).

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1.0 Introduction

Vertical elevation, wave exposure, particle size, and salinity are identified as four major environmental gradients that determine biological patterns and ecological processes in intertidal zones (Raffaelli and Hawkins 1996). A number of spatial analyses were undertaken to quantify these environmental gradients so that their effects on individual taxa and community structure for benthic communities on the Lummi Reservation tidelands could be investigated. These analyses produced GIS data layers that represent beach elevation, salinity, beach slope, wind fetch distance, and substrate particle size. The output layers created by this analysis were used as inputs to the ecological analysis of benthic communities (Appendix I) and for population analysis of individual taxa (Appendix A). This appendix details the methods used to create each of these GIS data layers. The final data layers are provided on the LIBI DVD, and further discussed in Appendix K.

2.0 Beach Elevation Mapping

2.1 Introduction

Vertical elevation is identified as one of four major environmental gradients that determine biological patterns and ecological processes in intertidal zones (Raffaelli and Hawkins 1996).

Beach elevation combined with tidal amplitude determines the length of time that organisms are exposed as the tide recedes. Aquatic organisms near the top of the beach spend most of their time exposed to the air and consequently endure prolonged periods of desiccation and temperature extremes during the low tides of the summer and winter. By contrast, organisms situated near the subtidal fringe are seldom exposed to air and are therefore less likely to risk desiccation or extreme temperatures.

Beach elevation can be challenging to accurately measure using traditional field survey methods, especially across large bays and deltas with subtle elevation gradients. This section describes the methods used to map beach elevations of the Lummi Indian Reservation (Reservation) relative to a local tidal datum based on remote sensing results.

2.2 Methods

Measuring beach elevations over several thousand acres of tideland required Light Detection and Ranging (LiDAR) acquisition from an aircraft. The Lummi Natural Resources Department (LNR) had previously obtained LiDAR elevation data for the Reservation uplands. These data were collected during high tide in Portage Bay and the only tideland elevation data obtained were for the upper part of the tidelands in Lummi Bay (Terrapoint USA Inc. 2005). This meant that the existing elevation data were not suitable for this analysis. In order to obtain LiDAR-derived elevation data for the tidelands, LNR contracted with Watershed Sciences (257B SW Madison St, Corvallis, Oregon 97333) to conduct LiDAR remote sensing flights over the Reservation tidelands during two low tides on the lowest low-tide series of the summer in 2008. These flights were conducted on July 2, 2008 and July 5, 2008 during –3.0 feet Mean Lower Low Water (ft MLLW) and –2.3 ft MLLW tides, respectively.

As shown in Appendix G, the resulting data from the 2008 flights was provided as a 3-ft resolution digital elevation model (Watershed Sciences Inc. 2009), which referenced beach elevation in feet relative to the North American Vertical Datum 1988 (NAVD88). The 2008 data were merged with the existing 2005 (Terrapoint) LiDAR dataset, which also uses the NAVD88 datum, by using the ArcGIS 9.3 Mosaic Raster tool with areas of overlap. Wherever there was overlap between the two datasets, the higher quality 2008 data were retained.

The NAVD88 datum is a hypothetical ellipsoid surface, which corresponds roughly to mean sea level on a global scale, but on a local scale, it can diverge from the local tidal datum by a small amount depending on location. The digital elevation model obtained through this study was converted from the NAVD88 datum to the local Mean Lower Low Water (MLLW) tidal datum, which reflects the local conditions accurately.

To achieve this, we determined the vertical difference between the two datums and subtracted this value from the NAVD88 elevation value in each cell, because the NAVD88 ellipsoid surface differs from MLLW by a different amount from site to site. The National Geodetic Survey (NGS) (a division of the National Oceanographic and Atmospheric Administration [NOAA]) has created a software utility called VDatum that determines the difference between NAVD88 and a specified local tidal datum, such as MLLW. To make best use of this tool, a regular grid of points was created first using the Generate Regular Points tool in the Hawth’s Analysis Tools v.3.17 software extension in ESRI Arc GIS 9.3. This point layer covered the full vertical and horizontal extent of the Reservation tidelands with points spaced approximately 0.2 miles apart.

The spatial coordinates of each data point were exported along with an NAVD88 elevation value of 0 ft. The exported data were then batch-processed by the VDatum software, which calculated the difference between the two vertical datums (datum shift) at each point. The location and datum shift for each point was imported back into ArcMAP, and the Spatial Analyst extension in ESRI Arc GIS 9.3 was used to create a 3-ft resolution raster dataset using simple linear interpolation between the points (Figure H.1). The datum shift layer was then used with the Raster Calculator tool of the Spatial Analyst software extension to convert the digital elevation model values from NAVD88 to the MLLW tidal datum (Figure H.2).

The elevation data created by this process were then extracted for each of the sample locations from the Intertidal Biota Survey. This was accomplished using the Surface Spot tool in the 3D Analyst Tools software extension to obtain the specific elevation values at each site, which were then exported in dbf format so that the data could subsequently be imported into the ‘DigSurvey.mdb’ Microsoft Access database for further statistical analysis.

2.3 Results

Figure H.1 shows the vertical difference between the NAVD88 datum and the MLLW tidal datum (datum shift) across the Reservation tidelands. Figure H.2 shows the final digital elevation model of the tideland elevations relative to the MLLW tidal datum.

