The Ledgewood-Bonair Landslide toe and where did it go? A case study in littoral sediment budgets from a deep-seated landslide in Island County, Washington

Matthew Teich

A report prepared in partial fulfillment of
the requirements for the degree of

Master of Science
Earth and Space Science: Applied Geosciences

University of Washington

March 2016

Project Mentor:
Ian Miller, Washington Sea Grant

Internship Coordinator:
Kathy Troost

Reading committee:
Brian Collins
Steven Walters

MESSAGe Technical Report Number: 031

Abstract

On the morning of March 27th, 2013, a small portion of a much larger landslide complex failed on the western shoreline of central Whidbey Island, Island County, Washington. This landslide, known as the Ledgewood-Bonair Landslide (LB Landslide), mobilized as much as 150,000 cubic meters of unconsolidated glacial sediment onto the coastline of the Puget Sound (Slaughter et al., 2013, Geotechnical Engineering Services, 2013). This study aims to determine how sediment from the Ledgewood-Bonair Landslide has acted on the adjacent beaches 400 meters to the north and south, and specifically to evaluate the volume of sediment contributed by the slide to adjacent beaches, how persistent bluff-derived accretion has been on adjacent beaches, and how intertidal grain sizes changed as a result of the bluff-derived sediment, LiDAR imagery from 2013 and 2014 were differenced and compared to beach profile data and grain size photography. Volume change results indicate that of the 41,850 cubic meters of sediment eroded at the toe of the landslide, 8.9 percent was redeposited on adjacent beaches within 1 year of the landslide. Of this 8.9 percent, 6.3 percent ended up on the north beach and 2.6 percent ended up on the south beach. Because the landslide deposit was primarily sands, silts, and clays, it is reasonable to assume that the remaining 91.1 percent of the sediment eroded from the landslide toe was carried out into the waters of the Puget Sound. Over the course of the two-year study, measurable accretion is apparent up to 150 meters north and 100 meters south of the landslide complex. Profile data also suggests that the most significant elevation changes occurred within the first two and half months since the landslides occurrence. The dominant surficial grain size of the beach soon after the landslide was coarse-sand; in the years following the landslide, 150 meters north of the toe the beach sediment became finer while 100 meters south of the toe the beach sediment became coarser. Overall, the LB Landslide has affected beach profile and grain size only locally, within 150 meters of the landslide toe.

Table of Contents

Acknowledgements

First and foremost, I would like to thank Dr. Ian Miller for allowing me to assist him in his research at the Ledgewood-Bonair Landslide. This project would not have been possible without him. I would also like to thank Steven Walters for his time, guidance, and GIS assistance and Brian Collins for his thorough review.

Introduction

On March 27th, 2013, around 3:45AM, a deep-seated, rotational-translational landslide commenced on the western shoreline of central Whidbey Island, Island County, Washington (Figure 1) (Slaughter et al., 2013, Geotechnical Engineering Services, 2013). This landslide, also known as the Ledgewood-Bonair Landslide (LB Landslide), mobilized as much as 150,000 cubic meters of unconsolidated glacial sediments onto the coastline of the Puget Sound (Slaughter et al., 2013), significantly impacting the coastal community of Ledgewood, Washington (Figure 2). At the site of the landslide, a huge section of the residential road Driftwood Way was completely destroyed, leaving many of the homes along the waterfront without access into town or to Washington State Route 525, the major route through Whidbey Island (Burrett, 2013).

Landslide hazards and coastal bluffs are prevalent throughout the Puget Lowland and are a direct consequence of the shaping of the landscape by the last glaciation (Troost and Booth, 2008). The last glaciation deposited sequences of glacial sediments of variable thicknesses, elevations, and compositions (Troost and Booth, 2008). Specifically in Island County, the Vashon-age drift consists of older lakebed silts and clays (the Lawton Clay), a thick package of advanced outwash sands and gravels (Esperance Sand), and a capping of glacial till (Vashon Till) (Polentz et al., 2009). In some locations, the till is overlain by glacial marine drift, recessional outwash, or post-glacial lake sediments (Polentz et al., 2009). The combination of steep slopes and the widespread occurrence of the relatively permeable Esperance Sand over the less permeable Lawton Clay causes pervasive coastal landsliding along these settings (Shipman, 2001).

The Puget Sound shoreline contains many large prehistoric landslides, typically consisting of a complex of individual slide blocks (Shipman, 2004). Particularly in Island County, of the 221 miles of shoreline, 112 are considered potentially unstable (Shipman 2004). The location of the LB Landslide is part of a larger prehistoric landslide complex, extending nearly 3-kilometers along the coastline of central Whidbey Island (Figure 2). This 3 kilometer stretch on the western shoreline of central Whidbey Island has been eroding and experiencing intermittent landslides for several thousand years where shoreline erosion and groundwater conditions combine to create slope instability (Geotechnical Engineering Services, 2013). Within this 3-kilometer area, the LB Landslide area represents a continuation of a natural process that has been ongoing for centuries and will remain so for the foreseeable future (Geotechnical Engineering Services, 2013).

Debris from the landslide event extended approximately 90 meters into the Admiralty Inlet (Slaughter et al., 2013), displacing large amounts of sediment onto the nearshore environment. Fundamentally, beaches and nearshore areas are a buffer between the energy transported through the marine environment and a coastal zone increasingly occupied by human infrastructure (Miller and Warrick, 2012). Sediment transport on mixed beaches (beaches having multiple grain size modes) is poorly understood in comparison to sand and coarse grained beaches (Miller, et al., 2011). Thus, the addition of various types of debris to the already mixed beaches at Ledgewood creates an opportunity to assess how sediments associated with a mass-wasting event respond to hydrodynamic forces along nearshore environments and how their movements assemble into long-term shoreline evolution (Miller and Warrick, 2012).

The location and failure mechanism of the Ledgewood-Bonair Landslide makes it an interesting case study for both bluff erosion and sediment budgets along coastlines. In the Puget Sound, bluffs are primarily prone to failure due to the local geology in the region, and, as a result, most landslides occur from subaerial erosion in response to heavy precipitation, initiating shallow failure landslides (Johannessen and MacLennan, 2007). Conversely, elevated groundwater conditions have been known to reactivate large, deep-seated landslides and although the cause of the LB Landslide has not been determined, the fact that it was deep-seated is widely accepted. Since many coastal failures occur from erosive processes happening on the bluff, resulting in bluff failures and shallow landslides, the deep-seated LB Landslide occurring on a coastal setting makes this landslide unusual. The stratigraphically-lower fine-grained layers that became exposed also contribute to the unusual nature of this landslide. The newly exposed sediments are susceptible to coastal processes and erosion occurring along the beach.

This study aims to determine how sediment from the Ledgewood-Bonair Landslide has nourished, or augmented the volume of, the adjacent beaches 400 meters to the north and south. By computing the difference in elevation of LiDAR (light detection and ranging) imagery taken a day after the landslide commenced with imagery taken nearly a year later, I determine the volume decrease at the toe of the landslide, the portion beneath Driftwood Way, and volume increase along the beaches. Assessing grain size photography and beach profile data taken post-landslide provides insight into how the grain sizes and elevation changed along the beaches through time. The results of this study will reveal how long landslide erosion will contribute sediment to adjacent beaches and will provide insight into how coastal landsliding influences nearshore environments. In the coming decades where climate change, a rise in sea level and human landscape alterations can lead to an increase in coastal landsliding and an acceleration in shoreline erosion, understanding the management of mixed beaches will become vital for the state of Washington (Miller et al., 2011).

Scope of Work

The goal of this project is to see how the adjacent beach, 400 meters to the north and south of the Ledgewood-Bonair Landslide, has been influenced by landslide sediments. Specifically, how much, why, and where has the sediment acted to nourish these locations and how persistent has this nourishment been over time?

To answer these questions, the project is divided into three phases, which are: (1) differencing LiDAR collected immediately after the slide against data collected at a later date to estimate total volume of sediment eroded from the landslide; (2) analyzing sediment composition of the toe and along the beaches to determine how beach sediment size has changed in the two years after the slide occurred; and (3) evaluating when, where, and how much of the landslide volume ended up on adjacent beaches.

In the first phase, I use geospatial software ArcGIS to calculate the volume change of the landslide area between 2013 and 2014. The differences between the data collected one day after the landslide and that collected one year later provides an estimate of the volume changed at the toe to establish the potential beach volume that can contribute to nourishment along the adjacent shorelines.

For the second phase, I examine grain size images taken along the beaches, collected over the two-year study, to determine how grain sizes have changed in response to the landslide event. I analyze the grain size images using a Matlab script, which identifies average grain size in each photograph, so that intertidal sediment changes along the beaches can be evaluated.

In the final phase, I analyze the results from the first two phases with alongshore sediment transport data and bathymetry data to evaluate the volume changes that occurred at the landslide and how those changes influenced the elevation and grain size changes on the adjacent beaches. Repeat topographic survey profiles also provide supplemental evaluations into how elevation has changed over the two-year study.

Study Area Setting

Landslide setting and history

Ledgewood is a primarily residential, coastal community that lies adjacent to Admiralty Inlet, located nine miles south of Coupeville, Washington on the west-facing shoreline of central Whidbey Island (Figure 1). In the 1960s, plats along Ledgewood Beach and Bonair (Figure 2) were approved and filed, prior to current land use practices and regulations that consider proximity and impacts of landslides (Geotechnical Engineering Services, 2013). The lower Ledgewood portion of the Ledgewood Beach Plat, including Driftwood Way, is built within an ancient landslide complex, with homes and infrastructure supported on slide debris while the upper portion of the plat includes Fircrest Avenue residences. Landslides have destroyed homes along the lower Ledgewood Beach since at least the 1970s (Geotechnical Engineering Services, 2013).

Shoreline areas on Whidbey Island, such as the LB Landslide area, encompass well-drained soil units that are interbedded with fine-grained deposits such as silt, clay, and dense glacial till (Geotechnical Engineering Services, 2013). Groundwater tends to accumulate above these fine-grained units, leading to over-steepened bluff slopes that fail episodically as transitional or rotational landslide blocks (Geotechnical Engineering Services, 2013). Reported slides here have been relatively shallow, while two active slide areas within the ancient landslide complex, the Driftwood Way Landslide and North Driftwood Way Landslide, have been larger and have caused damage along Driftwood Way (Geotechnical Engineering Services, 2013).

Within the recent LB Landslide was a previously active Driftwood Way Landslide (Figure 2). This mass was within the Ledgewood Beach Plat and included approximately 75 to 90 meters of the Driftwood Way road alignment (Geotechnical Engineering Services, 2013). The other active slide area, the North Driftwood Way Landslide, is north of the LB Landslide area and is also located within the Ledgewood Beach Plat and ancient landslide complex. After destroying two homes in the late 1980s, this slide area was considered inactive for about 8 to 10 years until 2012, when several episodic movements began occurring, requiring roadway repairs in the area (Geotechnical Engineering Services, 2013). Both of these active slide areas extend down into the beach area of the Admiralty Inlet and have damaged portions of Driftwood Way. The recent Ledgewood-Bonair Landslide enlarged the limits of the previously active Driftwood Way Landslide to include 200 meters of Driftwood Way (Geotechnical Engineering Services, 2013) (Figure 2).

Ledgewood-Bonair Landslide

Around 3:45AM on March 27, 2013, the LB Landslide, a small portion of a much larger landslide complex failed on Whidbey Island, Island County, Washington (Figure 3). This ancient landslide complex, which extends nearly 3-kilometers along the west-facing shoreline of central Whidbey Island, dates back nearly 11,000 years (Slaughter et al., 2013). The LB Landslide was approximately 335 meters long, extended 90 meters in the Admiralty Inlet, and mobilized as much as 150,000 cubic meters of debris (Slaughter et al., 2013) (Figure 3). It produced a 180 meter long scarp and resulted in roughly 45 meters of westward lateral movement along Driftwood Way. The scarp along the backyards of several residences at Fircrest Avenue also resulted in a nearly 30 meter vertical drop (Geotechnical Engineering Services, 2013). Two properties located south of the dislocated section of Driftwood Way were displaced by the landslide movement while an additional 18 residences were without utilities and access due to the unstable slide mass and destroyed Driftwood Way access road (Geotechnical Engineering Services, 2013).

