

University of Washington

**Mapping Whidbey Island and
Possession Sound Landslide
Susceptibility Using an Additive
Linear Model**

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Senior Thesis

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Abstract

The Puget Sound region has a multitude of natural disasters dating back over thousands of years. Due to extreme weather conditions and seismic activity landslides have been a frequently occurring disaster. Multiple landslides occur annually causing massive destruction. Using an additive linear model including four landslide inducing factors: slope, aspect, topographic position index, and ground type, a susceptibility model will be produced to model landslide susceptibility in Possession Sound and on the southeastern coast of Whidbey Island. The additive linear model is a foundational method for landslide hazard analysis and needs to be implemented in the Puget Sound.

Introduction

The Puget Sound is a region known for its extreme weather conditions and seismic activity that produce hazardous events. High levels of precipitation, seismic activity, and geomorphic processes have all been identified as factors influencing natural disasters within the region. Due to frequent flooding, the stability of the ground material is weakened leading to a failing slope or landslide. Landslides are frequently occurring disasters in the Puget Sound that pose a potential hazard to people and the environment. Multiple landslides can occur per year. Being a region experiencing extreme weather conditions, the Puget Sound is subject to coastal erosion that creates tall steep bluffs capable of failing and harming surrounding areas (Komar, Coastal Erosion Processes and Impacts). With the Puget Sound accumulating a high quantity of rainfall, these hazards increase and need to be understood (Baum, 2005).

Determining and assessing areas affected by erosion and natural processes such as high levels of rainfall has become an important part in disaster planning and hazard assessments. This study will

be adopting the following terminology used by the National Research Academy and United States Geological Survey terminology concerning landslide hazards:

1. **Landslide susceptibility:** refers to the likelihood of a landslide occurring in an area on the basis of local terrain conditions. Susceptibility does not consider the probability of occurrence, which depends also on the recurrence of triggering factors such as rainfall or seismicity. The terms hazard and susceptibility are frequently used incorrectly as synonymous terms (NAP, 2004).
2. **Landslide** - describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these (USGS, 2004).
3. **Landslide hazard:** refers to the potential for occurrence of a damaging landslide within a given area such damage could include loss of life or injury, property damage, social and economic disruption, or environmental degradation (NAP, 2004).

Many studies have been done to establish methods to assess landslide hazards. These methods possess information gathered from LiDAR imaging, surveying, and analysis within ArcGIS and other GIS or statistical software. The methods define factors that influence landslides while other studies delve into the statistical models, and analysis of an increasing amount of influential factors (Oh, 2011).

This study's purpose is to map the Whidbey Island topology as well as Possession Sound's bathymetry to produce a susceptibility model that will illustrate the potential landslide areas. The susceptibility model incorporates 4 important factors that influence landslides: slope, aspect, topographic position index, and ground type (Xu, 2012). These four factors have been established in

previous studies as some of the most important factors that influence landslides. They are important to understand because they play a large role in landslide triggers, processes, and predicting future events that can be prepared for (Masson, 2006).

Understanding Whidbey Island and Possession Sound's geomorphology is key to modeling habitats and predicting future events that can have an effect on the local environment. The susceptibility model encapsulates the important factors that will allow researchers to understand the geomorphology. I do expect to find a variety in susceptibility but I am confident of finding medium to high risk areas on the east coast of Whidbey Island due to the extreme angle of the bluffs as well as the amount of rainfall that influences the occurrence of a landslide. The additive linear method to create the susceptibility model is very common in the realm of landslides and other environmental risk assessment procedures, so I expect this model will be highly useful when preparing for a natural disaster (Park, 2008). Incorporating highly influential landslide factors within the susceptibility model can make this method increasingly sought after.

Whidbey Island has a history of having costly landslides, so creating a model to predict future hazardous landslides is key to preserving the safety of the public and the environment.

Methods

Data Acquisition

A hydrographic surveying cruise was conducted on November 13th through 15th aboard the R/V Thompson: multi-beam sonar backscatter data was gathered from a Kongsberg EM302 echo system. This study focuses on the south eastern coast of Whidbey Island and the Mukilteo coastline in Possession Sound. Figures 1, 2, and 3 illustrate the area of research, track lines followed to acquire the data in Possession Sound, and a three dimensional visualization of the seafloor derived from

digital elevation models (DEMs). A DEM is model comprised of a group of cells that are individually given an elevation value. Following specified ship track lines provided this study with raw depth estimates. Coupled with the multi-beam sounding is the backscatter intensity data. This data is measured by the intensity of the acoustic return from the transmitted beams that reflect off the seafloor. Backscatter intensity provides insight as to the hardness of material that comprises the seafloor. Backscatter intensity provides insight as to the hardness of material that comprises the seafloor. The higher the intensity of multi-beam reflection off of the seafloor means that the material has a higher impedance thus concluding that it is harder material. Classification of intensities for the purpose of this research will be referred to as hard, medium, or soft depending on their intensities.