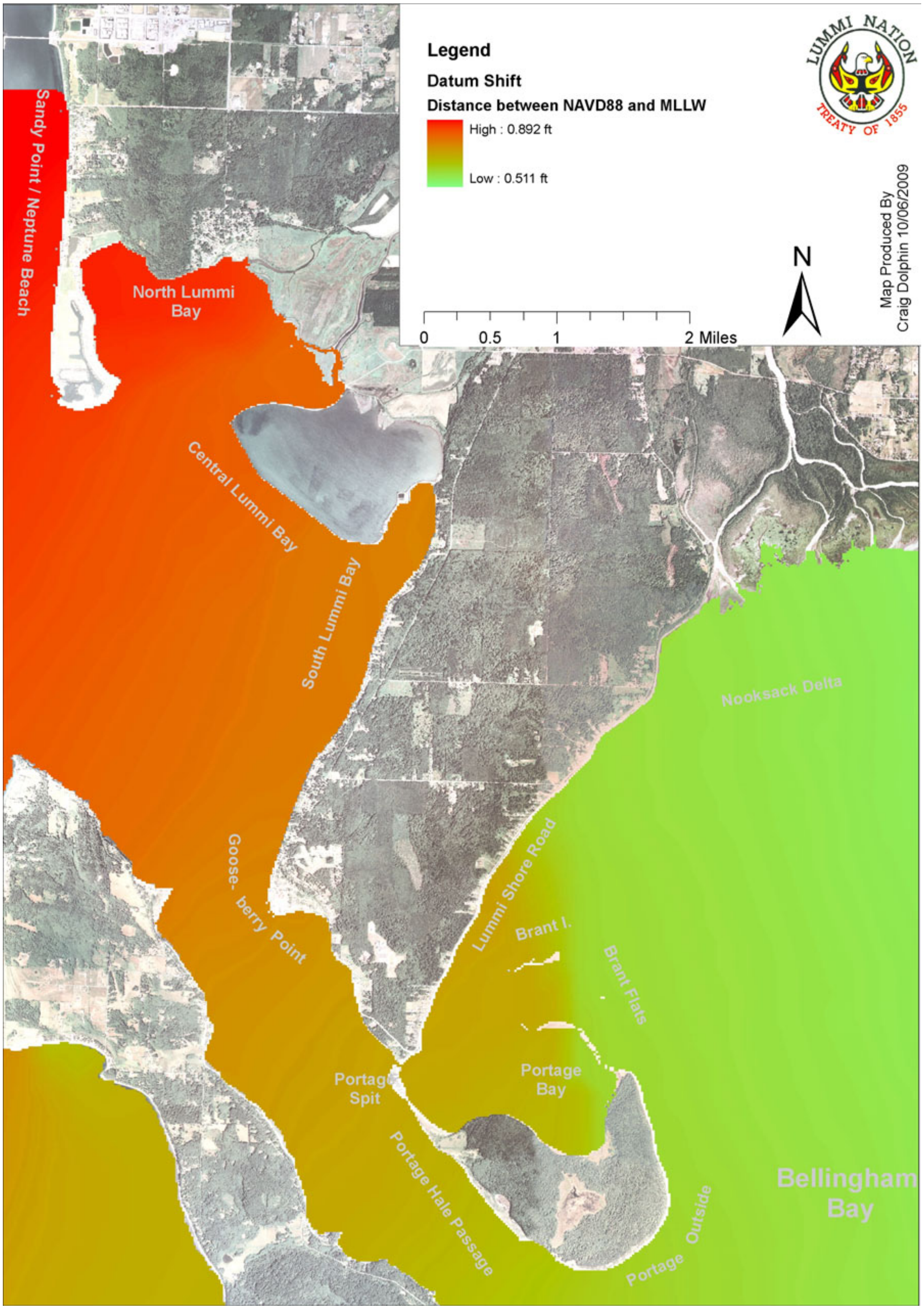

Figure H.1. Datum Shift Between NAVD88 and Local MLLW

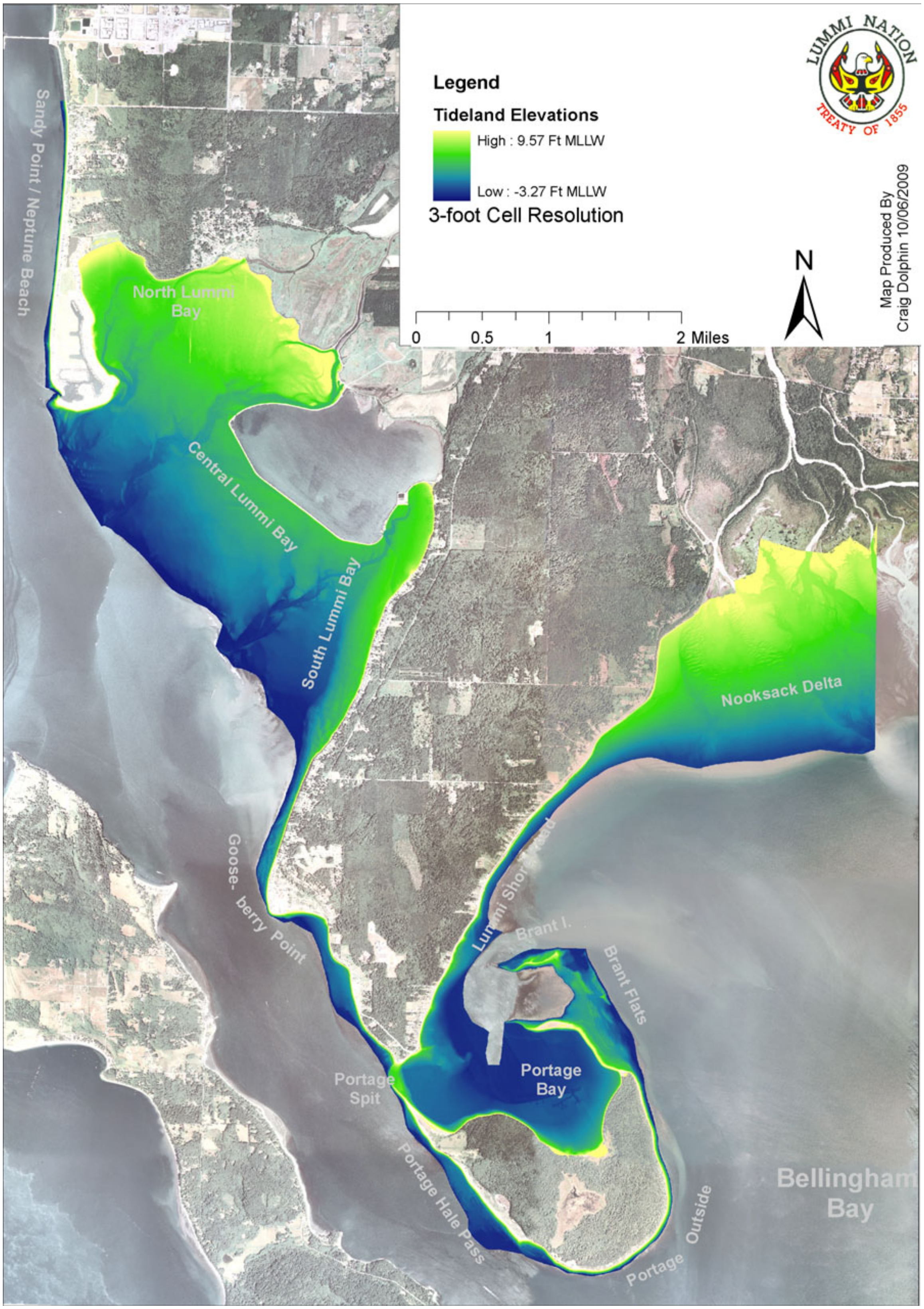

Figure H.2. Tideland Elevations Based on 2005 and 2008 LiDAR Data

2.4 Discussion

Beach elevation data have historically been collected using cadastral survey techniques along shore-perpendicular transects. Such methods are typically very accurate and precise but the number of points that can be surveyed is extremely limited. Remote sensing offers the ability to sample virtually all of the tidelands equally, albeit sometimes with slightly less precision than traditional techniques.

Although LiDAR is a relatively new technology, it has been successfully used to map upland elevations for many years. By contrast, the application of LiDAR technology to mapping intertidal areas is a much more recent approach and there are few local examples. One such example is a 10-ft cell resolution digital elevation model for Willapa Bay that was created from LiDAR data (NOAA CSC 2003), but the elevation values of these data are reported relative to NAVD88 only.

During the LIBI, some of the issues known to exist for terrestrial LiDAR usage were also found to be true for intertidal work. For example, terrestrial LiDAR flights are usually conducted during wintertime or early spring prior to the emergence of leaves on deciduous trees. This prevents the leaves on the trees from attenuating the LiDAR signal and degrading the quality of the results. Although there are no trees on the Reservation tidelands, a similar issue was found to exist with Pacific eelgrass (*Zostera marina*). The blades of dense eelgrass meadows can float on the surface of standing water, and this was found to prevent the detection of the true ground elevation in some areas, particularly in low elevations in Lummi Bay. More accurate results for areas with dense eelgrass and standing water could be acquired during a mid-winter low tide series since eelgrass senesces during the fall and winter. However, the likelihood of achieving a suitable weather window to conduct a LiDAR survey at night during winter seems low. In the Puget Sound region, extreme low water tides occur in summer through the day and in winter through the night.

Using remote sensing to survey tidelands does add one new issue that does not apply to upland surveys and should be considered carefully. If the elevation data are to be used to analyze the biology of the tidelands, then the data should be reported relative to a local tidal datum (e.g., MLLW) instead of using a theoretical vertical datum (e.g., NAVD88) that has no direct biological relevance at a local scale. The LIBI data were successfully transformed from NAVD88 to MLLW with the support of the VDatum software. This is possibly the first instance where intertidal elevations derived from LiDAR have been explicitly converted to a biologically meaningful vertical datum.

3.0 Nearshore Salinity Mapping

3.1 Introduction

Salinity is identified as one of four major environmental gradients that determine biological patterns and ecological processes in intertidal zones (Raffaelli and Hawkins 1996).