Analyses from Geotechnical Engineering Services suggest that the landslide occurred as a multi-stage compound landslide. It likely began with a reactivation of the Driftwood Way Landslide with a toe rotation, followed by lateral/translational slide movement towards the beach (Geotechnical Engineering Services, 2013). The movement of the landslide also suggests that the deep-seated failure plane is located below sea level and uplifted the pre-existing beach as high as 10 meters above the shore (Slaughter et al., 2013). Initial observations found extensive deformation at the toe zone and radial cracks extending perpendicular to the lobate toe. The headscarp, averaging about 60 meters above sea-level, is vertical to sub-vertical and exposes the glacial geology of that particular area (Slaughter et al., 2013). There was significant erosion at the toe in the days following the landslide due to the tidal and storm waves acting on the loose sediments. Additional failure of about 5 to 10 meters of material calved off the headscarp along the northern edge of the LB Landslide approximately two weeks later (Geotechnical Engineering Services, 2013). The mechanisms for why the LB Landslide area failed is not yet understood.

Subsurface stratigraphy

At the LB Landslide site, Geotechnical Engineering Services performed subsurface explorations and tests following the landslide event to evaluate soil materials. Upland borings identified a profile of dense to very dense sand with some layers of hard silt and clay (Figure 4). Below this profile were predominantly very dense sand or silty sands with some gravel and intermittent layers or lenses of hard silts. At the very bottom was a deposit of low-plasticity silt and clay (Geotechnical Engineering Services, 2013). Borings completed on post-landslide debris along Driftwood Way were more variable and contained a mixture of landslide debris, intact blocks of landslide material, and undisturbed inter-glacial deposits. Borings here identified loose to medium dense sand, likely previously landslide debris, and a deeper layer of dense clay which may be older landslide debris. The recent landslide deposit and older landslide deposits were overlaying hard silts and clay (Geotechnical Engineering

Services, 2013). Figure 5 shows the geology of the failure interpreted from the borings shown in Figure 4.

Mixed beach sediment transport

Mixed beaches, comprised of a homogeneous mixture of sand and gravel, are common in previously glaciated regions but are comparatively rare on a world-wide basis (Finlayson, 2006). As a result, many conventional beach models of wave environment, sediment properties, and transport mechanics are not suitable for the Puget Sound (Finlayson, 2006). Obtaining field measurements on mixed beaches is also difficult due to high wave energy, mobile substrate and fragile instrumentation (Miller and Warrick, 2012). Three techniques are commonly applied to measure volumetric sediment transport on mixed beaches: repeat topographic surveys, sediment traps, and sediment tracers. These techniques provide high-resolution quantitative estimates of volumetric changes and can be used to estimate sediment convergence, divergence, and flux (Miller and Warrick, 2012). Surficial grain size measurements can also provide insight into the structure of the mobile layer of sediment on a mixed beach (Miller and Warrick, 2012). Repeat topographic surveys and surficial grain size measurements are used for monitoring the Ledgewood beach due to the deep-seated nature and coastal setting of this study.

Tidal and current setting

Central Whidbey Island is situated on the convergence of the Strait of Juan de Fuca and the Puget Sound. Within this convergence, the Strait of Juan de Fuca plays a fundamental role in filtering and attenuating wave energy incidents, with the strait defined as an east-west orientated, deep (~200 m), narrow (~20 km), long (~200 km) channel (Miller and Warrick, 2012). Each tidal day in the Puget Sound, there are two unequal low tides and two nearly equal high tides (Miller and Warrick, 2012). In accordance with these tides, the transport of sediment on coarse and mixed beaches higher on the beach foreshore is thought to occur due to the unequal low tide water levels (Miller and Warrick, 2012). Located 12 kilometers across the Admiralty Inlet, NOAA tidal monitoring station 9444900 in Port Townsend, Washington has a mean tidal range of 1.63 meters and a morphologically relevant daily range (between Mean Higher High Water and Mean Lower Low Water) of 2.60 meters (NOAA

CO-OP, 2015), which demonstrations the variability of tidal heights near the study area. In addition to this, drift cells along Admiralty Inlet (Washington State Department of Ecology Coastal Atlas Map) reveal that the dominant sediment transport direction north of the LB Landslide, and including the slide area, is from right to left, which is essentially north. Directly south of the landslide complex is a divergence zone, which occurs when two drift cells with net shore drift in opposite directions, causing the erosional shoreline to have a net shore drift in either direction depending on tides and storm events (Figure 6).

Prior work

Since the landslide's occurrence, Dr. Ian Miller of the Washington Sea Grant has monitored the toe as well as the adjacent beaches to the north and south. He has been using monitoring techniques such as grain size photography and beach profile surveys to fully gauge the changes at and around the toe. Dr. Miller also set up time-lapse photography, which takes photos every 30 minutes, directed at the bluff's toe. This starts on April 2, 2013 and ends on April 5, 2014, with some multi-day time gaps and a month long gap in January 2014. In addition, Dr. Miller ventured to the field site to obtain field images, beach profile data, and grain size photography from 4/2/13, 6/26/13, 8/7/13, 10/24/13, and 4/5/14.

Other government and private agencies have studied the landslide as well, providing supplemental data for this study. On the day following the landslide, the Washington State Department of Natural Resources went out to the landslide area for field reconnaissance and described and studied the scarp, toe, and debris. Geotechnical Engineering Services performed a six-month study to analyze the landslide, evaluate the risk of additional landslide movement, and recommend further monitoring of the slide area (Geotechnical Engineering Services, 2013). Quantum Spatial was contracted by Island County Public Works to collect LiDAR data and digital imagery for the Island County areas of interest (Quantum Spatial, 2014).

Methods

I conducted field work, lab tests, and several data analyses that focus on both the toe of the Ledgewood-Bonair Landslide and its adjacent beaches. On June 5th, 2015, I went out to the study area and assisted Dr. Ian Miller in data collection. Throughout this day we recorded beach profile data on previously measured transects and took grain size photography at preexisting locations which Dr. Miller established on his initial excursions on April 2nd and June 26th of 2013. I also gathered samples from the adjacent beaches to be tested in the lab. I then graphed the beach profile data to visualize beach height changes and processed the grain size photographs using a Matlab script, which identifies average grain size, to determine surficial sediment composition changes through time. I used LiDAR and geographic information systems (GIS) to find the volume changes at the toe and adjacent beaches by differencing LiDAR from when the landslide occurred in 2013 against LiDAR from nearly a year later in 2014. Determining the volume differential provides a basis for how sediment from the toe has influenced and changed the nearshore environment.

Field work

On the morning of June 5th, 2015, I went to the Ledgewood-Bonair Landslide field area with Dr. Ian Miller, meeting at the north end of Driftwood Way. The schedule for the day was to use a GPS to walk transects along the beach and to obtain grain size images at pre-determined locations that Dr. Miller had been monitoring since the 2013 landslide event. To create new topographic lines, we set up the GPS unit and antenna so that it displayed the beach transects that were being monitored. We connected the GPS unit to the Washington State Reference Network for accurate data collection and as I traversed the beach to record data, the GPS recorded data continuously every second. In the afternoon, we took digital grain size photos, along select transects, every half-meter by placing a camera between 0.5 and 1.0 meters above the sample area. In the late afternoon, I examined the toe of the landslide and gathered beach samples from both the north and south side of the scarp in order to determine the beaches grain size distribution.

Laboratory work

In the lab, I placed about three-quarters of each beach sample into a tin and dried it in the oven at 105 degrees Celsius for 24 hours. I then performed a grain size analysis of the two samples to determine the relative proportions of the different grain sizes present. This involved putting the sample through a stack of sieves and shaking them for ten minutes in a mechanical sieve shaker. I weighed the samples in each individual sieve and used this information to compute the percent retained and percent passing for each sieve. I plotted these finding to show the grain size distribution of each sample and to correlate it to the grain size changes monitored from photographs.

Profile transects

Dr. Miller collected transect data during April 2013, June 2013, October 2013, and April 2014. In June 2015 I assisted Dr. Miller in additional data collection. For each survey, topographic lines were traced using a GPS unit that recorded data every second, including the easting, northing, elevation, and coordinates at each point. This GPS unit has a vertical resolution of 3 centimeters. To process and graph the transects, I transferred the data into Excel tables which were then brought into ArcGIS. This involved converting and georeferencing the points so that they would be mapped onto the LB Landslide area. In total, 16 transects were monitored over the two-year study with six on the north beach, six on the toe complex and four on the south beach. I created a profile graph for each transect and a cross-section through the entire study area, encompassing all the transects (Figure 7). This cross-section is drawn using the mid-shoreline of the 2014 DEM and is used as an example of how elevations over the two-year study fluctuate, specifically how elevation changed through time along the beaches and toe complex.

Surficial grain size measurements

Photographic data was collected in June 2013, August 2013, April 2014, and June 2015. An 8.0 megapixel digital camera is used for the grain size photography, held approximately 0.5 to 1 meter above the bed with a ground scale included in the frame of each photo. I assisted Dr. Miller for data collection on June 2015. Grain size photographic data are located on both north and south beach and follow select transects. On the north beach, transects 2 through 6 and on south beach, transects 13 and 14 have grain size data. Since the photographic datasets are not all located on the same coordinates and were not thoroughly monitored over the two year study, the data is examined by comparing changes from 2013 to 2014, 2014 to 2015, and 2013 to 2015. Sieve analyses from the June 2015 samples come from the mid-beach area, where the north beach sample is from transect 6 and the south beach sample is from transect 13 and this analysis is used to compare results from the surficial grain size measurements.

To analyze the photos I used MatLab, a computer programming software, and a grain-size algorithm provided by Dr. Miller. This grain analysis tool manually measures grain sizes in a photo similarly to a pebble count. After running the script, I selected the photos to analyze and zoomed into the scale on the photograph and set the scale of the image, which is 150mm for this study. The following step is determining the view size, which depends on the type of sediment and the uniformity in the photograph. A view size value of 1 indicates cobble bed, a view size of 4 indicates a cobble and sand bed, and a view size of 16 indicates a sand and gravel bed. The value of the view size then divides the image up into different panes. Most images for this study utilized a view size of 16, so each photograph was split into 16 panes so that the sand and gravels could be measured precisely in a more magnified pane. In each pane, points appear and where the points intersect a grain, the intermediate axis of that grain is then measured. Once this procedure is done for the entire image, a spreadsheet of results and raw data is created. Using the coordinates of each point, I then brought them into ArcGIS and projected the coordinates onto the adjacent beaches. I noted points that overlapped and produced a table showing the changes in grain sizes through time.

A major limitation in regards to grain size measurements is that there is about a 20 percent uncertainty in this method for this particular algorithm, according to Dr. Miller who provided the algorithm for this study. To account for this uncertainty, grain size changes over the two year study are assumed to be undetectable if the median grain size, at the same location the following year, is within a 20 percent difference for grain sizes larger than 4.75 millimeters, which is defined as fine gravel. For grains smaller than 4.75 millimeters, defined as anything finer than course sand, a grain size change smaller or equal to one millimeter is considered undetectable. Problems leading to this 20 percent uncertainty include using the tool to measure fine sand, which is not effective since none of the view sizes in the algorithm magnify close enough to measure sand. For this reason, the one millimeter standard is applied. The random points that are displayed on the image panes using the algorithm may not give the most accurate grain size distribution in the image as well. There may be several gravels on a sandy bed surface and a possibility that a point never intersects a gravel. If the point falls onto a non-grain item, such as the measurement board or a piece of seaweed, a grain measurement needs to be taken elsewhere on the image so an alternate procedure needs to be implemented. Shade and overlapping grains also cause visual discrepancies in measuring the intermediate grain sizes (Warrick et al., 2009).

Another limitation to the photographic grain size measurements is that the data is taken nearer to the landslide complex and does not depict how the beaches, 400 meters to the north and south, are changing over time. Along with this, grain size measurements are sensitive to the time of year in which they are observed. The photographs taken in 2014, at the beginning of spring, are taken a season before the other three datasets. Because they are taken during different times of the year, seasonal differences from storms and variations in wave energies can cause surficial differences on the beach sediments.

GIS analysis

i. GIS data sources

Three datasets are used to find volume changes of the landslide area as well as the adjacent beaches. Dr. Miller obtained the 2013 dataset from Island County, who obtained LiDAR on the day following the landslide event. This dataset has a resolution of three feet and is projected in Washington State Plane North, NAD 1983. The 2014 dataset was gathered between March 21st and April 11th of 2014 for Island County Public Works. This 2014 DEM has a resolution of three feet and is projected in Washington State Plane North, NAD 1983 (PSLC, 2015). The 2005 DEM is a combination of bathymetry and topographic data of the Puget Lowland projected in Washington State Plan North, NAD 1983 (Finlayson, 2005). For this study, all data were projected in Washington State Plan North (feet), NAD 1983.

ii. Identifying and creating areas of interest

The first step to finding volume changes between 2013 and 2014 is identifying elevation changes between the two datasets. To visualize the LB Landslide study area, I created a hillshade layer for both the 2013 and 2014 datasets. Utilizing the hillshade layers I then mapped the features of the landslide and nearby beaches by digitizing polygons at these locations. I initially mapped the entire landslide area and then I mapped the toe of the landslide. I considered the portion beneath Driftwood Way the toe to exclude elevation changes at the upper-scarp. Following the same procedure, I mapped both the north and south beach of the landslide. Using the digitized polygon data layers, I then extracted the 2013 and 2014 rasters that intersected these polygon data layers. As a result, the new layers included: a landslide extent area, landslide toe area, a north beach and south beach.