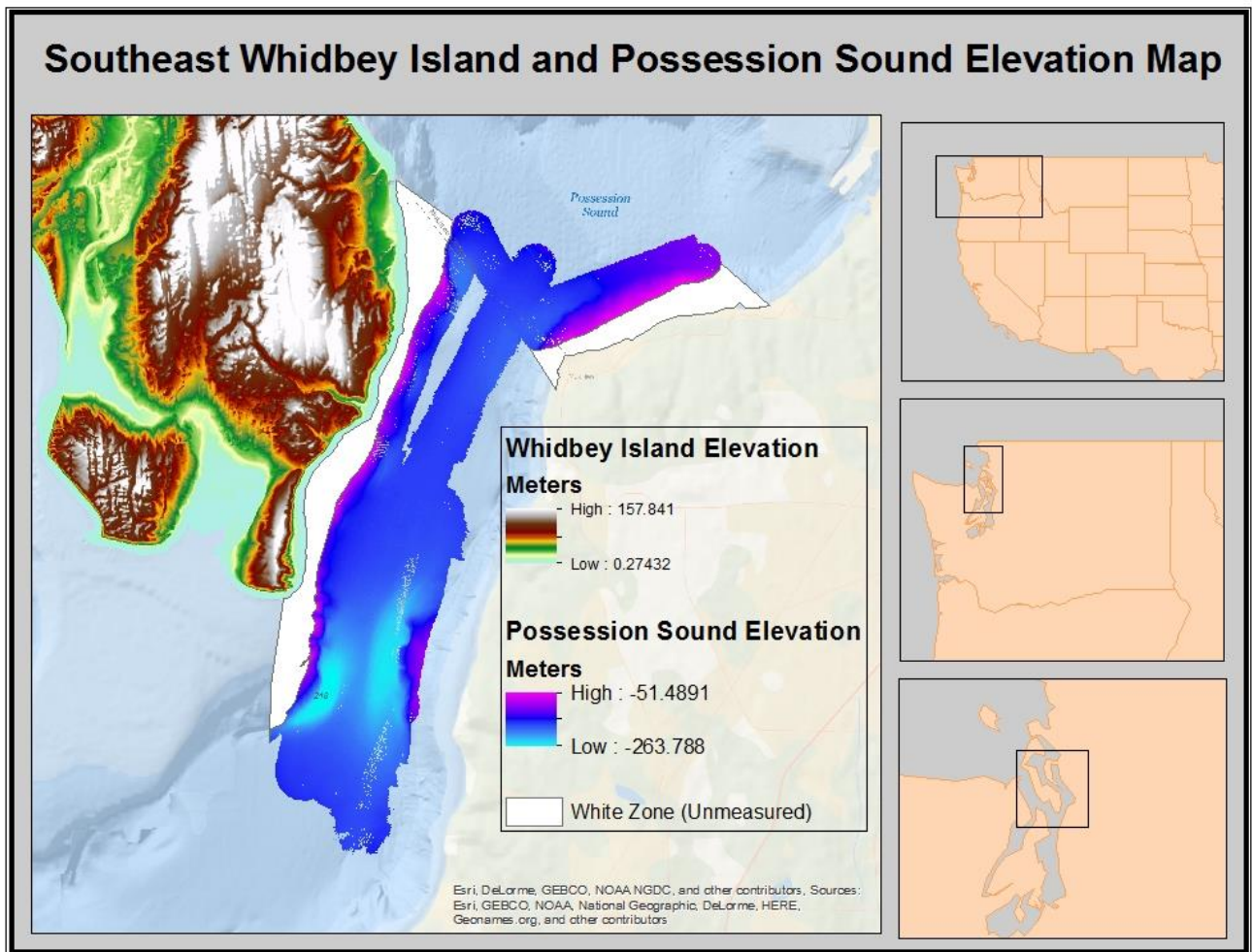


Figure 1: Research location on the southeastern coast of Whidbey Island in the Puget Sound, Washington.

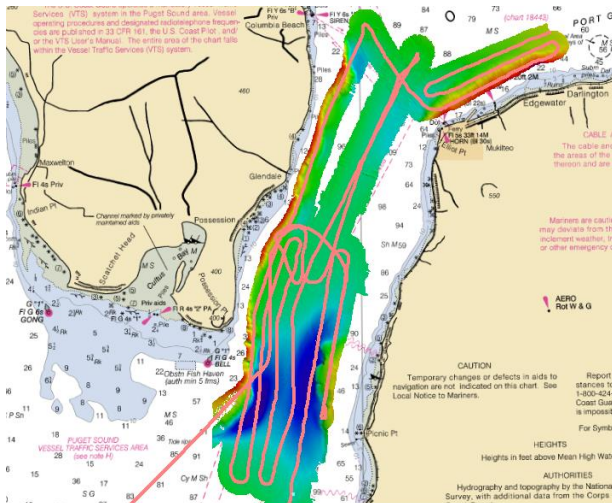


Figure 2: Possession Sound track lines

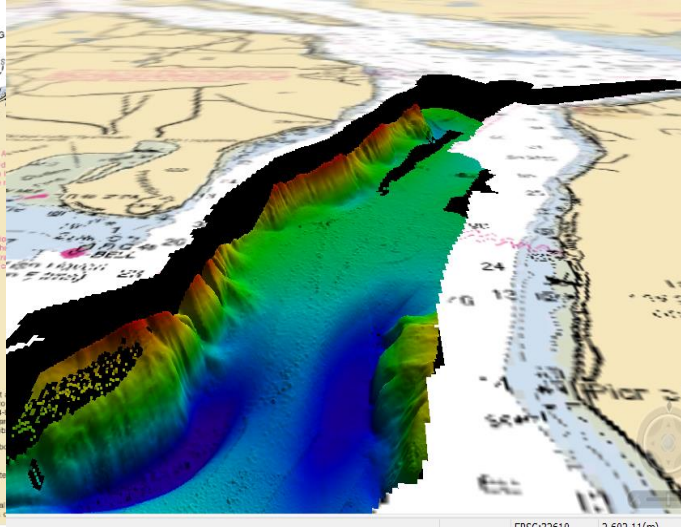


Figure 3: 3-D digital elevation model of the multi-beam survey in Possession Sound

Data Analysis

Following the acquisition phase, the Possession Sound bathymetric data was converted and processed in CARIS' HIPS and SIPS 9.0 (CARIS). Within CARIS the converted data is used to create a 1 meter resolution DEM. From CARIS the DEM produced can be exported into ArcGIS, which is a geographical information system that provides data management, data visualization, and tools to conduct spatial data analysis of the DEM. LiDAR imaging of Whidbey Island is the second constituent that will be analyzed with the Possession Sound DEM within ArcGIS. LiDAR imaging is a remote sensing method that uses the principle of a radar to measure elevation, (mostly) on land. LiDAR imaging also produces DEMs. A susceptibility model determining the land slide potential will be created with the following layers and criteria (Oh, 2011):

Layer 1) Slope – The slope angle is calculated with horizontal and vertical units in meters.

- a. Ranking the slope angle from 1 (low risk) – 9 (high risk). The greater angle of the slope the more likely it is to fail (Kenny, 2003).

The ranking system for the slope angle is as follows:

- 1 is a very low angled slope
- 9 is an extremely steep angle

Layer 2) Aspect – The aspect is calculated by determining which compass direction the downward facing slope is facing. Direction is given in a 360 degree range clockwise from north (0 and 360 degrees).

- b. Ranking the aspect of the slope from 1 – 5. The aspect ranking corresponds to the downhill direction.

The ranking system for the aspect is as follows:

- 1 means the downward slope faces away from Possession Sound (west)
- 5 means the downward slope faces Possession Sound (east)

Layer 3) Topographic Position Index (TPI) – TPI is a metric defined by first calculating the average elevation of a 10x10 cell group and subtracting the center cell's elevation from it.

Horizontal and vertical units are in meters.

- c. Ranking from Topographic Position Index from 1 – 4. The TPI corresponds to a single pixel's relationship with the surrounding elevation. In essence this tells us where a pixel lies on a slope.

The ranking system for TPI is as follows:

- 1 means the pixel's variation from the mean is very small.
- 4 means the pixel's variation from the mean is very large.

Layer 4) Ground Type (Strictly land-based) – The ground type classifications were created from separating specific land cover types specified by the National Land Cover Database, United States Geological Survey.

- d. Ranking the ground type from 1 – 7. The ground type corresponds to how soft the material is (Dartnell, 2014).

The ranking system for ground type is as follows:

- 1 means very solid hard stable ground
- 7 means very soft and unstable ground

Layer 4) Bottom Type (Strictly Water-based) – The Bottom Type was derived from the backscatter intensity during the hydrographic survey. The Intensity readings were divided into 3 classes.

- e. Ranking the bottom type from 1 – 3. The bottom type corresponds to the softness of the seafloor.

The ranking system is as follows:

- 1 means harder material.
- 2 means medium soft/hard material.
- 3 means softer material

Layer 5) The White Zone – This zone is an area where it is too shallow to do a hydrographic survey and where there isn't any available LiDAR data. The White Zone's width varies throughout Possession Sound from about 100 meters to 750 meters.