Salinities in Puget Sound and the Strait of Georgia are widely variable depending on proximity to rivers, ground water seeps, prevailing currents, wind direction, and river flows. Organisms in the Strait of Georgia and Puget Sound area exhibit different tolerances to variations in salinity. Euryhaline species (e.g., purple varnish clams, Pacific herring, Pacific salmon) can adapt to a wide range of salinities for prolonged periods of time. By contrast, stenohaline species (e.g., butter clams, horse clams) are generally restricted to a much narrower range of salinities. Despite this, some stenohaline species do have adaptive strategies that allow them to tolerate, or avoid, low-salinity events of short or moderate duration. For example, mobile species can temporarily or seasonally move down the shore into deeper and higher-salinity water. Sessile marine organisms such as clams and barnacles can simply close their shells for several hours at a time to avoid contacting low salinity water until the rising tide immerses them in higher salinity water.

To determine whether spatial trends in salinity could help explain patterns in community assemblages found in the Intertidal Biota Survey, surface salinity data were collected during fieldwork for the Intertidal Finfish survey (Appendix C). This section details the methods used to objectively determine minimum salinity values across the Lummi Reservation tidelands.

3.2 Methods

To assess salinity gradients across the Lummi Reservation tidelands, surface water salinity data were obtained from two primary sources. First, surface salinity data collected by the Lummi Water Resources Division (LWRD) (LWRD 2008) were obtained from the Lummi Water Quality Database. This provided surface salinity data for 38 marine water sites around the Reservation. The marine water sites were periodically sampled and ranged from Sandy Point to Portage Bay. The period of record for the combined sites was July 1993 through September 2009. Additional data sources were the surface salinity measurements collected during the monthly LIBI finfish survey (Appendix C). The Finfish Survey provided data for 16 additional sites for the time period between June 2008 and September 2009.

Information with comparable time series data on surface salinities at the Nooksack River delta itself was not available. Surface salinities at this location were expected to have significantly lower salinities due to the freshwater outflow from the Nooksack River itself. The only data available for the area was a LWRD survey along Kwina Slough documenting the extent of the saltwater wedge extending upstream into the lower river.

Surface salinities during high tide with a low river flow were close to zero (0.6 parts per thousand). This represents the most likely circumstance for elevated surface salinities because the tide was high and river flows were very low during the LWRD survey. It was assumed, therefore, that periods of high river discharge, coincident with strong SSE wind, could result in the formation of a freshwater lens across the delta. Accordingly, four points were added at the vegetation line of the delta, where the primary Nooksack River distributary channels emerge. Each of these points was assigned an estimated low surface salinity of 0 ppt.

Surface salinities across the Reservation tidelands are highly variable over time, and periods of low salinity are likely to be transient. To represent the potential for low salinities to impact organisms on the tidelands, the lower 95% confidence limit of the mean salinity was selected as the most suitable metric for our analysis. This choice excludes unusually low outlier values, but still represents the lower end of the range of salinities that were measured at each site.

The selected surface salinity sites were combined into a single point-shapefile data layer in ESRI ArcGIS 9.3 software and then spatially interpolated with the Spatial Analyst software extension using linear interpolation of the three nearest points. This resulted in a raster dataset with a cell or grid resolution of 90 ft with values that represent the interpolated low-salinity measurement.

The data values from the this process were then extracted for each Intertidal Biota Survey location using the Surface Spot tool in the 3D Analyst Tools software extension, and exported in dbf format so that the data could then be imported into the DigSurvey.mdb Access database for further statistical analysis.

3.3 Results

Figure H.3 shows the lower 95% confidence limits that were calculated for each location with water quality data and the final salinity data layer that was interpolated from these values.

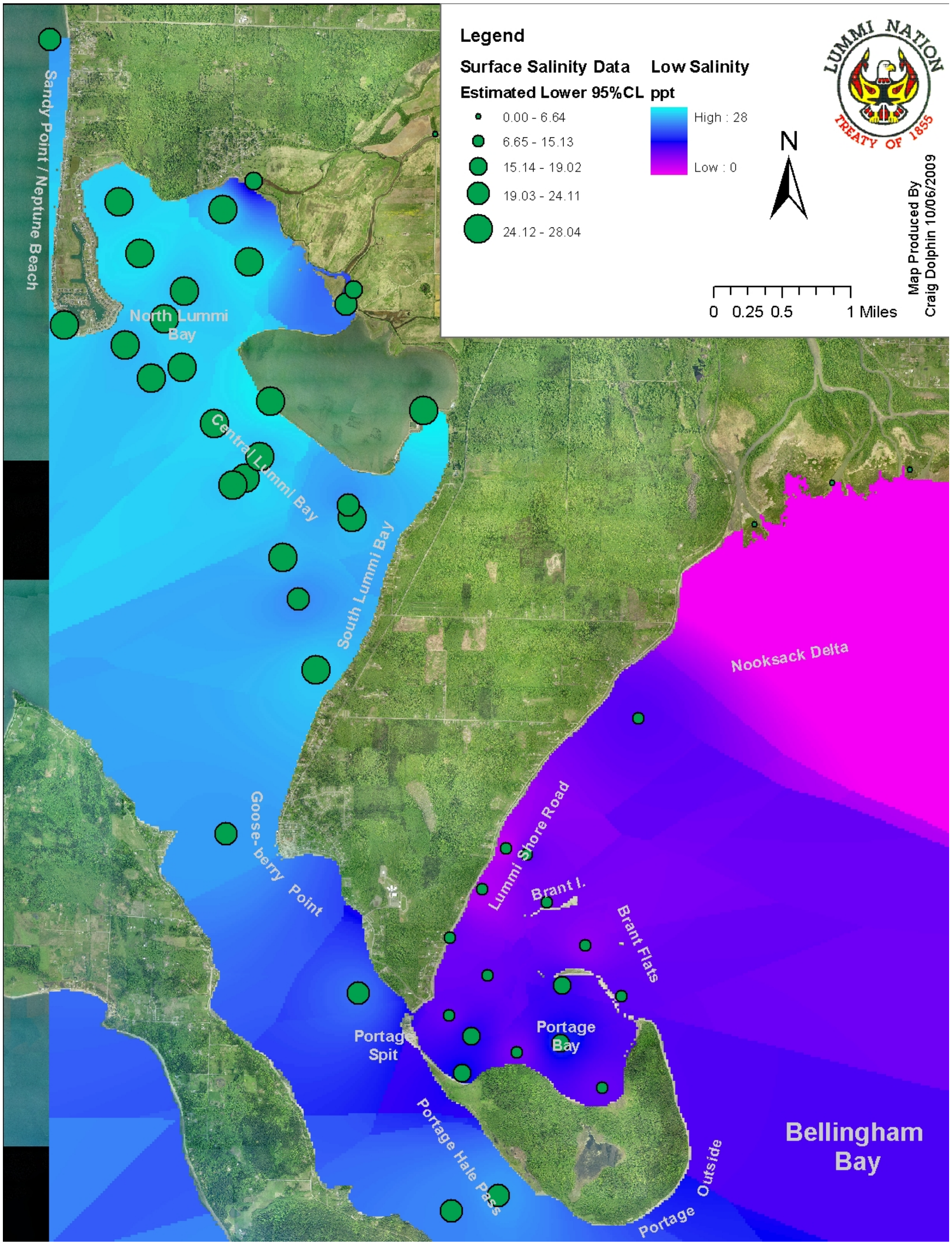

Figure H.3. Lower 95% Confidence Limit of Surface Salinities and the Low-Salinity Data Layer Generated Using 3-Point Linear Interpolation

3.4 Discussion

Lummi Bay and Neptune Beach/Sandy Point were found to have consistently high salinities, as did most of Hale Passage with the exception of a location adjacent to Portage Spit. This small area may periodically experience reduced salinities due to low salinity water spilling over Portage Spit from Portage Bay during high tide.