A constraint to creating areas of interest is that tidal heights between the 2013 and 2014 datasets cause data along the 2013 shoreline to be unusable since it was obtained at a lower tide. Due to the tidal difference, a large portion of the landslide toe cannot be compared against 2014, and thus this portion needed to be mapped and compared with another dataset. The tidal differences also influence how the beach polygons are mapped. Thus, the 2013 DEM was used as the upper foreshore's mapping extent since the study is interested in how the beach has changed since the landslide's occurrence, whereas the 2014 DEM was used as the lower foreshore's mapping extent due to the tideline.

iii. Finding the change in volume between 2013 and 2014

I determined the elevation change between the two datasets using the raster subsets of each area of interest. To calculate this, I subtracted the 2013 dataset cell-by-cell from the 2014 dataset. Following this, I isolated the increased material from the decreased material and created an analysis mask. In essence, values below 0 were reclassified as elevation decreases and values above 0 were reclassified as elevation increases. I then used these layers as masks to find the volume of material, both increased and decreased, at each subset location.

I then calculated the increase or decrease in volume of material from the landslide extent, the landslide toe, the north beach, and the south beach. For each cell, I calculated a volume increase or decrease based on the measured change in elevation at each cell location and multiplied by the planar area (i.e., size) of each cell (ESRI Canada, 2011). This output is the increased or decreased volume. I then summed the per-cell volumes within each of the mask areas to get the total volume of material represented by the net elevation increase or decrease.

iv. Finding the change in volume between 2005 and 2013

To find the volume change of the portion of landslide toe that extends beyond the 2014 dataset, the Far Toe, I used 2005 bathymetry data. The purpose for the bathymetry data is that it covers both topography and bathymetry at the study area, providing an area of comparison for the toe of the landslide that was deposited into the Puget Sound. Though the 2005 data is derived from the most optimal mapping systems from 2004 (Finlayson, 2005), the resolution is much lower than the 2013 dataset. Because of this lower resolution, I resampled the 2013 raster to match the 30x30 cell size of the 2005 DEM. Then, following the same procedure used to find the change in volume between 2013 and 2014, I determined the elevation change between the 2005 and 2013 datasets and created an analysis mask.

To find volume change of an area, the older dataset needs to be subtracted from the newer dataset. In this case, the 2005 DEM is subtracted from the 2013 DEM and the output is an increase because the landslide debris at this location does not exist in 2005. However, this area, identified as the Far Toe, does not exist in the 2014, which is a later date than 2013, since this portion of the landslide has been eroded. Because this Far Toe no longer exists in 2014, the area is considered a decrease for this study although it is calculated as an increase.

v. Areas of interest within the landslide complex

Figure 8 displays the areas of interest at the site of the LB Landslide. The Landslide Extent is the portion of landslide that is within the 2014 dataset. Likewise, the Landslide Toe is also the portion of landslide that is within the 2014 dataset but focuses on the area beneath Driftwood Way, in essence the toe. The Far Toe is the area in which bathymetry data was used to calculate the volume of landslide that could not be compared against the 2014 DEM. The Landslide Complex is a combination of the Landslide Extent and the Far Toe and the Toe Complex is a combination of the Landslide Toe and Far Toe (not pictured in the figure).

vi. Calculating volume uncertainty

Because the 2013 and 2014 datasets were taken under different conditions, I implemented an accuracy test to see if the elevation difference between the two datasets would be negligible between the two years. For this, I selected an area on both polygons where I assumed no change would have taken place and created a polygon layer. Upon calculating the elevation change at this location, the average difference was 0.012 meters, with a standard deviation of 0.055 meters.

Using these values, I calculated the uncertainty of each area of interest, including the LB Landslide Complex, Landslide Toe, North Beach and South Beach. The equation used was:

$$(area \times .012) + \sqrt{.055 \times number\ of\ nodes} \qquad (1)$$

where the area is the area of the polygon of interest and the number of nodes is equivalent to the area of the polygon. Due to the lower resolution of the 2005 dataset, an uncertainty value of the Far Toe is assumed to be half of its calculated volume since the DEM's had to be resampled to a larger cell size.

Results

Initial landslide changes

On April 2nd, Dr. Miller set up time-lapse photography directed at the southern portion of the toe to monitor the erosive processes and beach morphology changes. From the time of initiation of the landslide on March 27th to Dr. Miller's field reconnaissance on April 2nd, the toe of the landslide had already been significantly eroded from tidal and wave action based on comparisons between the 2013 LiDAR and photographs taken by Dr. Miller. Throughout the period covered by the photoset, significant erosion of the toe bluff occurs, particularly in the days following the time-lapse photography set-up (Figure 9). It is assumed that during the landslide event, large gravels were sorted and deposited at the base of the landslide due to mass movement and loosening of sediments within the complex. These gravels, now at the base of the landslide toe, are exposed to wave and tidal action and it is assumed that they are redeposited onto the adjacent upper foreshore based on the photos taken at the landslide and from the time-lapse photographs. The gravels are then either buried by finer sediments from the toe bluff or are carried away through alongshore sediment transport in the following days and weeks. Over time the bluff recedes, depositing colluvium and interglacial and glacially derived sands, silts, and clays into the waters of the Puget Sound and onto the beaches. As a result, there is accretion along the north and south beaches closest to the landslide scarp.

Volume changes

The three areas with a net volume decrease are the Landslide Extent, the Landslide Toe, and Far Toe area (Figure 8). Within these locations, there are areas in which volume is increasing (Table 1 and Figure 10). A volume increase is occurring at the Landslide Extent due to continued slope failure throughout the bluff, particularly from the headscarp where calving of material is being redeposited on the landslide debris. At the Landslide Toe, the volume increase comes from two source areas: the upper toe slope and adjacent edges. Along the upper slope, settling and slumping of material has led to small volume increases, while the adjacent edges, defined as the beginnings of the beaches, have had post-landslide debris pushed up and deposited there. The North Beach and the South Beach both exhibit a net volume increase where the small decrease in volume comes from shoreline erosion.

The entire Far Toe is combined with the Landslide Extent and Landslide Toe so that a net volume change of the Landslide Complex and Toe Complex can be determined. Nearly 90 percent of the total net volume decrease of the Landslide Complex occurred at the Toe Complex. At the Toe Complex, 8.9 percent of the volume decrease has been transported to the adjacent beaches, which is calculated by comparing the net change of the north and south beach to the net change of Toe Complex. Comparing both the north and south beach separately, the north beach’s net volume increase is 6.3 percent and the south beach’s net volume increase is 2.6 percent of the 8.9 percent volume decrease from the Toe Complex. These findings demonstrate that most of the volume decrease within the landslide occurred at the toe and only a small portion of that material ended up on the adjacent beaches, with the north beach experiencing more accretion than the south (Figure 10).

The volume changes of the study areas, as calculated using GIS, are summarized in Tables 1. Highlighted rows indicate summed results (refer to GIS methods section *v*). In these calculations, an uncertainty factor is included due to the 0.012 meter elevation difference between the 2013 and 2014 datasets and due to the poor resolution of the 2005 bathymetry dataset.

Table 1: Summary of the volume changes found between the 2013 and 2014 datasets.

Location	Volume Decrease (m^3)	Volume Increase (m^3)	Net Change (m^3)	Uncertainty (m^3)
Landslide Extent	50,600	15,270	35,330	+/- 850
Landslide Toe	31,610	1,110	30,500	+/- 260
Far Toe	11,350	0	11,350	+/- 5,670
North Beach	330	2,970	2,640	+/- 120
South Beach	1,030	2,110	1,080	+/- 130
Landslide Complex	61,950	15,270	46,680	+/- 6,520
Toe Complex	42,960	1,110	41,850	+/- 5,930
North and South Beach	1,360	5,080	3,720	+/- 250

Elevation changes

A cross-section along the mid-shoreline and through the transects illustrates how, over the two-year study, the elevation decreases at the toe complex and increased on the beaches closest to the toe complex (Figure 11). Within the toe complex, there is a significant decrease in elevation from April 2nd to June 26th of 2013 due to the quick erosion of landslide debris. The beach areas closest to the toe also experience the most accretion from April 2nd to June 26th. After this first two and half months, the rate of erosion at the toe became much slower while the rate of accretion along the beaches subsided, where material did not remobilize but remained at a steady elevation (Appendix A).

Grain size changes

On the north beach, the overall trend is that the beach is experiencing a fining of surficial sediment. Over the two-year time frame, coarse sand has been replaced by finer sands in the areas closest to the landslide complex, within 150 meters (Figure 12 and Figure 13). A sieve analysis from the north beach also suggests that the dominant grain size nearer to the landslide in fine to medium sized sand (Appendix B). The area of south beach closest to the landslide complex, within 100 meters, experiences sediment coarsening, particularly along the mid-beach area (Figure 12 and Figure 14). Over the two-year study, the grain size changes from medium to coarse sand to finer sized gravels. A sieve analysis on the south beach suggests a dominant grain size of fine to medium size gravels mixed with well-graded sand (Appendix B). It should be noted that grain size changes are sensitive to the time of year in which they are observed. On both the north and south beach, from 2013 to 2014, there is evidence of coarsening of surficial sediment which can be attributed to seasonal variations in storm events and wave energies, since 2014 photography was taken in April. Data from 2015 then suggests that the north beach has been experiencing a fining and the south beach has been experiencing a coarsening of surficial sediment over the two-year study.

Discussion

This study aimed to determine how sediment from the Ledgewood-Bonair Landslide has nourished, or augmented the volume of, the adjacent beaches to the north and south. Of the sediment displaced at the LB Landslide complex, nearly 90 percent came from the toe of the landslide. However, of that displaced material, only 8.9 percent ended up on the adjacent beaches to the north and south, with the north beach experiencing more accretion than the south beach. The small percentage that did end up on the beaches is assumed to be some of the sands, silts, and clays that made up the toe of the landslide. The fine-grained material in which the toe was composed of could have been washed away into the inlet and transported away from the adjacent beaches. The portion of beach that did experience significant accretion was the areas closest to the landslide complex, 150 meters north and 100 meters south.

Alongshore transport is influential in how the beaches changed geomorphologically and why the north beach experienced more accretion than the south. As previously mentioned, the dominant direction of alongshore transport at the site of the landslide is to the north, while at the southern edge of the landslide complex, alongshore transport shifts to a divergence zone. Since the landslide toe lies in the dominant northward direction of alongshore transport, the north beach experienced more accretion, which is based on the volumetric analysis and supplemental graphed profile data. Additionally, since the sediment of the landslide and bluff are of finer materials, it is the reason why the surficial grain size on the north beach adjacent to the landslide became finer over time. The south beach, on the other hand, experiences less accretion than the north beach since the alongshore current can change direction, which can transport sediment either northward or southward. The coarsening in grain size at the south beach, however, should to be studied further due to the small amount of data.

A significant impact on the beaches of Ledgewood would encompass a complete change in grain sizes along the beaches as well as total accretion 400 meters to the north and south. In the case of the LB Landslide, only a small fraction of the toe debris was redeposited onto the beaches, with measureable accretion occurring 150 meters north and 100 meters south. The dominant grain size on the already mixed beaches shifted from a coarse-sand to a fine-sand on the north beach and from a coarse-sand to fine-gravel on the south beach over the two-year study. From grain size photography and sieve analysis, the fine sediments from the landslide toe were insufficient to change the mixed-sediment beaches at Ledgewood to a non-mixed, uniform grain size.

In a time when sea levels are expected to rise and global climate will be changing, hazardous events and severe weather will become more widespread. Within the Puget Sound of western Washington, the subsurface geology in the region combined with additional water from precipitation events or groundwater transport greatly increases the nature of landsliding. Due to this combination, ancient landslide complexes along coastlines, which have had observable movement within the past few years, need to be monitored. More studies like this one are needed to fully gauge the beach morphology changes experienced by a deep-seated coastal landslide in order to improve future planning strategies.