Source	Factor	Susceptibility Rank	Derivation and Description
DEM 1 meter resolution	Slope	1 (flat) – 9 (steep)	Derived from the DEMs
DEM 1 meter resolution	Aspect	1 (west) – 5 (east)	Derived from the DEMs
DEM 1 meter resolution	Topographic Position Index (TPI)	1 (small variation) – 4 (large variation)	Derived from the DEMs finding the 10mx10m local average and subtracting the center cell's elevation. Average Local Elevation (10m x 10m) – Individual Pixel Elevation
National Land Cover Database (NLCD)	Ground Type	1 (solid/developed) - 8 (unstable/less developed)	Removed unnecessary land cover types (Alaska native) and reclassified
Multi-Beam Backscatter	Bottom Type	1 Soft, 2 Medium, 3 Hard	Derived from multi-beam sonar backscatter readings.
Digitized	White Zone	NA	Area where there is no data

Table 1: This table expresses the derivation of each layer and their susceptibility ranking scheme as illustrated within their individual maps.

Additive Linear Method: Slope + Aspect + TPI + Bottom Type

Susceptibility Code: Slope*1000 + Aspect*100 + TPI*10 + Bottom Type

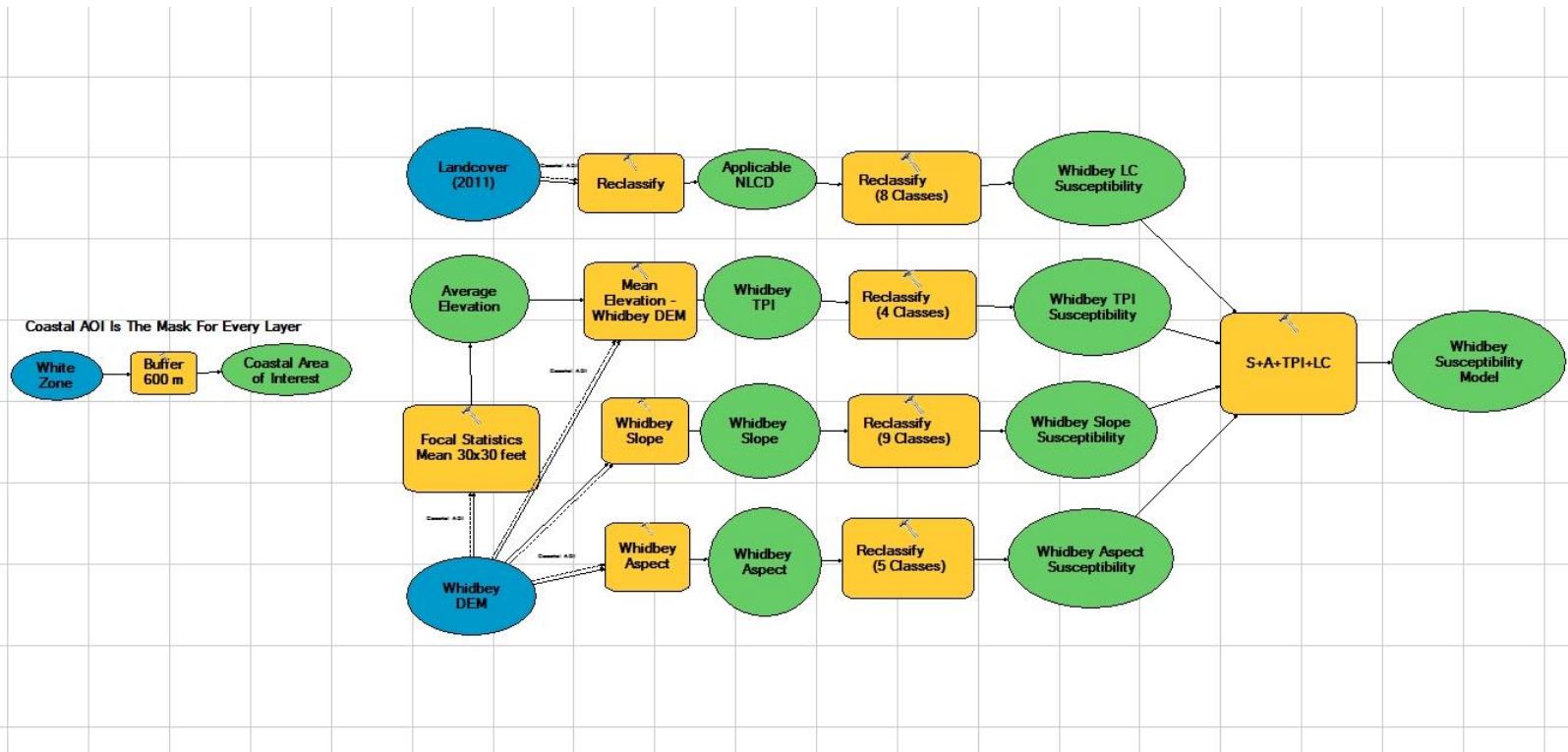
The **additive linear method** is a function that sums up the susceptibility ranks for each factor in each individual cell. The resulting summation is a new layer with a susceptibility score that is used to create the susceptibility model (figure 10a). A layer is a mechanism that displays geographic datasets. In this study the four (4) layers, defined above, will be combined to provide a susceptibility score for each cell concerning the likelihood of failure as expressed in the **additive linear method**. These scores will then be reclassified into low (<10), medium low (10-14), medium high (15-19), and high susceptibility (>19).

The **Susceptibility Code** is a function that will create a new layer assigning each cell a 4 digit code corresponding to the slope, aspect, TPI, and bottom type rank. Figure 10b illustrates

the **susceptibility code**. This provides a map and table that can easily be queried to analyze the 4 factors that make up the susceptibility model.

The workflow to illustrate the required steps to produce the susceptibility model has been adjusted to separate the land and water models. Below are the two separated workflows that were created in ArcMap's Model Builder.

Land Based



Results

The first constituent of the susceptibility model is the derivation of the slope angle. Figure 4 illustrates the slope derivation within ArcMap. The steepest of slopes lie along the bluffs on the east coast of Whidbey Island having extremely steep slopes, measuring in the range of 30-72 degrees.