The lower 95% confidence limits of surface salinities were particularly low on the Nooksack River delta. The data also suggest that surface salinities are periodically reduced along Lummi Shore Road and into Portage Bay, probably during periods of high Nooksack River discharge.

4.0 Beach Slope Analysis

4.1 Introduction

Wave exposure is one of four major environmental gradients that determine biological patterns and ecological processes in intertidal zones (Raffaelli and Hawkins 1996). Wave exposure was not directly measured during the LIBI; related characteristics such as beach slope and wind fetch were analyzed instead. Wind fetch is considered separately in Section 5.0.

Beach slope determines how wave energy is dissipated across the shore, and conversely, wave energy can shape the profile/slope of a beach over time (Short and White 1983). Steep slopes dissipate wave energy over shorter distances than gradual slopes, and changes to the slope of a beach can alter the pattern of sediment deposition and suspension on that beach. This can also alter the amount of physical turbulence experienced by epibenthic organisms by exacerbating or ameliorating exposure to high-energy waves. The amount of turbulence experienced can affect epibenthic community structure (McLaughlan 1996).

A beach slope analysis can also be used to visualize and quantify areas of the tidelands that remain covered by standing water during low tide. Although field measures of water depth were taken at each site during the Intertidal Biota Survey, the depth of standing water can vary considerably over very small spatial scales. Because the sampling density obtained using the LiDAR was much higher than the sample density of the Intertidal Biota Survey, the slope analysis of the LiDAR data was preferred for identifying areas of the tidelands that remained covered by standing water during low tide.

To examine the effects of beach slope on benthic community richness and abundance and to identify areas with standing water, a beach slope analysis was conducted on the LiDAR elevation data.

4.2 Methods

To estimate beach slope, ESRI ArcMap 9.3 software was used to average tidal elevations from the 3-ft grid resolution tideland elevation layer (Section 2.0) to a coarser 30-ft grid resolution. The purpose of this step was to generalize any small-scale variation that could create localized slope artifacts. Such variation might arise from sampling error, small-scale surface features such as floating rafts of drift macroalgae, boulders, debris, or wind-driven waves. This grid size is commonly used for representing landscapes in GIS data layers because is represents a reasonable compromise between resolution and data volume (Zhang and Montgomery, 1994). The 30-ft grid data layer was then analyzed with the Slope Surface Analysis tool in the ESRI Spatial Analyst software extension. This tool determines the average slope of each cell by comparing the difference in elevation between that cell and the surrounding cells in the input elevation layer and converting the elevation difference into degrees of slope (Figure H.4)

The slope data values from the this process were then extracted for each Intertidal Biota Survey location using the Surface Spot tool in the 3D Analyst Tools software extension and exported in dbf format so that the data could then be imported into the DigSurvey.mdb Access database for further statistical analysis.

4.3 Results

Figure H.4 shows the beach slope data layer. Locations colored in blue have a slope that is very flat and generally correspond well with places where standing water is present (Dolphin, personal observation). Green indicates beaches that are generally flat, yellow and orange colors indicate moderate slopes, and red indicate the steepest slopes.

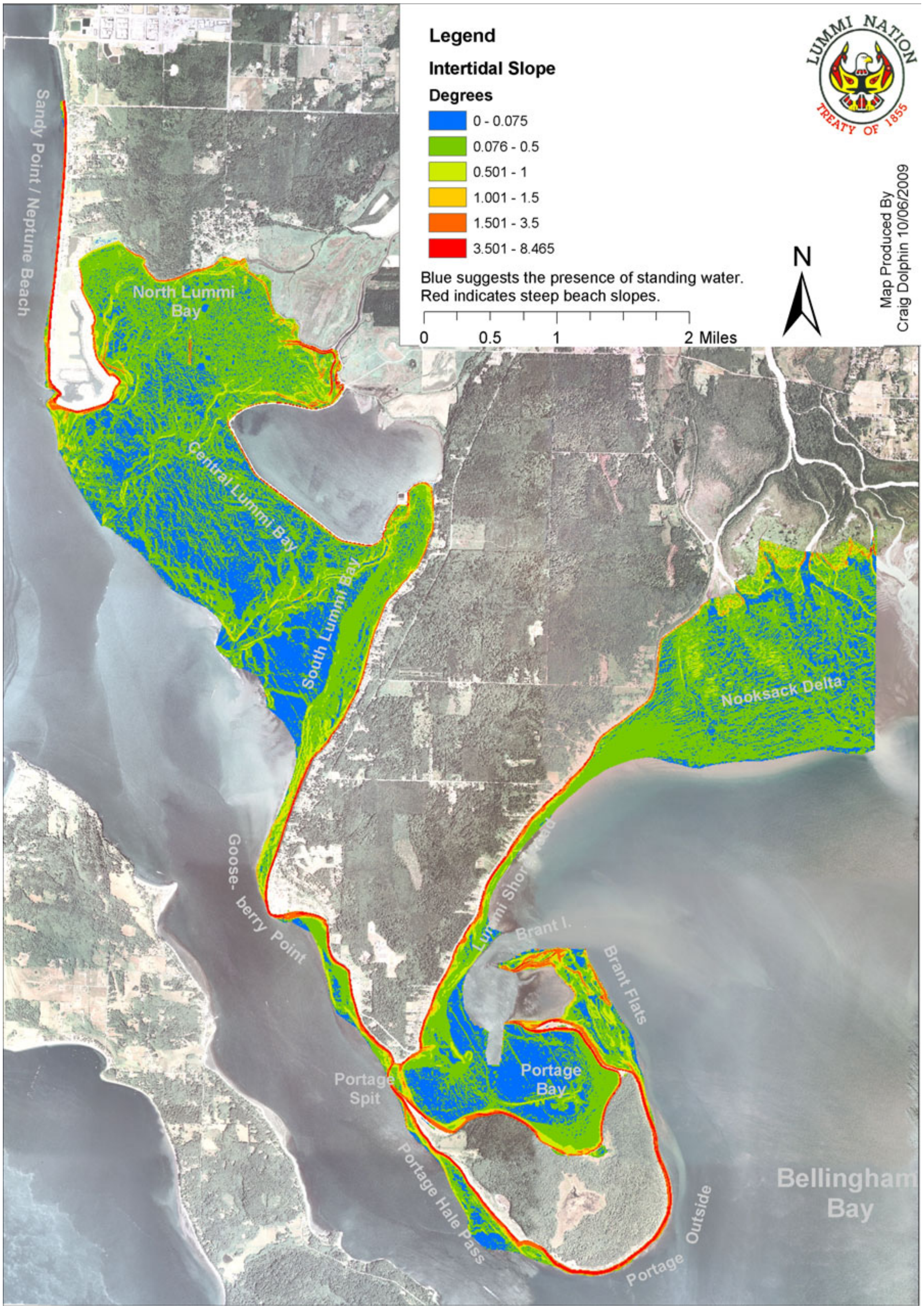

Figure H.4. Beach Slope Calculated from LiDAR Data

4.4 Discussion

Beach slopes and profiles varied across the Reservation tidelands. Neptune Beach and the beaches on the outside of Portage Island near Point Francis were uniformly steep and relatively narrow in width.

The beach profile surrounding the Lummi Peninsula, Portage Island, and the inside of Sandy Point can be characterized as having a relatively narrow band of steep slopes in the upper intertidal zone but a much wider extent of flat ground at the lower intertidal elevations.

The Nooksack River delta and the remainder of Lummi Bay showed relatively uniform flat gradients with particularly large areas of standing water present in the lower elevations of Lummi Bay.

Brant Flats and Brant Island have a heterogeneous mixture of slopes due to the presence of multiple bars and swales throughout the area.