Conclusion

Volumetric analysis indicates that of the 41,850 cubic meters of material that eroded at the toe of the landslide, 8.9 percent was redeposited on the adjacent beaches to the north and south. Due to the assumed rotational-translational failure mechanism and underlying geologic composition of the landslide, erosion of the toe occurred after the landslide commenced due to the tidal and wave action acting on the debris. This erosion initially deposited debris and coarser sediments along the adjacent foreshore due to sorting during the landslide event, which placed coarse gravels and cobbles on the lower landslide toe. In the following days and months, the sands, silts, and clays of which the landslide debris was composed periodically calved off and eroded the toe, depositing finer sediments along the shoreline. Results show that the areas of beaches most affected by the deep-seated landslide were 150 meters to the north and 100 meters to south, where the difference is attributed to dominant alongshore transport paths found at the coastline. Surficial grain size at the north beach also became finer, resembling the material that was being eroded from the landslide while on the south beach the surficial sediment type became coarser. The volumetric changes measured from DEM differencing, in combination with repeat topographic surveys and grain size photography at the Ledgewood-Bonair Landslide and adjacent beaches, suggest that accretion from a deep-seated landslide composed of sands, silts, and clays has local effects on the beach profile and grain size.

References

ASTM, 2011. Standard practice for classification of soils for engineering purposes: ASTM International, Designation: D2487-11.

ASTM, 2011. Standard practice for description and identification of soils: ASTM International, Designation: D2488-09a.

Booth, D. B., Troost, K. G., and Clague, J. J., Waitt, R. B., 2003. The cordilleran ice sheet. *Developments in Quaternary Sciences* 1, 17 – 43.

Booth, D. B., Troost, K. G., and Hagstrum, J. T., 2004. Deformation of Quaternary strata and its relationship to crustal folds and faults, south-central Puget Lowland, Washington State. *Geology* 32, 505 – 508.

Bowles, J.E., 1978. Engineering Properties of Soils and their Measurement: McGraw-Hill, Inc. Second edition, 250 pp. ISBN 0-07-006752-X

Burrett, Justin, 2013. Ledgewood devastated by landslide. *Whidbey News-Times*. http://www.whidbeynewstimes.com/news/200282061.html (accessed December 2015).

ESRI Canada Education, 2011. Lessons for ArcGIS – Mount St. Helens before and after. *ESRI Canada*.

Finlayson, David, 2005. Combined bathymetry and topography of the Puget Lowlands, Washington State. School of Oceanography, University of Washington. Tile:g1230485.

Finlayson, David, 2006. The geomorphology of Puget Sound beaches. *Puget Sound Nearshore Partnership*. Report No. 2006-02.

Geotechnical Engineering Services, 2013. Ledgewood Landslide Evaluation Whidbey Island, Washington. File No. 0422-097-00.

Johannessen, J. and MacLennan, A., 2007. Beaches and bluffs of Puget Sound. *Puget Sound Nearshore Partnership.* Report No. 2007-04.

Johnson, S. Y., Potter, C. J., Armentrout, J. M., Miller, J. J., Finn, C., and Weaver, C. S., 1996. The southern Whidbey Island fault: An active structure in the Puget Lowland, Washington. *GSA Bulletin* 108, 334 – 354.

Liberty, L. M., and Pape, K. M. Seismic characterization of the Seattle and Southern Whidbey Island Fault zones in Snoqualmie River Valley, Washington. *Center for Geophysical Investigation of the Shallow Subsurface*.

Miller, I. M., 2013. A tour of the Ledgewood Slide, 2 April 2013. https://www.youtube.com/watch?v=c-_GWHbIT9Q (accessed January 2016).

Miller, I. M., Warrick, J. A., Morgan, C., 2011. Observations of coarse sediment movements on the mixed beach of the Elwha Delta, Washington. *Marine Geology* 282, 201 – 214.

Miller, I. M. and Warrick, J. A., 2012. Measuring sediment transport and bed disturbance with tracers on a mixed beach. *Marine Geology* 299, 1 – 17.

NOAA CO-OPS, 2015. Port Townsend, WA Station 9444900. National Oceanic and Atmospheric Administration. https://tidesandcurrents.noaa.gov/stationhome.html?-id=9444900 (accessed December 2015).

Polenz, M., Schasse, H. W., Kalk, M. L., Petersen, B. R., 2009. Geologic map of the Camano 7.5-minute quadrangle, Island County, Washington. *Washington State Department of Natural Resource Division of Geology and Earth Resources*, GM-68.

Porter, S. C. and Swanson, T. W., 1998. Radiocarbon age constraints on rates of advance and retreat of the Puget lobe of the Cordilleran ice sheet during the last glaciation. *Quaternary Research* 50, 205 – 213.

Puget Sound LiDAR Consortium (PSLC), 2015. 2000-2005 Lower Sound Projects. www.pugetsoundlidar.org.

Quantum Spatial, 2014. Technical Data Report – Island County LiDAR project. http://pugetsoundlidar.ess.washington.edu/lidardata/restricted/nonpslc/island2014/Island_County_LiDAR_Report.pdf

Shipman, Hugh, 2001. Coastal landsliding on Puget Sound – a review of landslides occurring between 1996 and 1999. *Washington Department of Ecology, Shorelands and Environmental Assistance Program* 01-06-019.

Shipman, Hugh, 2004. Coastal bluffs and sea cliffs on Puget Sound, Washington. *U.S. Geological Survey Professional Paper* 1693, 81 – 95.

Slaughter S., Sarikhan, I., Polenz, M., and Walsh, T., 2013. Quick report of the Ledgewood Bonair Landslide, Whidbey Island, Island County, Washington. Department of Natural Resources, Division of Geology and Earth Resources.

Swanson, T. W., 2013. Landslide processes and hazards on Whidbey Island, WA. https://designlangley.files.wordpress.com/2013/05/whidbeyislandlandslides.pdf

Swanson, T. W., Late Pleistocene glacial history of Whidbey Island, WA. http://faculty.washington.edu/tswanson/302add/Field%20Trips/Trip2009.pdf

Troost, K. G., Booth, D. B., 2008. Geology of Seattle and the Seattle area, Washington. *Geological Society of America Reviews in Engineering Geology XX*, 1 – 35.

United States Census Bureau. Cartographic Boundary Shapefiles – State. http://www.census.gov/geo/maps-data/data/cbf/cbf_state.html

Warrick, J. A., George, D.A., Gelfenbaum, G., Ruggiero, P., Kaminsky, G.M., and Beirne, M., 2009. Beach morphology and change along the mixed grain-sized delta of the dammed Elwha River, Washington. *Geomorphology* 111 (3-4), 136 – 148.

Warrick, J. A., Rubin, D.M., Ruggiero, P., Harney, J., Draut, A.E., and Buscombe, D., 2009. Cobble-cam: grian-seize measurements of sand to boulder from digital photographs and autocorrelation analyses. *Earth Surface Processes and Landforms* 1811 – 1821.

Washington State Department of Ecology. Coastal Atlas. https://fortress.wa.gov/ecy/coastalatlas/Default.aspx

Washington State Department of Natural Resources. Whidbey Island Coupeville Landslide. https://washingtondnr.wordpress.com/2013/03/27/whidbey-island-coupeville-landslide/ (accessed January 2016).

Figures

Figure 1. Overview map of the study area where (a) indicates the location on Whidbey Island and (b) indicates where the Ledgewood-Bonair landslide occurred in 2013.

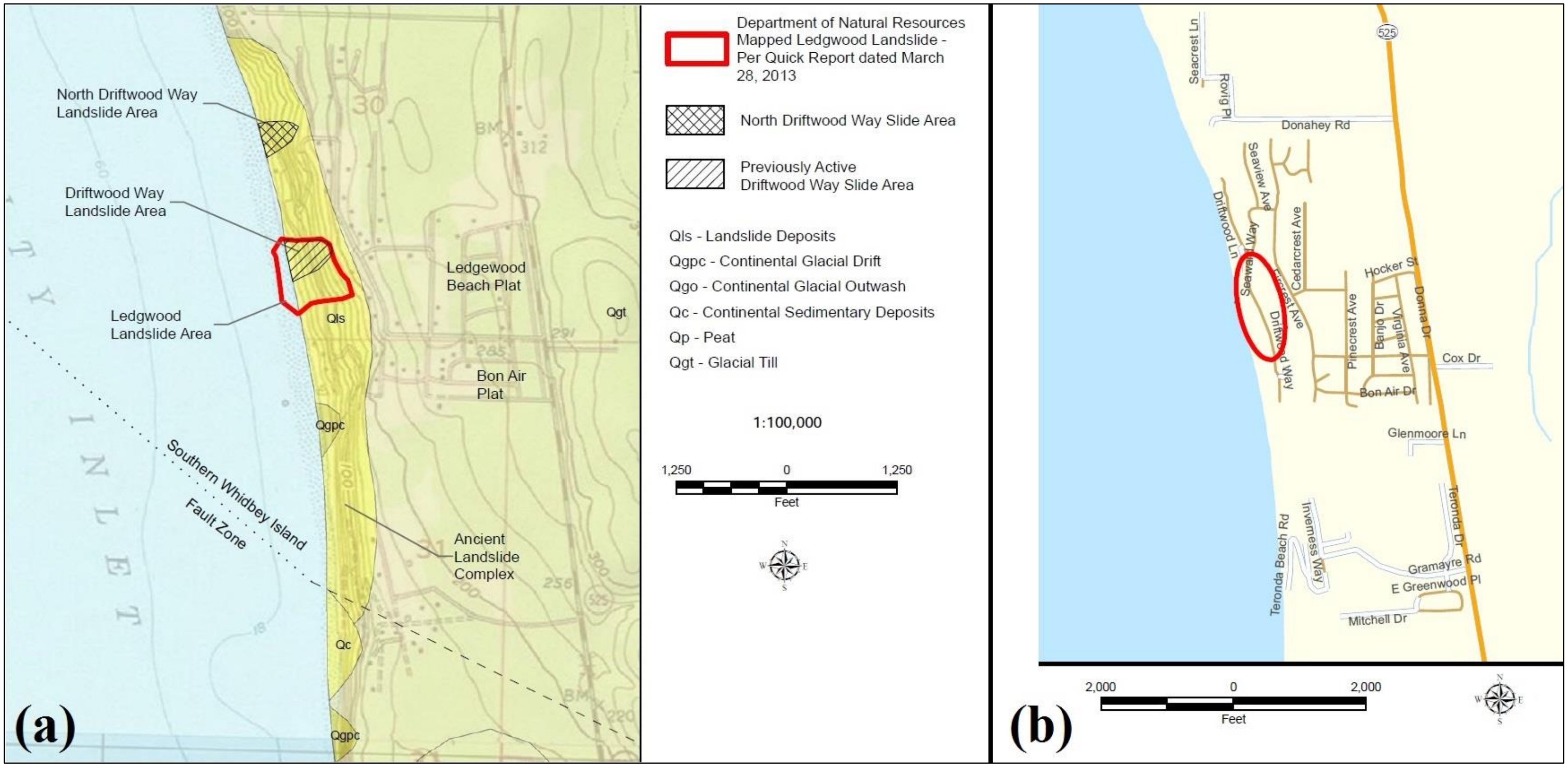

Figure 2. (a) Generalized geology and landslide map of the Ledgewood-Bonair Landside area. Note the positioning of the recent landslides within the ancient landslide complex. (b) Road map of the Ledgewood Community. The red circle indicates the location of the LB Landslide (Geotechnical Engineering Services, 2013). (Modified by Matthew Teich, 2016)

Figure 3. Before and after aerial images of the Ledgewood-Bonair Landslide area. The portion of landslide located beneath Driftwood Way is considered the Landslide Toe. The landslide occurred on the morning of March 27th, 2013 (Washington Department of Natural Resources, 2013). (Modified by Matthew Teich, 2016)