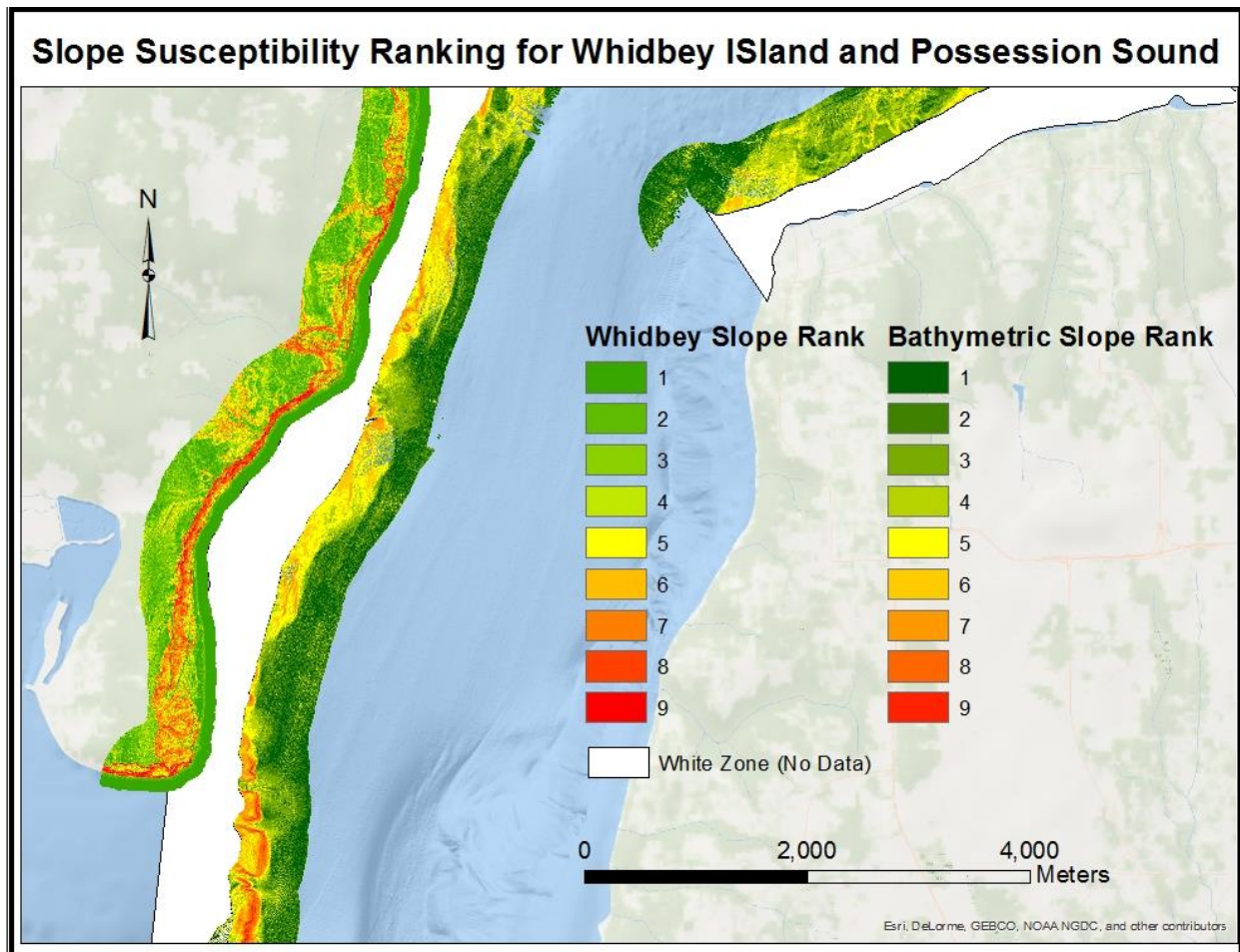


Figure 4: This map illustrates the slope rankings. The higher the number (9) and redder the color indicates areas of high susceptibility. The white zone indicates the disconnect between land and water that hasn't been surveyed.

Figure 5 shows the spatial pattern of aspect, the second derivation of elevation. The majority of the steep slopes face continuously east towards Possession Sound. The high risk

zones frequently occur along the steep slopes throughout the length of the coastline going north. There is highly intuitive connection between the high risk slope and aspect locations.

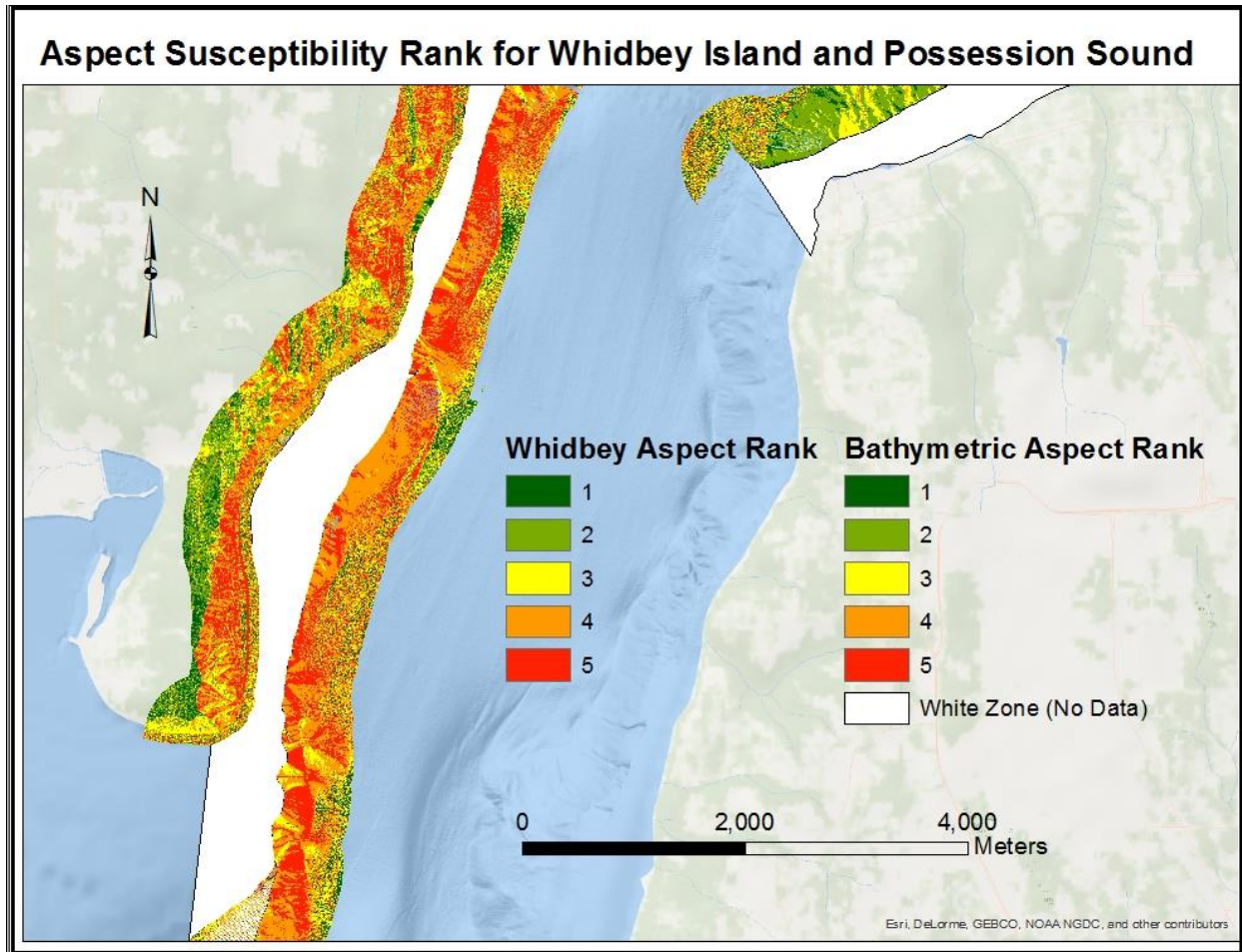
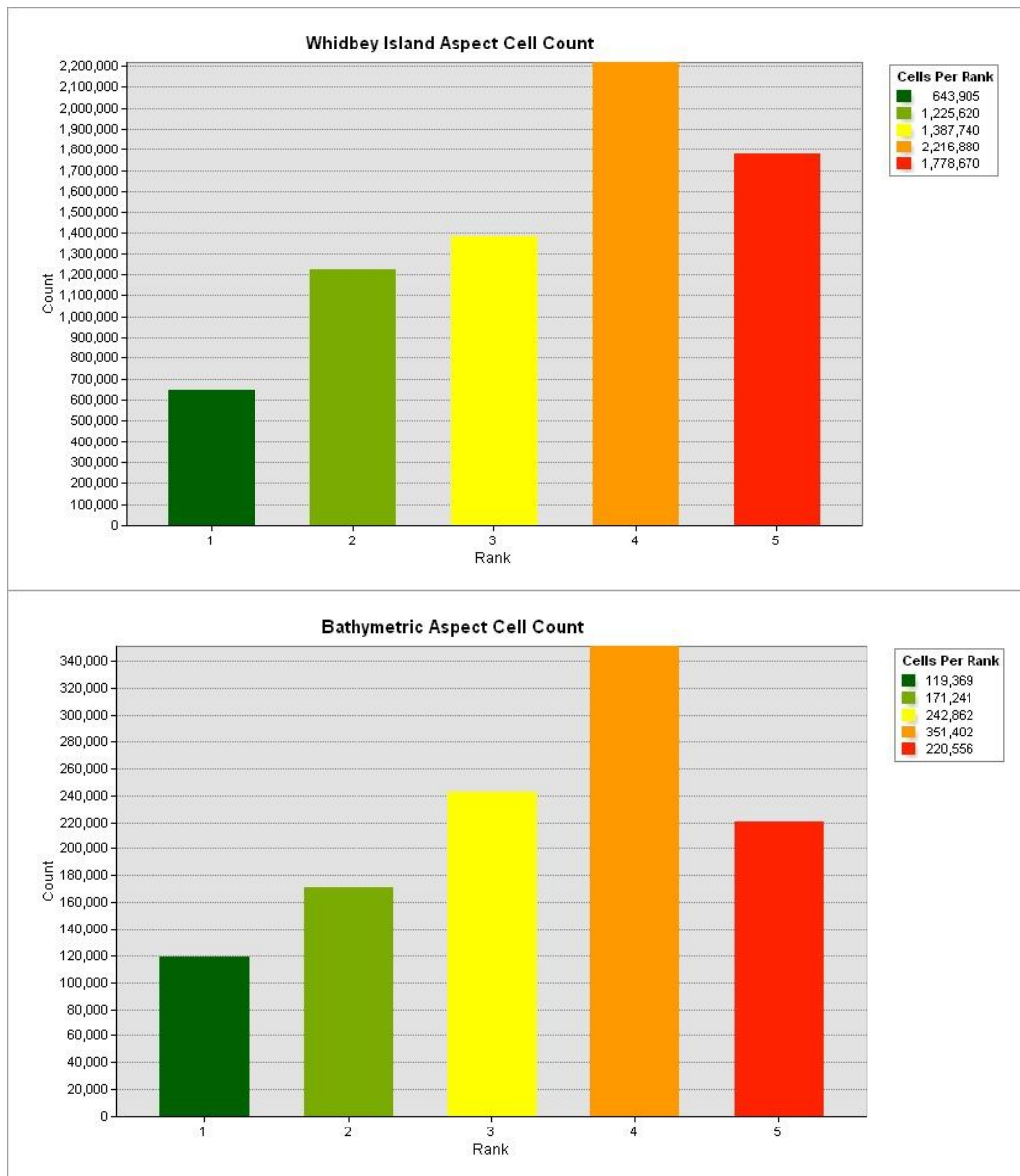