Standing water is an important characteristic that may directly influence community structure at sites. For example, tide pools on rocky shore habitats often contain specialized fauna and flora that are different from those found on the surrounding rocky platforms during low tide. The presence of standing water on soft-sediment tidelands may also offer many of the same environmental benefits to organisms in those habitats. For example, aquatic organisms located in tide pools benefit from a reduced risk of desiccation during low tide and from thermal buffering during extreme air temperatures.

The data shown in Figure H.4 indicates that there are significant quantities of standing water on Lummi Reservation tidelands. The largest of these are very large intertidal ‘pools’ at lower elevations in Lummi Bay. These pools are bounded to the seaward by sand bars that form barrier structures and retain the water. In places, channels penetrate through these sand bars and allow the pools to drain slowly but never completely before the tide returns. These areas are usually densely vegetated with Pacific eelgrass (*Zostera marina)* and *Ulva*, and are usually less than 2 or 3 feet deep during low tide. There are also similar, albeit much smaller, channels and pools found on Brant Flats and along Hale Passage that are likewise bordered by discrete bars of sand.

The large areas of standing water in Portage Bay are generally shallow, subtidal environments rather than intertidal pools. Despite this, across much of the area they seem to have similar water depths and dense vegetation, and probably provide highly similar ecological niches.

5.0 Wind Fetch Distances

5.1 Introduction

Wave exposure is one of four major environmental gradients that determine biological patterns and ecological processes in intertidal zones (Raffaelli and Hawkins 1996). The LIBI did not directly measure wave exposure but instead measured related characteristics such as beach slope and wind fetch. Beach slope is considered separately in Section 4.0.

The degree of wave exposure that can potentially impact a beach can have important effects on the biological community (Dayton 1971). In enclosed marine bodies that are protected from oceanic swells, like the Strait of Georgia and Puget Sound, wind is the primary driver of wave energy. According to Rohweder *et al*. (2008):

> *"Wind fetch is defined as the unobstructed distance that wind can travel over water in a constant direction. Fetch is an important characteristic of open water because longer fetch can result in larger wind-generated waves. The larger waves, in turn, can increase shoreline erosion and sediment resuspension".*

This section details the methods used to obtain the average wind fetch values across the Lummi Reservation tidelands.

5.2 Methods

The unobstructed distance that wind can travel over water at any site (wind fetch) varies with both location and wind direction. Because the Lummi tidelands are exposed to varying degrees to wind from different directions, and wind vectors also vary with time, it would be unrealistic to use just one wind direction to determine the wind fetch distance. Moreover, if the wind typically blows more powerfully from one direction than others, more wave energy may be generated from that direction over time than would be expected based solely on fetch distance. In addition, if the wind blows most frequently from one particular direction, the cumulative impact of wave energy on beaches exposed to that direction might be greater than on beaches facing wind vectors that result in wave action only infrequently.

To integrate all these variables into one parameter, the estimated wind fetch distance was calculated for each of 16 different wind directions (N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, NNW) using a GIS-based Wind Fetch Analysis Tool that implements the recommended procedures of the Shore Protection Manual (USACE 1984) to calculate effective fetch. This tool was originally created by David Finlayson (U. S. Geological Survey, Pacific Science Center) and later modified and updated by Rohweder *et al*. (2008).

Hourly wind strength and direction data were obtained online from NOAA's Center for Operational Oceanographic Products and Services for weather station 9449424 at Cherry

Point. The data used covered the time period from 12/7/2007 through to 9/23/2009. The wind bearing values were modified to round to the nearest of the 16 vectors considered in this analysis, and the data were summarized to determine the proportion of time that wind was blowing from each of the 16 vectors during the total time period being considered, and also to determine the maximum wind strength observed from each vector (Figure H.5).

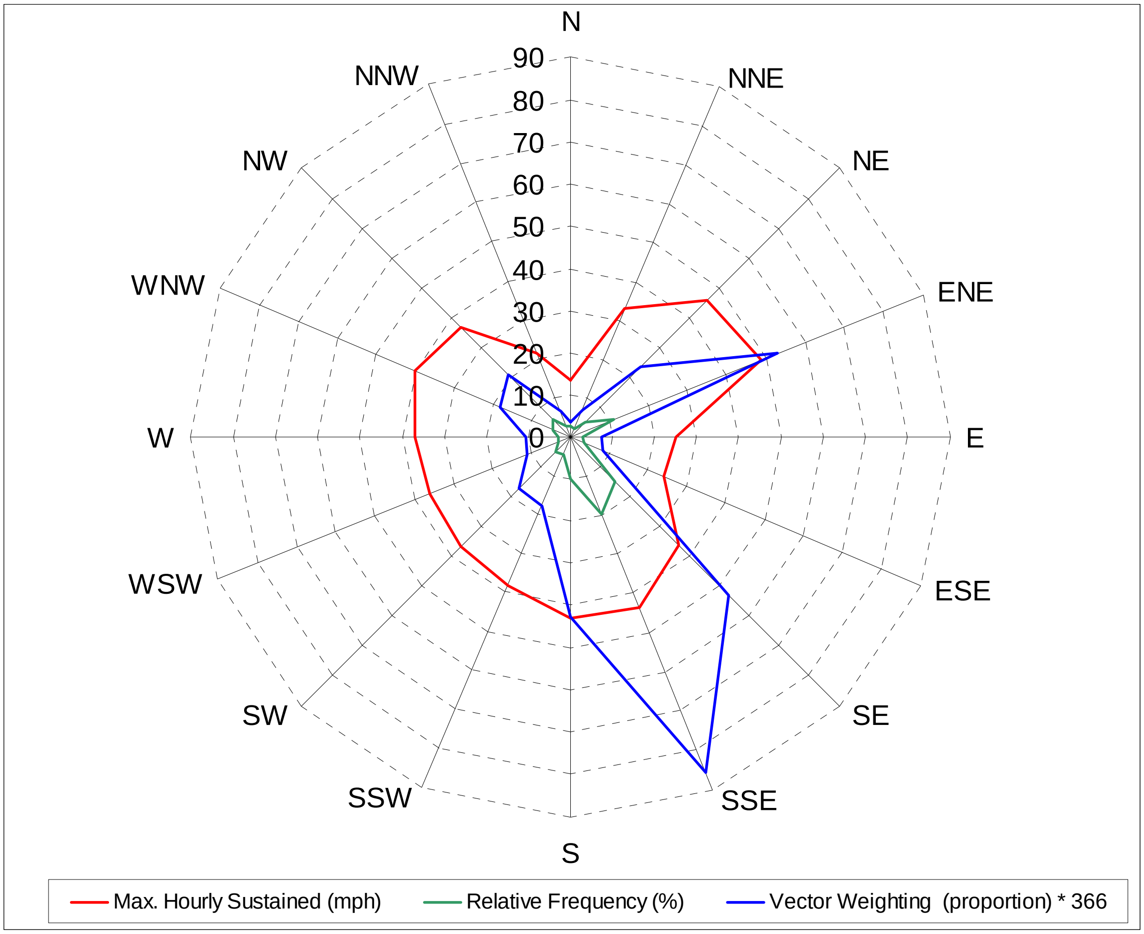

Figure H.5. Wind Vector Diagram for Cherry Point

The 16 wind fetch distance layers created by the fetch tool analysis were then averaged using the Spatial Analyst's Raster Calculator tool (ArcMap 9.3). This average integrated a proportional weighting for each layer that was the product of the proportion of time that the wind was blowing from that vector and the maximum-recorded wind strength from that vector. The GIS data layer produced by the Raster Calculator tool indicated the average wind fetch distance in feet.

5.3 Results

The average wind fetch distance that was calculated is shown in Figure H.6. As expected, the protected upper elevation areas of Lummi Bay and the majority of Portage Bay had relatively low average wind fetch distances. The largest average wind fetch distances were at Neptune Beach, and moderately large average wind fetch distances were also calculated for the Nooksack River delta and the Point Francis area.