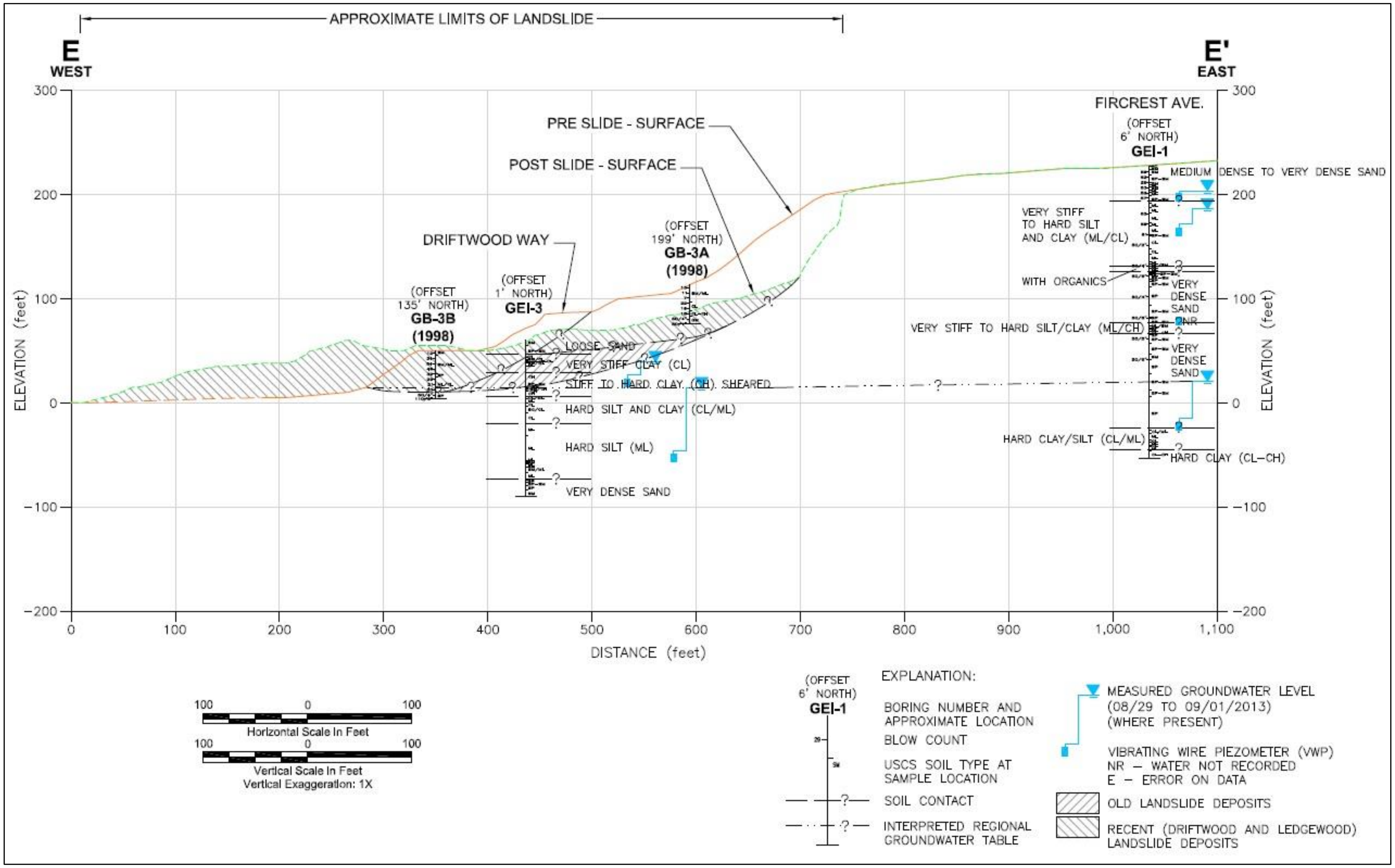

Figure 4. Cross section through the Ledgewood-Bonair Landslide where E is in the Admiralty Inlet and E' is upland of the landslide. This is based on interpolation and shows the subsurface conditions of the landslide complex (Geotechnical Engineering Services, 2013). (Modified by Matthew Teich, 2016)

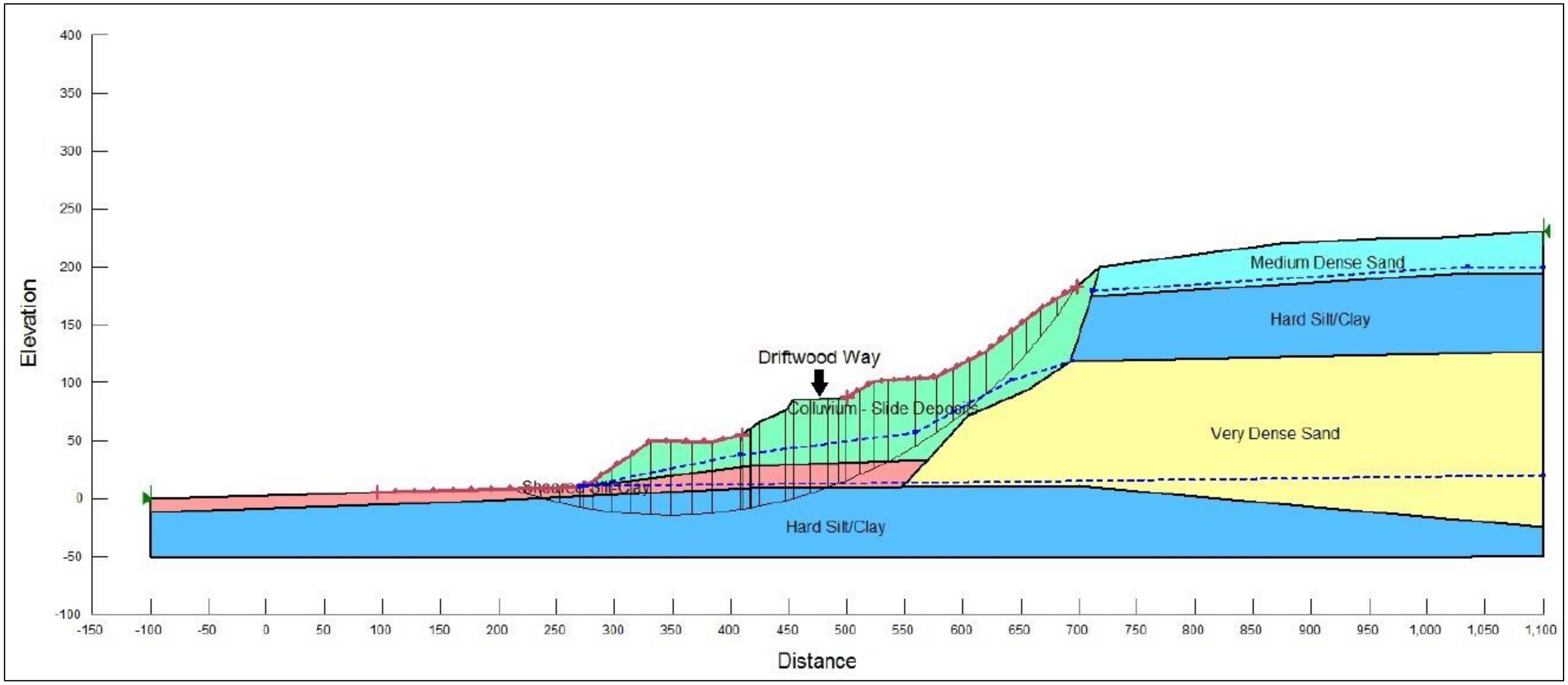

Figure 5. Slope stability model of the Ledgewood-Bonair Landslide. Note, this is an inferred schematic and underlying strata at the landslide can be different than shown (Geotechnical Engineering Services, 2013). (Modified by Matthew Teich, 2016)

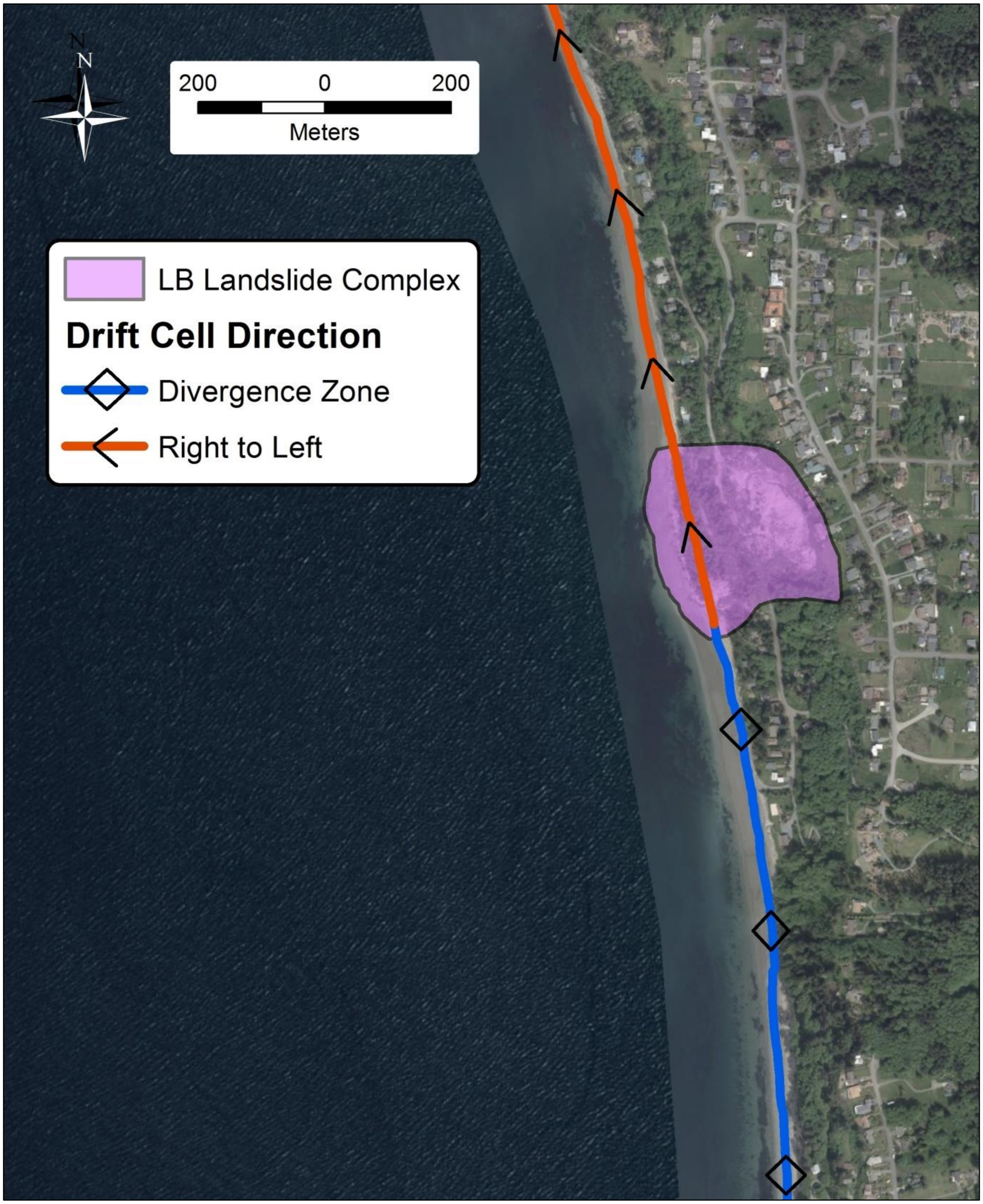

Figure 6. Map showing drift cell directions along the adjacent beaches of the Ledgewood-Bonair Landslide. In this instance, right to left is in the northern direction (Washington State Department of Ecology Coastal Atlas Map).

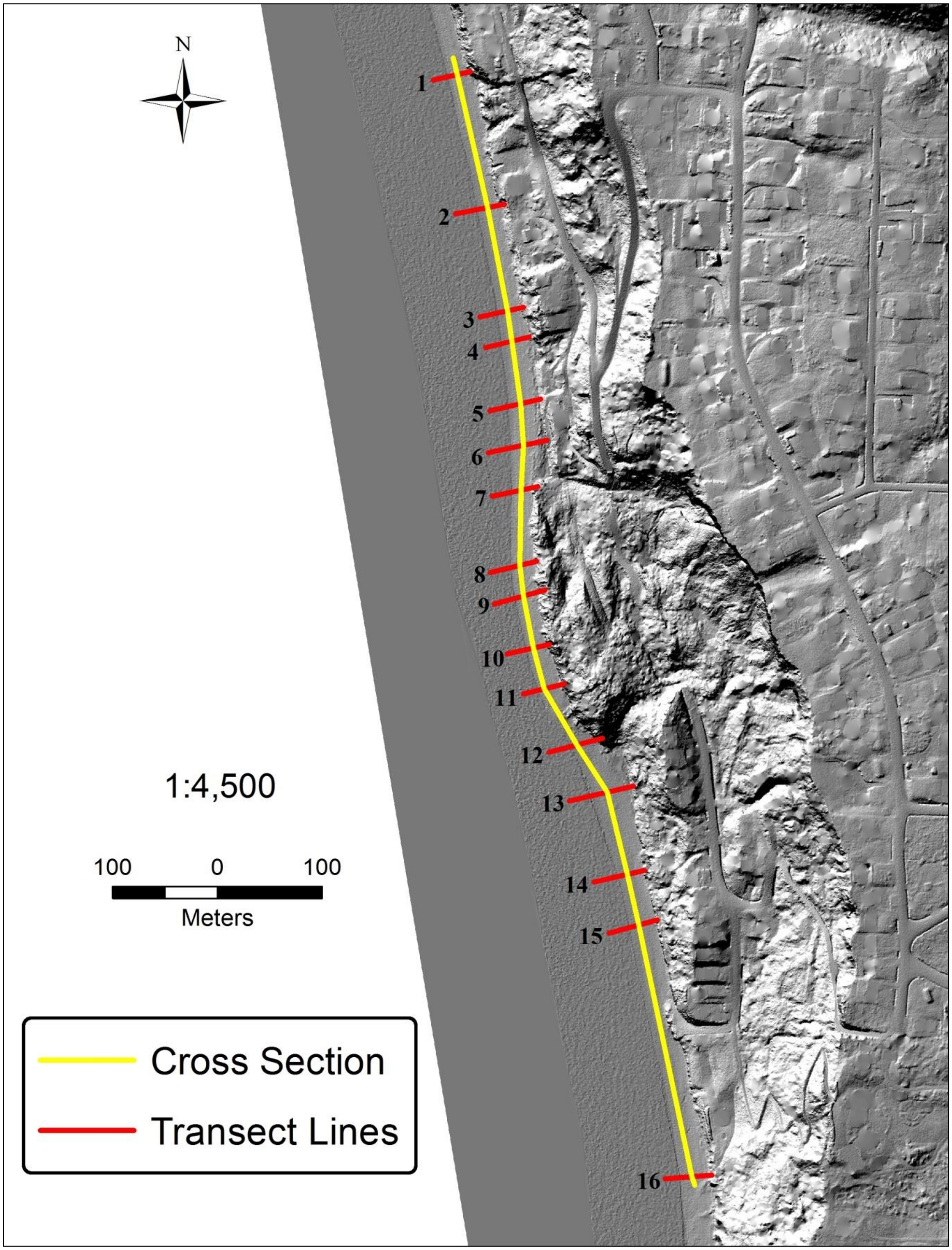

Figure 7: Map showing the monitored transect locations over the two year study and cross-section drawn following the mid-shoreline of the 2014 Hillshade.