Figure 5: This map illustrates the aspect rankings over the length of the southeast coast of Whidbey. The high risk (5) aspect locations lie on areas where the downward slope face in an easterly direction.



Figures 6 & 7: These graphs illustrate the amount of cells that fit within each susceptibility rank for each the land and water based derivations as expressed in figure 5.

Figures 6 and 7 show the number of cells in each aspect rank. In both the bathymetry and Whidbey aspect ranking, the second most susceptible area has the greatest cell count, while the most susceptible areas have the second and third largest cell count for Whidbey and bathymetric profiles respectively. The cell count translates to surface area since each cell is 1x1 meters.

Figure 8a illustrates the third factor regarding landslide susceptibility analysis, Topographic Position Index, a third constituent and metric of the susceptibility model. The areas of highest variation from the 10x10 meter mean elevation indicate cells that either lie on the upper part of a slope or on the lower part of a slope. The negative ranges indicate cells with a greater elevation than the 10x10 meter average around it. The positive ranges indicate cells with elevations lower than the 10x10 meter average around it.

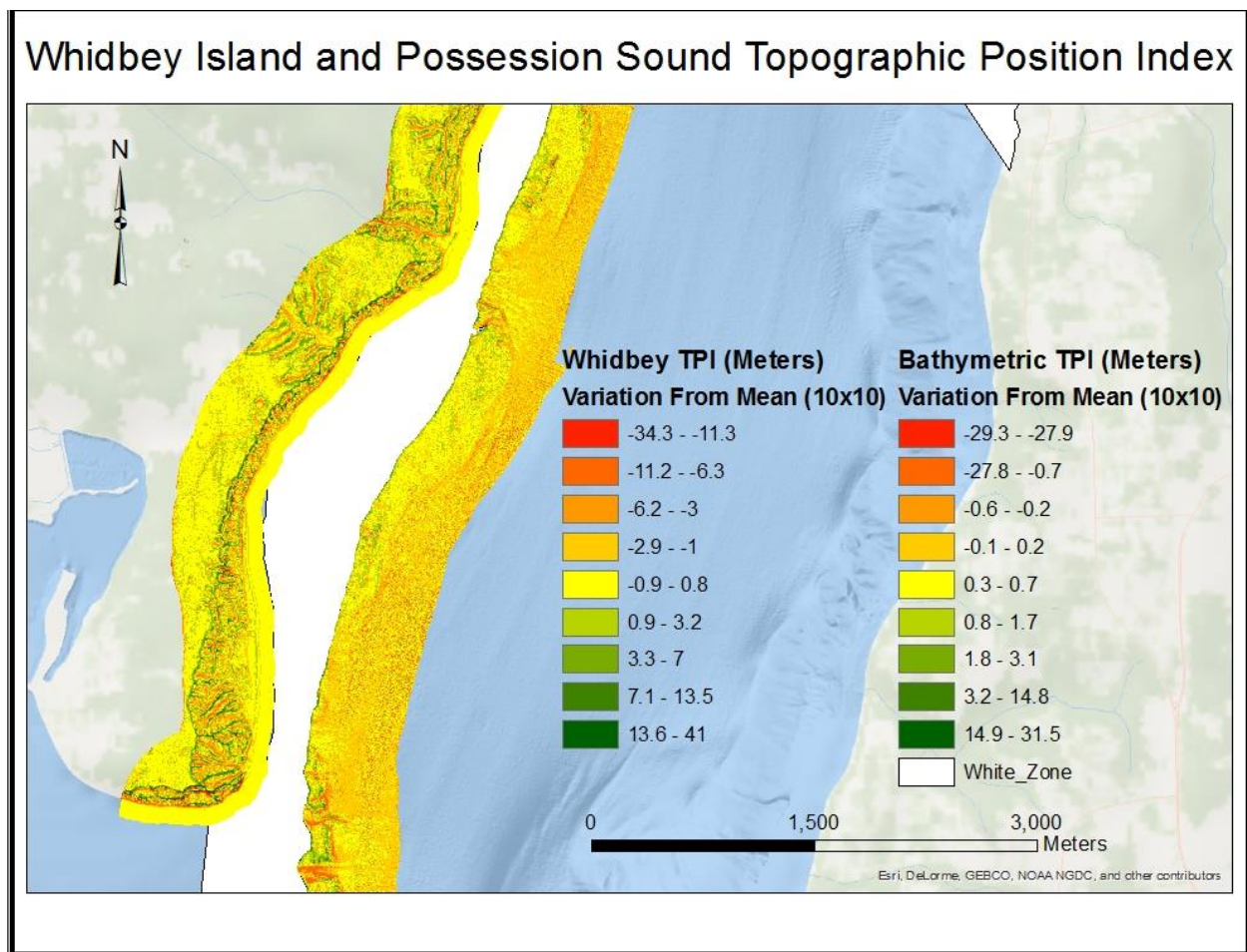


Figure 8a: This map illustrates the Topographic Position Index (TPI) classes indicating cell location relative to its 10x10 meter neighborhood average.