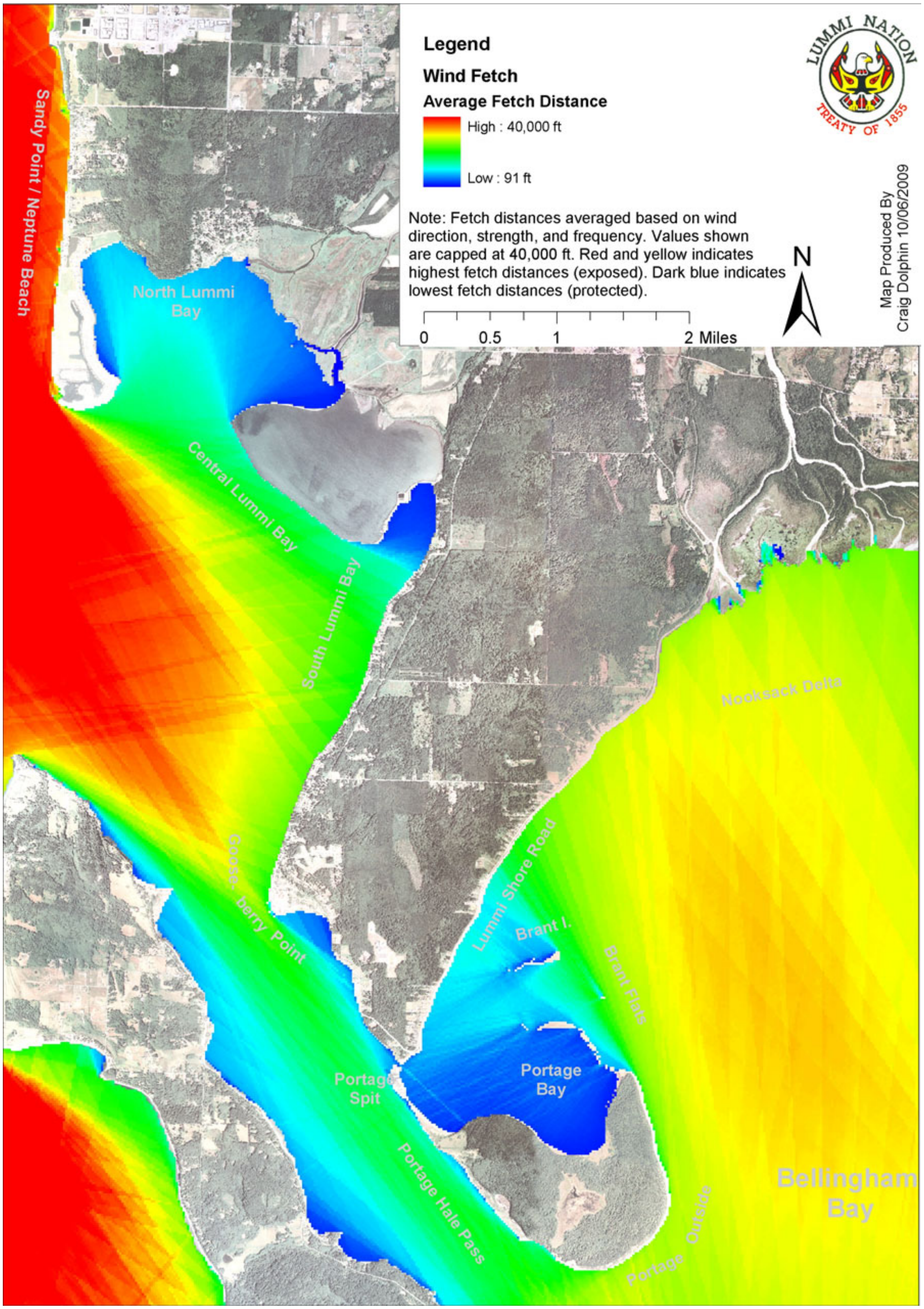

Figure H.6. Average Wind Fetch Distance Based on 16 Wind Vectors Weighted by Wind Direction Frequency and Strength

5.4 Discussion

Neptune Beach had the highest average wind fetch while the outer portions of Lummi Bay, the outside of Portage Island, and the Nooksack River delta were also relatively exposed. Hale Passage, Gooseberry Point, and sections of Lummi Shore Road had intermediate wind fetch values. The most sheltered areas of the Reservation tidelands were found to be in Portage Bay and the upper parts of Lummi Bay that were sheltered by Sandy Point or the Lummi Seapond.

It is noted that the average wind fetch model may not provide a perfect substitute for wave energy in some locations. For example, on the western side of the Lummi Peninsula near Gooseberry Point, the average wind fetch values close to shore are lower than those further away from shore because SSE is the dominant wind direction and the Lummi Peninsula usually affords protection when the wind is blowing in that direction. On the other hand, when the wind is blowing from the northwest the unobstructed fetch is considerably larger, and the wave energy reaching that beach is potentially as large as that reaching Neptune Beach. Future studies might consider using maximum fetch models instead of an average fetch model.

6.0 Substrate Coarseness Index

6.1 Introduction

Particle size is identified as one of four major environmental gradients that determine biological patterns and ecological processes in intertidal zones (Raffaelli and Hawkins 1996).

Particle sizes of inorganic substrates are determined by long-term patterns of erosion and accretion along the shore. The resulting substrate composition can play an important role in determining which organisms are found at a site. For example, burrowing species such as clams require sediments that permit them to burrow into the ground. Soft sediments are also required by deposit-feeding invertebrates, which ingest those sediments to digest organic detritus and microbes. Sessile species such as barnacles require hard substrates to keep them anchored in place. Boulders and cobbles provide localized shelter from strong wave action, shade from the summer sun, and refuge from potential predators.

Due to logistical considerations, the particle sizes of substrates were not directly measured in the LIBI field effort. Instead percentage of cover and percentage of volume were estimated for substrates classes that were defined using size ranges after Diethier (1990). This information was integrated into a Substrate Coarseness Index (SCI). The SCI was used instead of direct measurements of average particle size. This section details the methods that were employed to derive the SCI and to map the distribution of the SCI values across the Lummi Reservation tidelands.

6.2 Methods

Substrates are challenging to quantify for analysis and for mapping purposes. It was not possible for this study to explicitly measure particle sizes because the standard method of measuring this parameter (filtering substrate through a series of graduated screens) would have been too time-consuming to conduct at the site, and transport of heavy substrate samples for later lab analysis was not an option due to the large distances to be traversed across very soft substrates.

Substrate composition can be described using visual estimates of the relative quantities of different substrates from various particle size classes (e.g., mud, sand, gravel, cobble), or using categorical descriptors such as ‘mud’, ‘mud/sand’, ‘mud/sand/gravel’, or using simple descriptors such as ‘dominant substrate’.

Visual estimates of substrate quantities can lead to differences in perceived particle size classes between observers but they do not limit the investigators to classification systems that may not cover all possible combinations (e.g., only two or three substrate combinations when four or five may be required for some sites). In addition, this approach allows any gradation in the range of results to be retained. Furthermore, the results are numerical and can be used for statistical analysis although they must be analyzed with caution because the numerical values for different size classes are interdependent. As one value increases, the other values must decrease.

To map the visual estimates of substrate quantities at one site, there are several options available. Either several maps can be produced that each show the numerical value for a single substrate class, or one map can be produced that shows overlapping, semi-transparent color-coded polygons for each type of particle size class, which can become difficult to interpret. Another option is to reinterpret the data into a categorical system with assigned codes for mapping purposes, or to create a single statistic to integrate all these values for the different substrate classes into a single metric. But this is usually more difficult to interpret visually on a map.