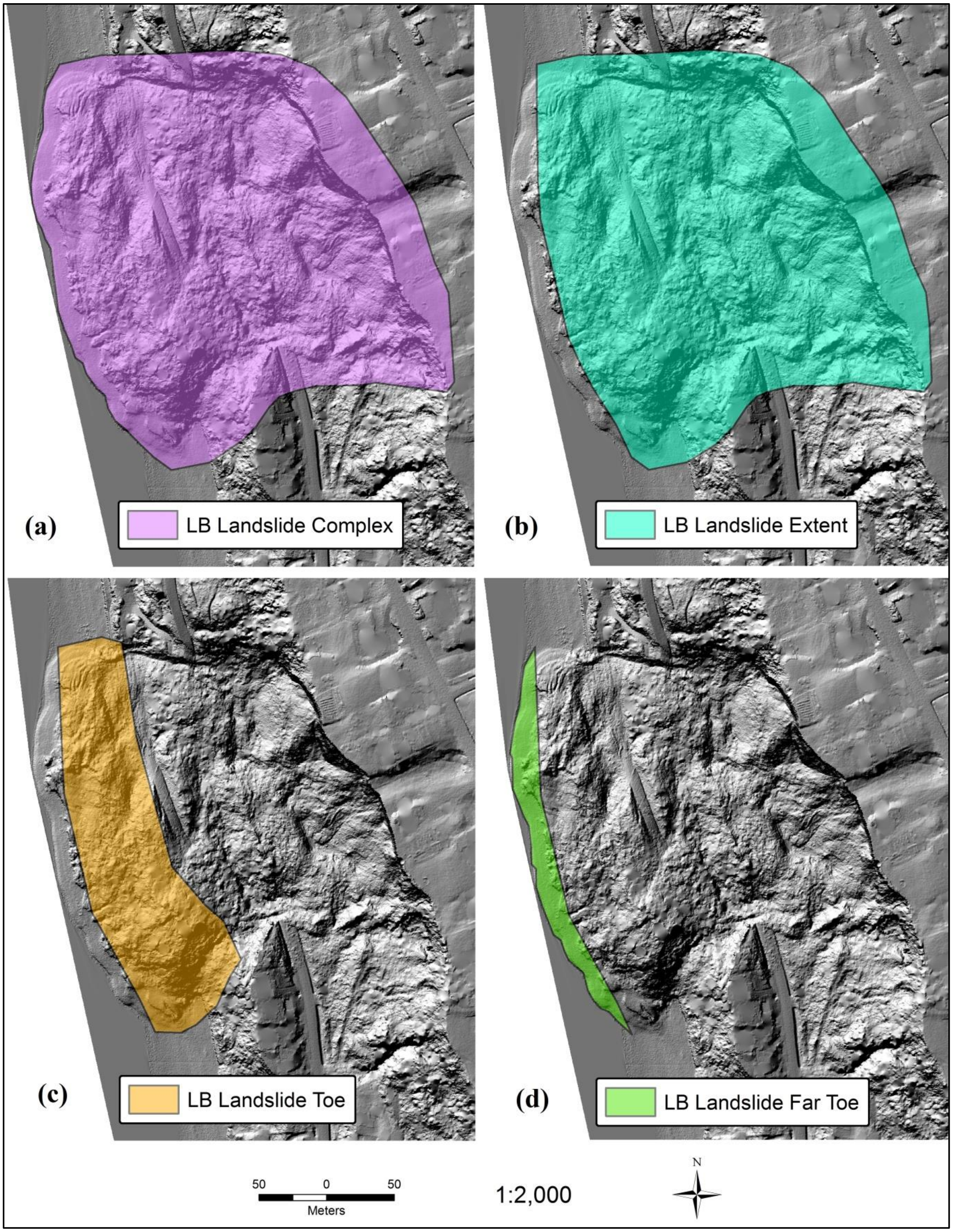

Figure 8: Mapped areas of interest overlaid on the 2013 Hillshade. (a) is the mapped LB Landslide area, (b), the LB Landslide extent, and (c), the LB Landslide Toe, are mapped as a result of the 2014 DEM tidal line. (d), the Far Toe, is compared against the 2005 DEM and added to (b) and (c) to create the LB Landslide Complex and Toe Complex.

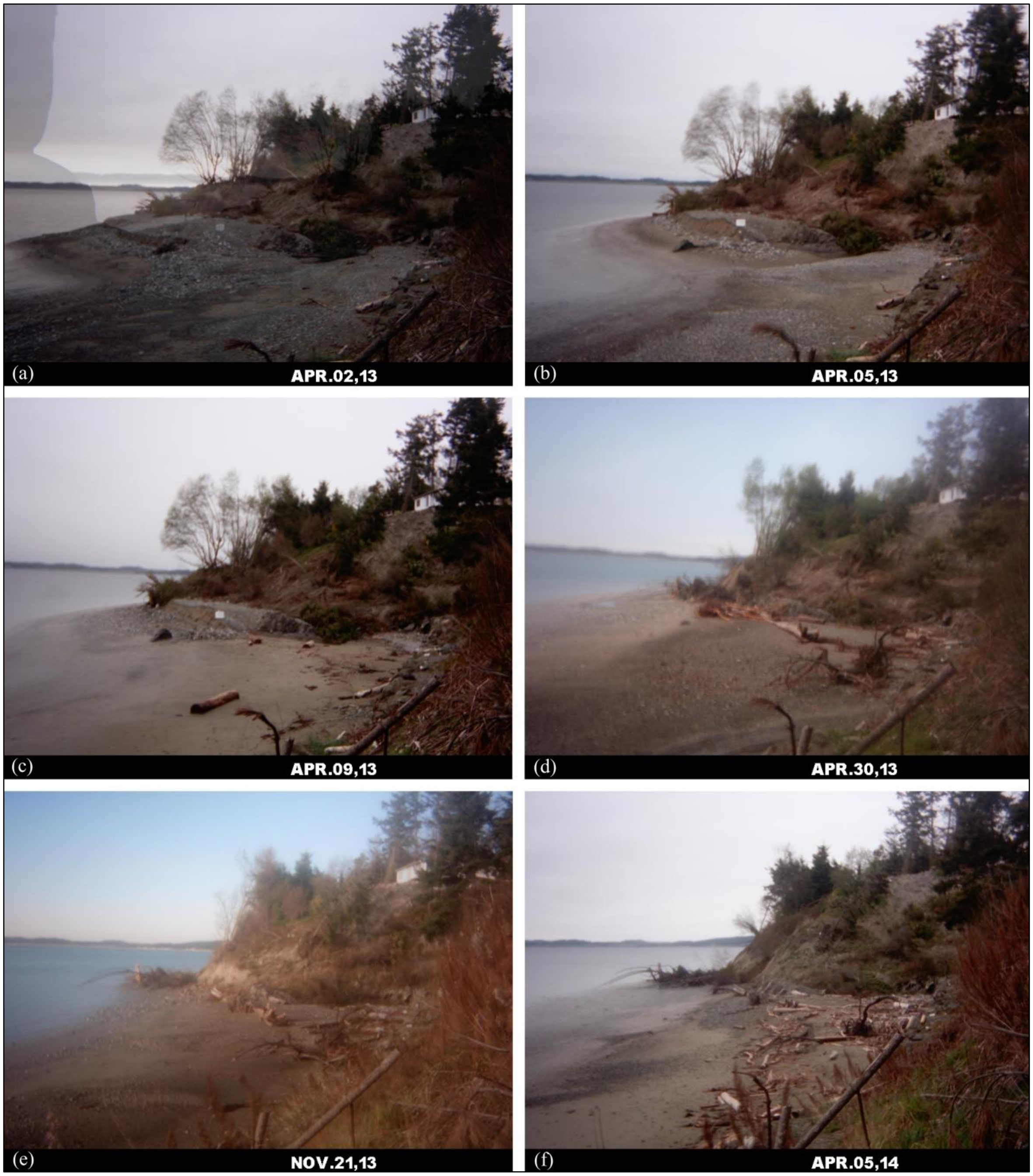

Figure 9. Over the course of the timelapse photography, each days photos were averaged together to create one image per day. Above are select images taken over the yearlong timelapse. (a) is the first day of the time lapse series and here terraces at the toe and coarse gravels on the foreshore can be seen. (b), which occurs three days later, reveals how quickly the toe is being eroded away. (c) shows how the beach went from being coarse post-landslide gravels to a sandy mixture. In (d) the tree on the toe is no long there, as it fell over onto the beach debris. (e) and (f) provide a sense of how the toe and southern adjacent beach changes through time.

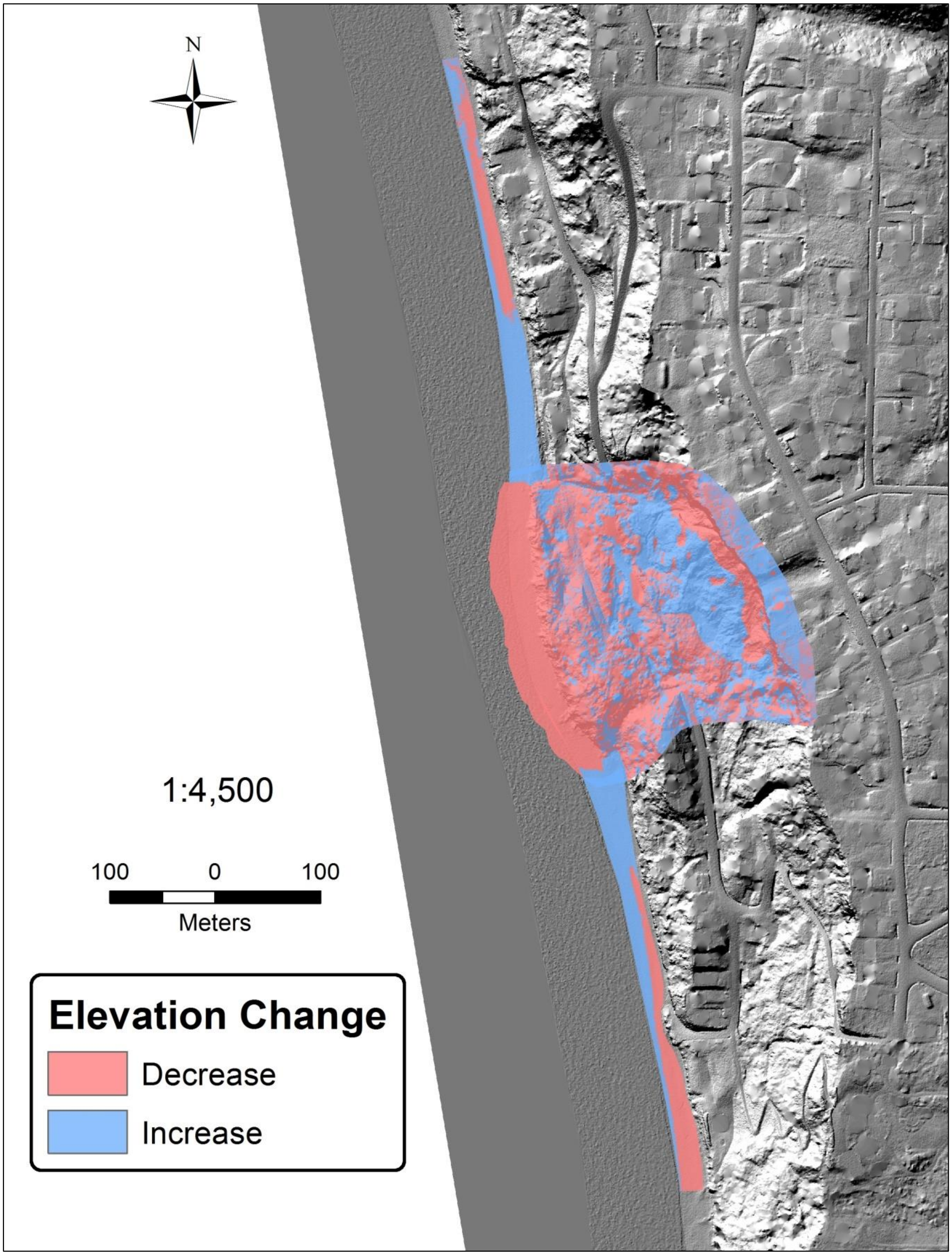

Figure 10. Map of the LB Landslide and adjacent beaches showing the areas where there is volume decrease and volume increase between 2013 and 2014.