Whidbey Island and Possession Sound Topographic Position Index

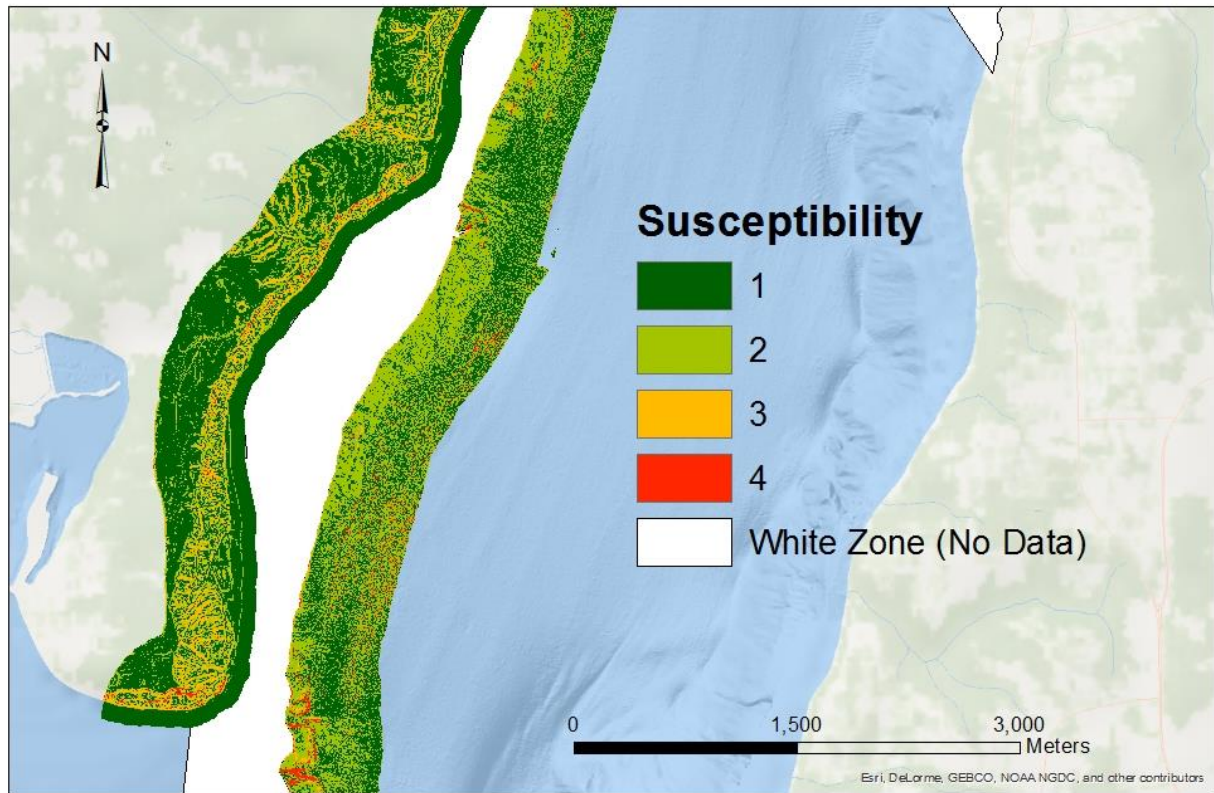


Figure 8b: This figure illustrates the 4 classes that values from figure 8a were reclassified into. The most negative variance in figure 8a is the highest susceptibility.

Figure 9 illustrates the fourth and final constituent for the susceptibility model, land cover and bottom type. A large portion of Whidbey Island is covered with forests whether it be deciduous, evergreen, or mixed. A smaller portion of Whidbey Island is comprised of grasslands, shrubbery, and low intensity developed areas.

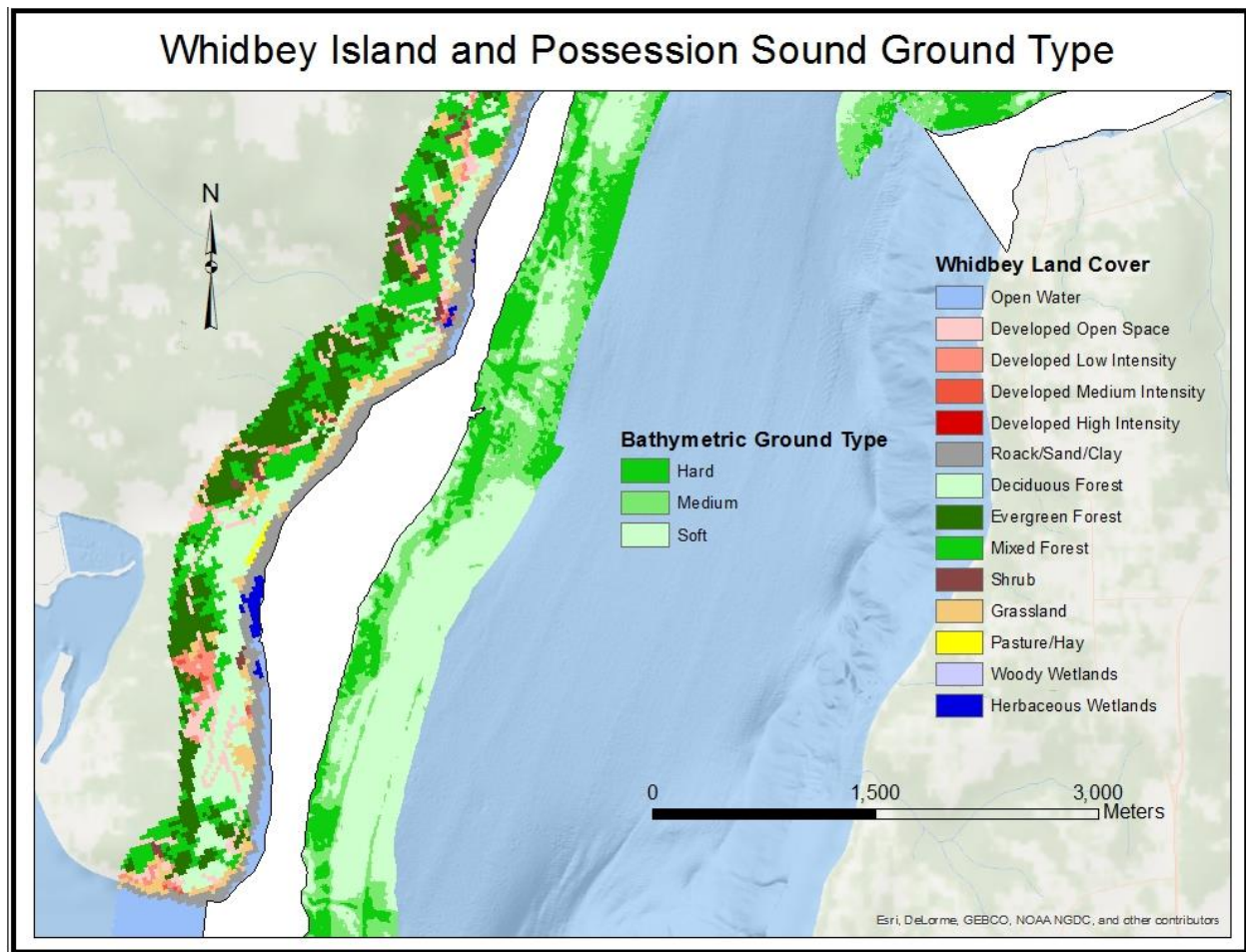


Figure 9: This figure illustrates land cover (Whidbey) and bottom type (bathymetry) depicting specific classifications given to each pixel.