Categorical descriptors, like ‘gravel’ and ‘mud/sand’, have the advantage of being intuitive and easy to understand, but are difficult to analyze quantitatively. Additionally, they may fit the data less well than comparable continuous data (e.g., Lindegarth and Gamfeldt 2005). To map these kind of data also requires using arbitrary numerical codes in mapping software, which typically provide no meaningful mechanism for interpolating data points spatially. There is also no ability to redefine class definitions afterward if the original class definitions are found to be inadequate as the data are usually interpreted and classified in the field using pre-defined classes. It is also possible that a classification system intended for use at one spatial scale would be inappropriate if applied at a different spatial scale.

Simple descriptors such as ‘dominant substrate’ can become an over-simplified version of a categorical descriptor system when two or more co-dominant substrates are present. Moreover, the presence of secondary substrates may be an important factor in community assemblages. For example, sites dominated by clean gravel substrates differ markedly from sites dominated by embedded gravel substrates. Dominant substrate classifications obscure this potentially important information.

A further parameter is the spatial extent of the substrate being evaluated at a site: to what depth is substrate assessed? How large an area is being assessed?

In this study, substrates were quantified in the field using subjective estimates of percentage of cover, and percentage of volume, within the sampling cylinders used in the Intertidal Biota Survey (Appendix A) for mud, sand, gravel, cobble, and boulders. The definitions for these classes were based on particle size range definitions after Diethier (1990) and were assessed subjectively by field personnel.

A commonly used substrate assessment system for marine substrates in Washington is the system derived by Diethier (1990), which created a series of substrate classifications that included threshold percentages that need to be met for a site to belong to a given class. Table H.1 shows the classes and definitions used by Diethier.

Table H.1 Substrate Classes and Definitions Used by Diethier (1990)

Substrate Classification	Class Definition
Bedrock	75% of the surface is covered with bedrock, commonly forming bluffs and headlands.
Boulder	75% of the surface is covered by boulders (>256 mm).
Cobble	75% of the surface is covered by clasts 64 to 256 mm in diameter.
Gravel	75% of the surface is covered by clasts 4 to 64 mm on diameter.
Sand	More than 75% of the surface area consists of sand 0.06 to 4 mm in diameter.
Mud	Silt and clay comprise 75% of the surface area. Often anaerobic, with high organics content. Tends to pool water on the surface and be un-walkable.
Hardpan	75% of the surface is hardpan clay, perhaps with a thin covering of surficial mud.
Mixed Coarse	No one size comprises > 75% of the surface. Cobbles and boulders are > 6%.
Fines with Gravel	No one clast size comprises more than 75% of the surface area. Cobbles and boulders make up > 6% of the surface area; Coarse sediments combined make up < 55%. Rich with epibenthic fauna.
Mixed Fines	Fine sand, silt, and clay comprise 75% of the surface area, with no one size class being dominant. May contain gravel (<15%). Cobbles and boulders make up < 6%. Walkable.

The Diethier system uses numerical metrics to define classes using physical parameters such as particle size and percentage of cover but has many of the disadvantages already mentioned for categorical descriptors. Additionally, the system has gaps where sites may have conditions that meet none of the classes. This leaves the class allocation for such sites up to the subjective judgment of the investigator in the field and can invalidate the class definitions used.

To overcome the disadvantages of the different approaches introduced above, for this report a comprehensive system was developed to derive a single numerical index that could be used to integrate numerical data on both the percentage of area and percentage of volume, and the sizes of substrate particles at a site. The numerical index chosen is the 'average' estimated particle size found at the site. It is referred to as the Substrate Coarseness Index (SCI).

The calculation is based on the mean particle size for each of the single-substrate classes that were defined by Diethier (1990) together with the proportion of the total substrate represented by that size class. However, because Diethier did not explicitly define a lower size limit for mud particles, or an upper size limit for boulders, threshold values of 0 mm and 1,000 mm respectively were assigned. Bedrock was not included in the analysis, as it was not encountered during sampling.

It should also be noted that some substrates were encountered that are not explicitly mentioned in Diethier's system. For example, bivalve shell fragments and woody debris were encountered at some sites. For the purpose of calculating the SCI, gravel and shell categories were combined into one class. Information on wood substrates was excluded when calculating SCI scores except to correct the percentages of the remaining inorganic substrates so that each site had a total percentage of 100%.

If a site were estimated to have 55% sand, and 45% gravel, the numerical index score would be calculated as follows:

Diethier defined a particle size range of 0.06 – 4 mm for ‘Sand’ and a range of 4 – 64 mm for ‘Gravel’. To represent the particle sizes of these two size classes, the arithmetic mean of the minimum and maximum values for each class was selected (2.03 mm and 34 mm respectively)

$$\begin{aligned} \text{SCI} &= (0.55 * 2.03\text{ mm}) + (0.45 * 34\text{ mm}) \\ &= 16.4165\text{ mm} \end{aligned}$$

Because this metric correlates with a physical environmental parameter, it can be used in statistical analyses, and interpolated spatially in GIS software using simplified models of hydrological sediment sorting based on particle size. It can also be applied on any spatial scale, and be used whether using surface substrate percentages or volumetric substrate percentages.

In order to create easily understood substrate maps, the SCI metric was used to define substrate classifications based on the index value. To achieve this, combinations of one, two, or three substrate classes were defined (Table H.2). The expected SCI score resulting from each potential combination was then determined assuming that each substrate class was co-dominant. The expected SCI value formed the mid-point value of the range of possible index scores that would be included within that classification. To determine the boundaries of each class, the classes were ranked by the ascending expected SCI value, and the midpoint between the ranked scores was determined. This process resulted in the class definitions shown in Table H.2

Table H.2 Class definitions based on SCI scores

Substrate Class Combination	Mean SCI Value for Class combination	Class Min SCI Value	Class Max SCI Value
Mud	0.035	0.000	0.53
Sand Mud	1.033	0.535	1.53
Sand	2.030	1.532	7.03
Gravel Mud Sand	12.022	7.027	14.52
Mud Gravel	17.018	14.521	17.52
Sand Gravel	18.015	17.517	26.01
Gravel	34.000	26.009	44.01
Cobble Mud Sand	54.022	44.012	59.35
Cobble Gravel Mud	64.678	59.351	65.01
Cobble Gravel Sand	65.343	65.012	72.68
Cobble Mud	80.018	72.681	80.52
Cobble Sand	81.015	80.517	89.01
Cobble Gravel	97.000	89.009	128.50
Cobble	160.000	128.501	185.01
Boulder Mud Sand	210.022	185.012	215.35
Boulder Gravel Mud	220.678	215.351	221.01
Boulder Gravel Sand	221.343	221.012	242.01
Boulder Cobble Mud	262.678	242.012	263.01
Boulder Cobble Sand	263.343	263.012	268.67
Boulder Cobble Gravel	274.000	268.673	294.01
Boulder Mud	314.018	294.010	314.52
Boulder Sand	315.015	314.517	323.01
Boulder Gravel	331.000	323.009	362.50
Boulder Cobble	394.000	362.501	511.00
Boulder	628.000	511.001	629.00

6.3 Results

The SCI scores in this analysis were based on the substrate percentage-of-volume data obtained in the Intertidal Biota Survey. Based on the data shown in Table H.2, SCI scores for individual sites were calculated, classified, and then mapped using Thiessen polygons to interpolate the results (Figure H.7).