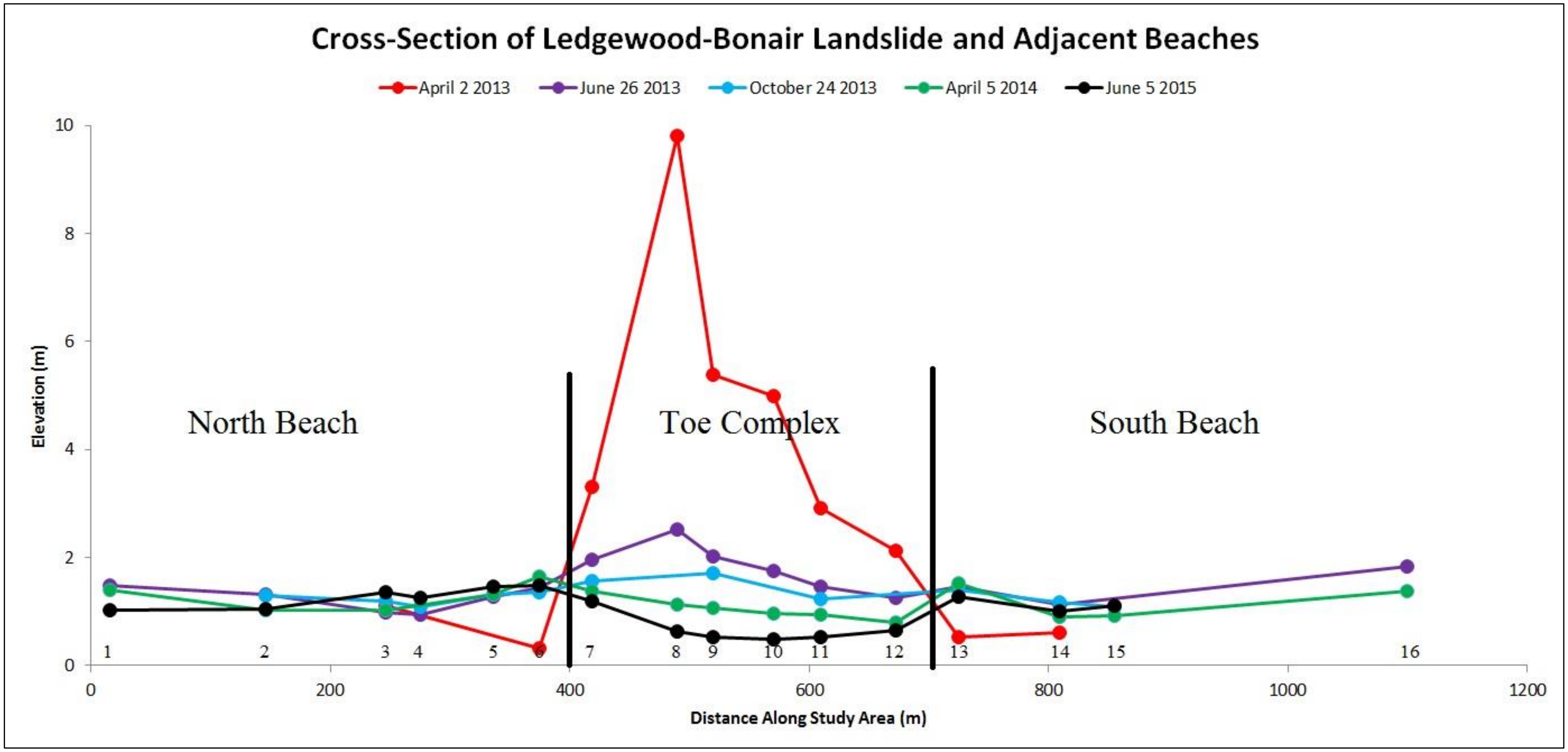

Figure 11. Cross-section through the monitored transects, refer to Figure 7. Transect locations are labeled above the x-axis and black vertical lines separate study areas.

Date	Transect	Mean Grain Size	2013 to 2014	2014 to 2015	2013 to 2015
2013	2	27.69	46.05		
2014	2	73.74			
2013	3	3.05	35.15		
2014	3	38.19		-37.73	
2015	3	0.46			-2.58
2013	3	12.80	17.24		
2014	3	30.04		-29.70	
2015	3	0.34			-12.46
2013	3	3.25	3.99		
2014	3	7.24		-1.78	
2015	3	5.47			2.22
2013	3	23.76	-15.14		
2014	3	8.62		-2.26	
2015	3	6.36			-17.40
2013	3	34.24	-32.46		
2014	3	1.78			
2013	3	19.55	1.00		
2014	3	20.56			
2013	4	4.05	-2.16		
2014	4	1.90		-1.47	
2015	4	0.42			-3.63
2013	4	4.24	-3.80		
2014	4	0.44		0.05	
2015	4	0.49			-3.75
2013	5	0.41	0.15		
2014	5	0.56		0.06	
2015	5	0.62			0.21
2013	5	0.88	-0.03		
2014	5	0.85		-0.22	
2015	5	0.63			-0.25
2013	6	0.38	45.12		
2014	6	45.50		-45.09	
2015	6	0.42			0.03
2013	6	6.84			
2015	6	0.46			-6.37
2013	6	1.10	-0.67		
2014	6	0.43		0.01	
2015	6	0.44			-0.66
2013	6	6.06			
2015	6	0.40			-5.66
2013	6	19.87			
2015	6	0.51			-19.36
2013	6	2.92			
2015	6	0.43			-2.49
2013	6	0.37			
2015	6	9.31			8.94

Date	Transect	Mean Grain Size	2013 to 2014	2014 to 2015	2013 to 2015
2013	13	0.79	-0.28		
2014	13	0.51		-0.05	
2015	13	0.46			-0.33
2013	13	1.09			
2015	13	1.85			0.77
2013	13	1.81	4.56		
2014	13	6.37		-4.77	
2015	13	1.60			-0.21
2013	13	1.03			
2015	13	5.69			4.66
2013	13	0.42			
2015	13	24.87			24.45
2013	13	0.52			
2015	13	37.39			36.86
2013	13	0.52			
2015	13	0.67			0.16
2013	14	6.18	13.78		
2014	14	19.96		-19.53	
2015	14	0.43			-5.75
2013	14	1.41			
2015	14	0.41			-1.00
2013	14	1.62			
2015	14	8.64			7.02
2013	14	2.01			
2015	14	13.80			11.79
2013	14	0.55			
2015	14	3.14			2.59

Figure 12. Mean grain size data (in millimeters) at monitored locations. Left is North Beach data and right is South Beach data. Dates are color coded and alternating gray and white within a transect indicate different locations along that transect. The top most location starts at upper beach foreshore.

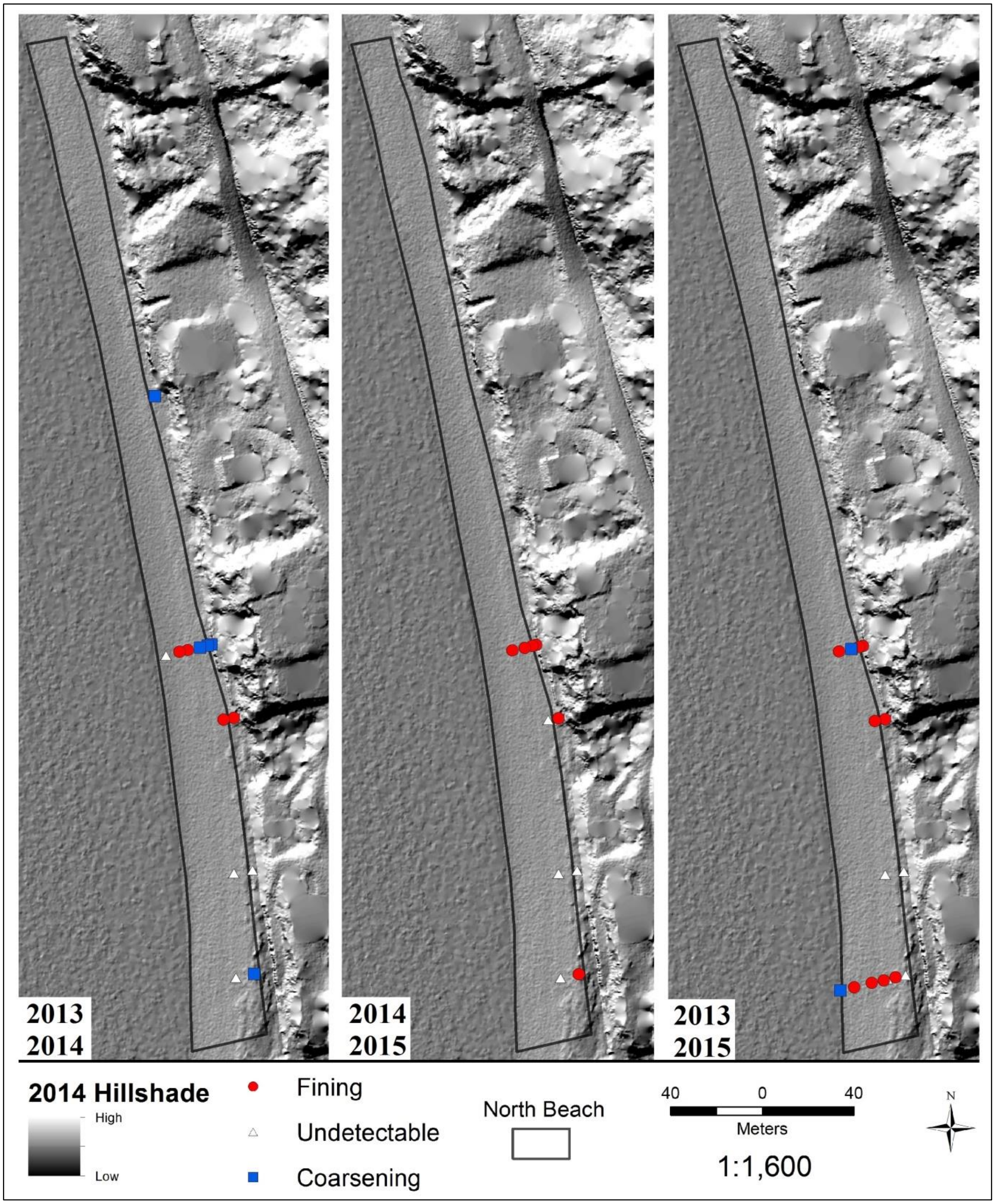

Figure 13. Mapped grain size changes along North Beach over the two years study.