A lot of the hard material lies right off of the eastern shoreline while the softer material lies further out away from Whidbey Island. That is true for the majority of the bathymetry, but about 3,000 meters north from the southern tip of Whidbey Island the ground type distribution has a different variation. The hard material surrounds the soft material about 750 meters off of the coast.

The susceptibility model complete with all constituents is illustrated in figure 10a. As a result of the **additive linear model**, the susceptibility model is a visualization of the summation

of every factor (layer). The highest landslide susceptibility scores indicate the high susceptibility. The lowest susceptibility scores indicate the low susceptibility. The scores have been classified into 4 categories as explained in the methods.

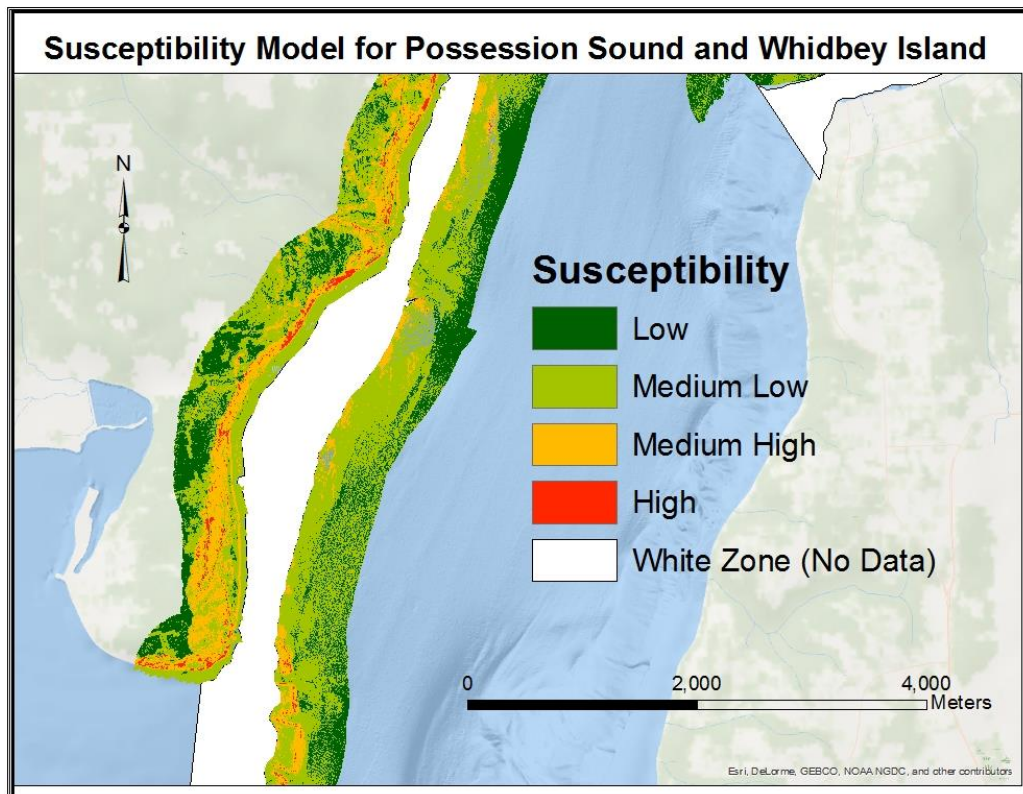


Figure 10a: This figure illustrates the susceptibility model. Each 1x1 meter cell in the layer has value that indicates its susceptibility rank sum.

Figure 10b, 10c, and 10d illustrate the **susceptibility code**. Each 1x1 meter cell is coded with a 4 digit number indicative of each individual factor's susceptibility ranks (slope, aspect, TPI, and ground type). The "value" column in figures 10c and 10d are an example of selected cells that have a 7421 susceptibility code in the bathymetry model and a 7424 susceptibility code in the Whidbey Island model.