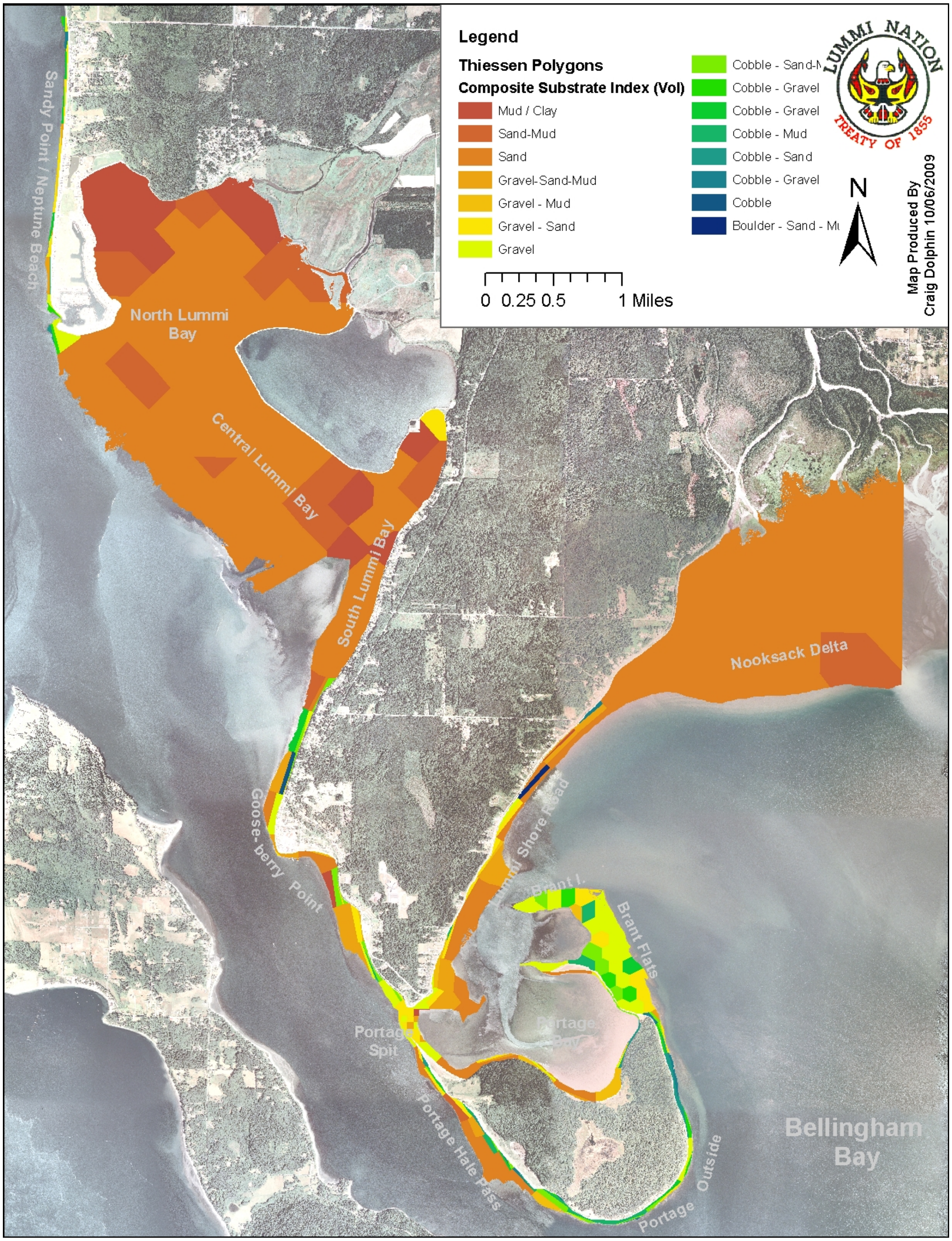

Figure H.7. Tideland Substrates Determined Using Substrate Coarseness Index Values Combined with Classifications Derived from Table H.2

6.4 Discussion

The system used in this report is analogous to the true mean particle size but cannot be accurately described as such because no particles were actually measured. As a result, the potential issues pertaining to between-observer variation remain problematic. On the other hand, the method is relatively quick and easy to apply in the field, unlike more formal screening methods. This is important for a survey that takes place in the intertidal zone where time limits are imposed on sampling by the tidal cycle.

A comparison with the personal observations of the investigators shows that the results provide a usefully accurate summary of substrates across the Reservation tidelands although a higher sampling density would be beneficial in some locations. For example, the portion of Lummi Bay near the shellfish hatchery is documented as a mixture of gravel and sand, but this is somewhat misleading because the only sample in that area happened to be relatively high on the beach margin. Although the result is accurate for the sampled location, the Thiessen polygon generated extends over an area of very soft mud. Additional sampling locations within the area would greatly improve the representation shown in Figure H.7.

The approach used takes advantage of the strengths of classification systems as well as of numerical systems by producing an easily interpretable map that is based on a numerical metric that can be used for quantitative analysis. Unlike more traditional field classification systems (e.g., Diethier 1990), the SCI values can be used to reclassify sites using a different set of class definitions whenever necessary.

The biggest weakness of the method used in this study stems from areas with silt and clay. Although the particle sizes of clay and silt are very small, in areas where the clay has become consolidated as hardpan, it is verging on becoming a sedimentary rock-like layer, which would respond very differently to hydrologic sorting than soft silt/clay deposits. It would probably be appropriate to define hardpan clay as having a large particle size like bedrock, and soft silt/clay/mud deposits as having a small particle size like mud. However, clay deposits with intermediate characteristics would be difficult to assess in the field and clear class definitions would likely be required.

7.0 References:

Dayton, P. K. 1971. *Competition, Disturbance and Community Organization: The Provision and Subsequent Utilization of Space in a Rocky Intertidal Community*. Ecol. Monogr 41: 351-389.

Diether, M. N. 1990. *A Marine and Estuarine Habitat Classification System for Washington State.* Washington Natural Heritage Program, Department of Natural Resources. Olympia, WA. 56 p.

LeMoine, M., C. Dolphin, and J. Freimund. 2009. *Lummi Intertidal Baseline Inventory, Work Plan*. Lummi Natural Resources, Bellingham, Washington.

Lindegarth, M. and Gamfeldt, L. 2005. *Comparing Categorical and Continuous Ecological Analyses: Effects of Wave Exposure on Rocky Shores*. Ecology vol. 86, n5, pp. 1346-1357.

Lummi Water Resources Division. 2006. *Lummi Nation Water Quality Monitoring Program, Quality Assurance Quality Control Plan*. Lummi Natural Resources, Bellingham, Washington.

Lummi Water Resources Division. 2008. *Water Quality Summary Report*. Lummi Natural Resources, Bellingham, Washington.

McLachlan, A. 1996. *Physical Factors in Benthic Ecology: Effects of Changing Particle Size on Beach Fauna*. Mar. Ecol. Prog. Ser. 131:205-217.

National Oceanographic and Atmospheric Administration. Center for Operational Oceanographic Products and Services Website. http://tidesandcurrents.noaa.gov/geo.shtml?location=9449424 Accessed on 9/23/2009.

National Oceanic and Atmospheric Administration Coastal Services Center. 2003. *2002 Willapa Bay, Washington LiDAR Project*. Charleston, SC.

Raffaelli, D.G. and Hawkins, S.J. 1996. *Intertidal ecology*. Chapman & Hall, London. 356 pp.

Rohweder, J.; Rogala, J.T.; Johnson, B. L.; Anderson, D.; Clark, S.; Chamberlin, F.; and K. Runyon. 2008. *Application of Wind Fetch and Wave Models for Habitat Rehabilitation and Enhancement Projects.* http://www.umesc.usgs.gov/management/dss/wind_fetch_wave_models.html Accessed on 10/15/2009.

Terrapoint. 2005. *Project Report: Reservation – Lummi Indian Nation* Contract #2290-H.

US Army Corps of Engineers (USACE). 1984. *Shore Protection Manual*. Coastal Engineering Research Center, Fort Belvoir, Virginia.

Watershed Sciences Inc. 2009. *LiDAR Remote Sensing Data Collection: Tidelands, Lummi Nation, WA. Final Report* (Appendix G of this report).

Zhang, W. and D.R. Montgomery. 1994. *Digital Elevation Model Grid Size, Landscape Representation, and Hydrologic Simulations*. Water Resources Research vol. 30, n4, pp 1019-1028.