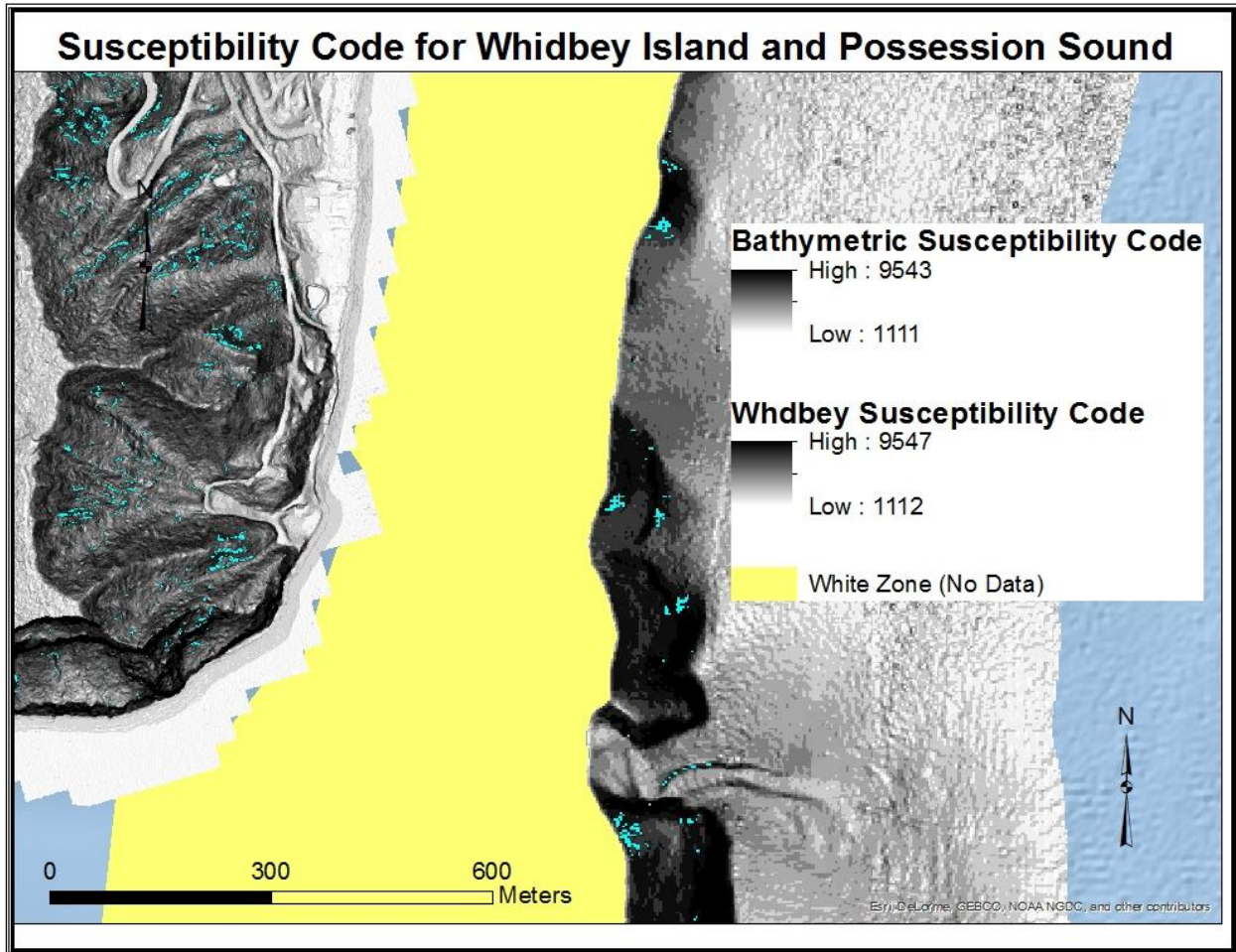


Figure 10b: This figure illustrates the susceptibility code for each cell. The light blue highlighted cells are indicated in figure 10c and 10d.

Bathy_Susceptibility_Code		
OBJECTID *	Value	Count
398	7421	3738

Figure 10c: This figure illustrates the 4 digit susceptibility code for the Possession Sound Bathymetry

Whdbey_Susceptibility_Code		
OBJECTID *	Value	Count
1003	7424	27644

Figure 10d: This figure illustrates the 4 digit susceptibility code for Whidbey Island

Discussion

Landslides have the potential to cause extreme destruction to the Puget Sound environment and danger its inhabitants. Landslide risk assessment has been a growing area of

research all around the world, and this study has provided a very basic linear additive model with 4 factors to illustrate the landslide susceptibility on the southeastern coast of Whidbey Island.

The aspect susceptibility ranking, for the purpose of this study, is interpreted by how susceptible the slope is to an active environment. Southwestern winds dominate the winter season when the weather is wettest and harshest, resulting in trees being blown over and soil erosion. Both processes increase the local susceptibility around the affected area. The aspect classes valued at 4 and 5 are the slopes that face eastward (east, northeast, and southeast) and are most susceptible to wind. A recommendation for future studies would be to analyze the connectivity of the aspect ranks. What this means is to locate and quantify the size of grouped cells that have the same slope direction. Since aspect is a spatial conditional connectivity susceptibility metric, this would be an important addition to this study to identify cell groups that satisfy specific conditions and are connected. This addition would increase the analysis detail and help set aspect susceptibility ranking parameters.

Comparing the land cover with slope and aspect, the type of land that overlays the steep slopes are the deciduous forests, woody wetlands, and grasslands. Woody wetlands and grasslands are less stable than forests with large stabilizing roots, so the areas where the land cover consists of wetlands and grasslands pose the greatest susceptibility. These unstable areas were ranked the highest.

Data gaps can result in difficult analysis, interpretation, and modeling issues. The “white zone”, area with no data in figures 1, 4, 5, 8, 9, and 10 between Whidbey Island and the Possession Sound bathymetry data, comes into question when analyzing the bathymetry between 0 and 51 meters. 100-750 meters of data are missing depending on where along the Whidbey Coast you are, but that is a significant amount of data that is missing. The bathymetric features

that exist in the white zone could alter the landslide susceptibility factors and result in an altered susceptibility model. Acquiring this data to fill in the “white zone” would benefit further studies and the production of more detailed susceptibility models. Not only would it benefit future susceptibility models, it would help future researchers interpret the influence Whidbey Island landslides might have on the Possession Sound geomorphology.

The methodology to calculate the Topographic Position Index is completely dependent on the context in which the Index is being used. The 10x10 meter neighborhood selected in this study was successful in providing a susceptibility score for each cell to intuitively express the position of the given cell relative to its neighbors.

Conclusion

Landslide susceptibility analysis has a wide variety of methods. A linear additive model is one of them that is extremely basic but very informative. This study implemented slope, aspect, TPI, and ground type/hardness to produce a susceptibility model on the southeastern coast of Whidbey Island and offshore in Possession Sound. The linear additive approach is a widely used model in the topic of risk and hazard analysis. The Puget Sound, Whidbey Island specifically, has been an active zone full of natural disasters throughout its history and needed a methodology to analyze and model its landslide susceptibility. The model provided in this study is meant to be a baseline for further studies to build upon to accurately model potential landslide risk areas with multiple influential factors. The safety of Puget Sound inhabitants and the environment that they live in is something that needs to be understood fully to implement policies and practices to prepare for natural disasters and that is possible by building upon this study.

References

- Baum, Rex L., Jeffery A. Coe, Jonathan W. Godt, Edwin L. Harp, Mark E. Reid, William Z. Savage, William H. Schulz, Dianne L. Brien, Alan F. Chleborad, Jonathan P. Mckenna, and John A. Michael. "Regional Landslide-hazard Assessment for Seattle, Washington, USA." *Landslides* 2.4 (2005): 266-79. Web. 31 May 2016.
- Komar, P.d. "Coastal Erosion Processes and Impacts." *Treatise on Estuarine and Coastal Science* (2011): 285-308. Web. 31 May 2016.
- "Landslide Types and Processes." *Landslide Types and Processes*. United States Geological Survey, July 2004. Web. 31 May 2016.
- Masson, D. G., C. B. Harbitz, R. B. Wynn, G. Pedersen, and F. Lovholt. "Submarine Landslides: Processes, Triggers and Hazard Prediction." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 364.1845 (2006): 2009-039. Web. 31 May 2016.
- Oh, Hyun-Joo, and Saro Lee. "Landslide Susceptibility Mapping on Panaon Island, Philippines Using a Geographic Information System." *Environ Earth Sci Environmental Earth Sciences* 62.5 (2010): 935-51. Web. 31 May 2016.
- Park, N.-W., and K.-H. Chi. "Quantitative Assessment of Landslide Susceptibility Using High-resolution Remote Sensing Data and a Generalized Additive Model." *International Journal of Remote Sensing* 29.1 (2008): 247-64. Web. 31 May 2016.
- *Partnerships for Reducing Landslide Risk: Assessment of the National Landslide Hazards Mitigation Strategy*. Washington, D.C.: National Academies, 2004. *National Academies Press*. 2004. Web. 31 May 2016.
- Whiteaker, William LN. "Landslide generated tsunamis: A smoking gun in Saratoga Passage, Puget Sound, Washington." (2008).
- Xu, Chong, Xiwei Xu, Yuan Hsi Lee, Xibin Tan, Guihua Yu, and Fuchu Dai. "The 2010 Yushu Earthquake Triggered Landslide Hazard Mapping Using GIS and Weight of Evidence Modeling." *Environ Earth Sci Environmental Earth Sciences* 66.6 (2012): 1603-616. Web. 31 May 2016.