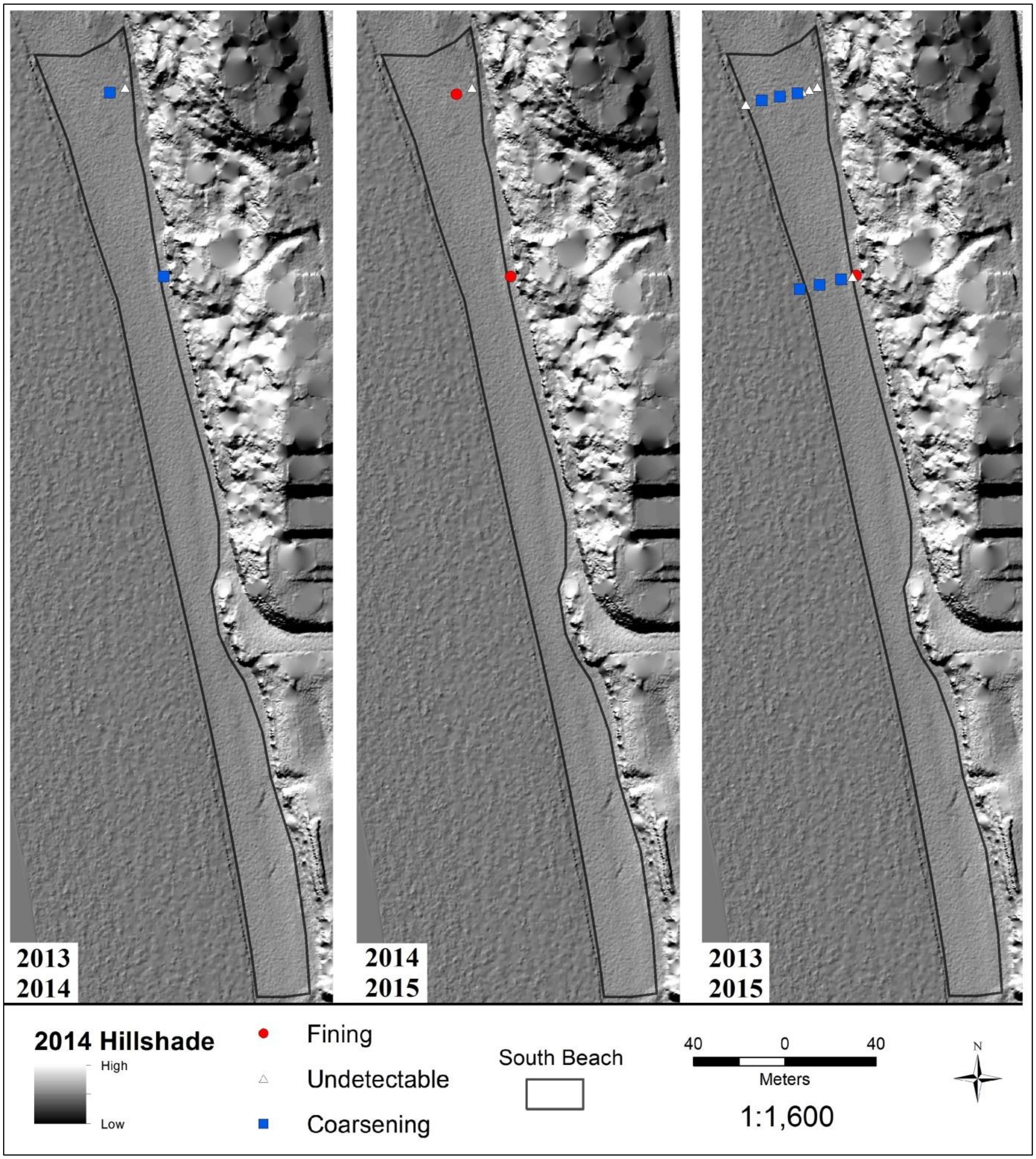

Figure 14. Mapped grain size changes along South Beach over the two years study.

Appendix A: Beach Topographic Profiles

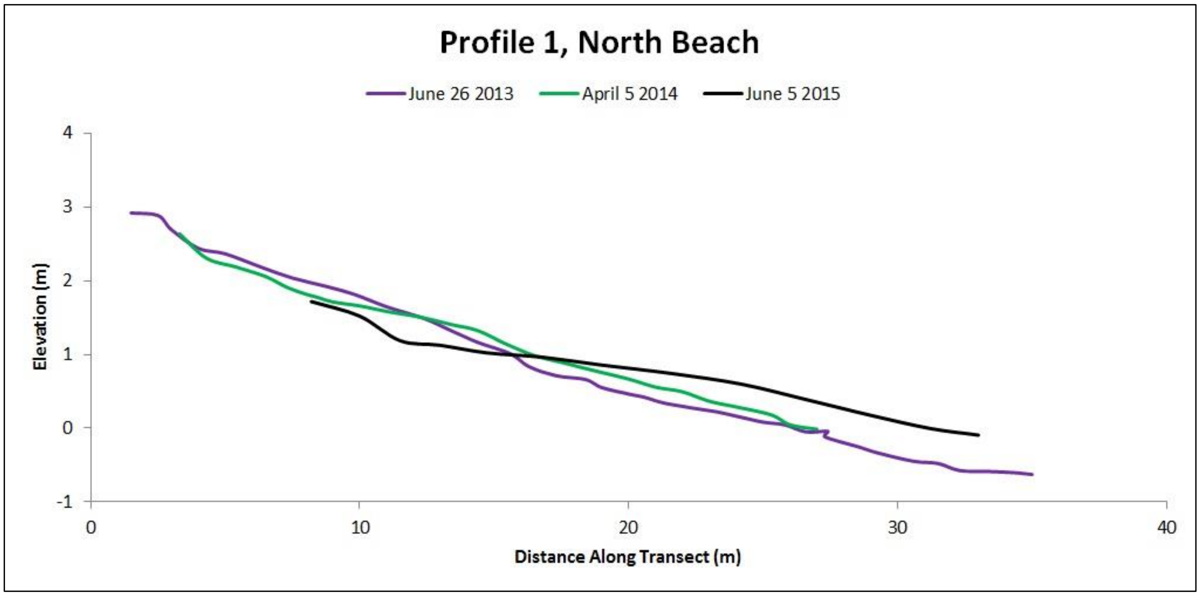

Figure A-1. Profile of Transect 1.

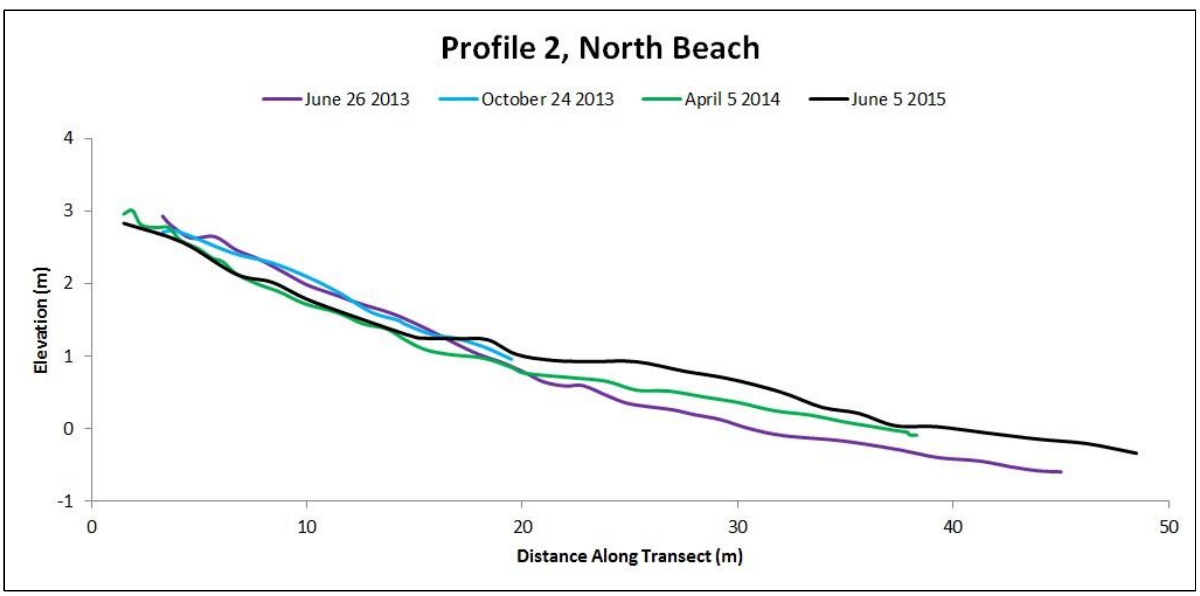

Figure A-2. Profile of Transect 2.

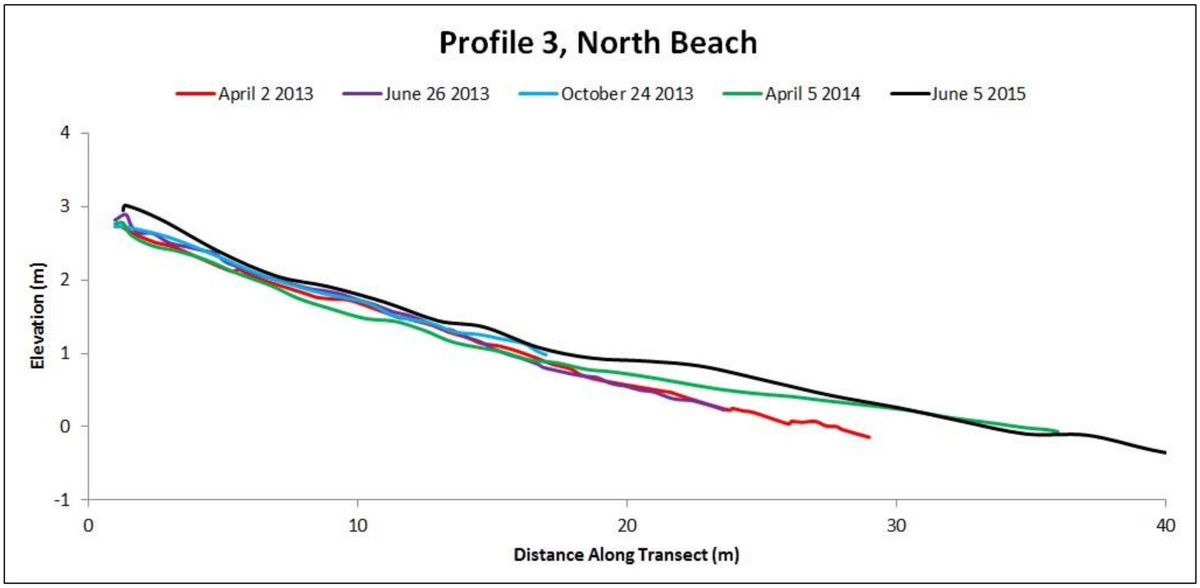

Figure A-3. Profile of Transect 3.

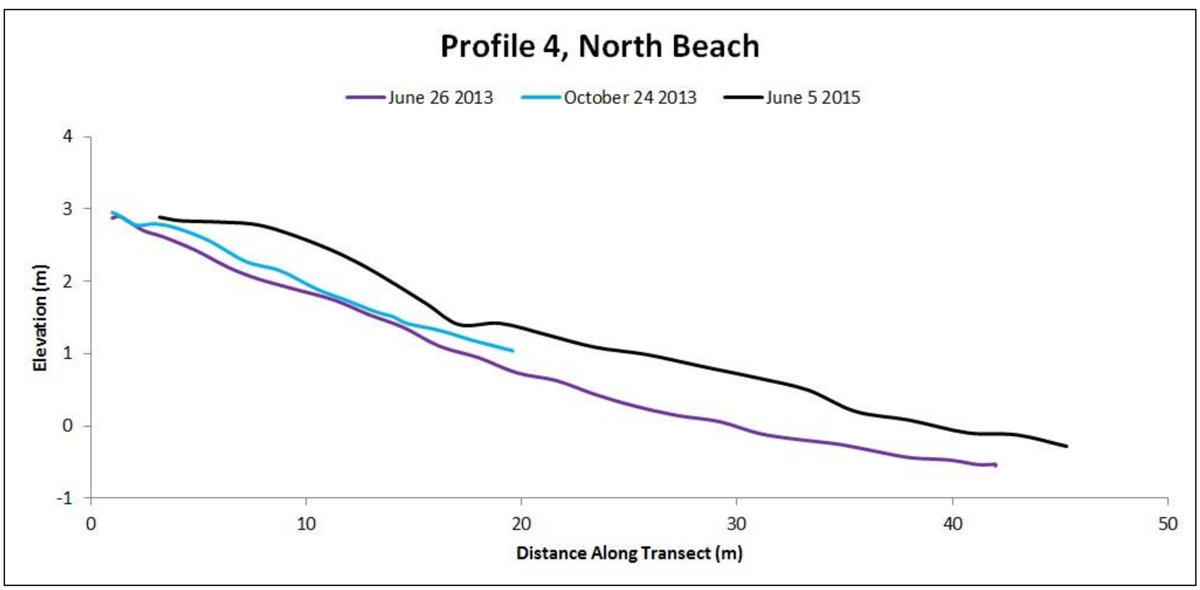

Figure A-4. Profile of Transect 4.

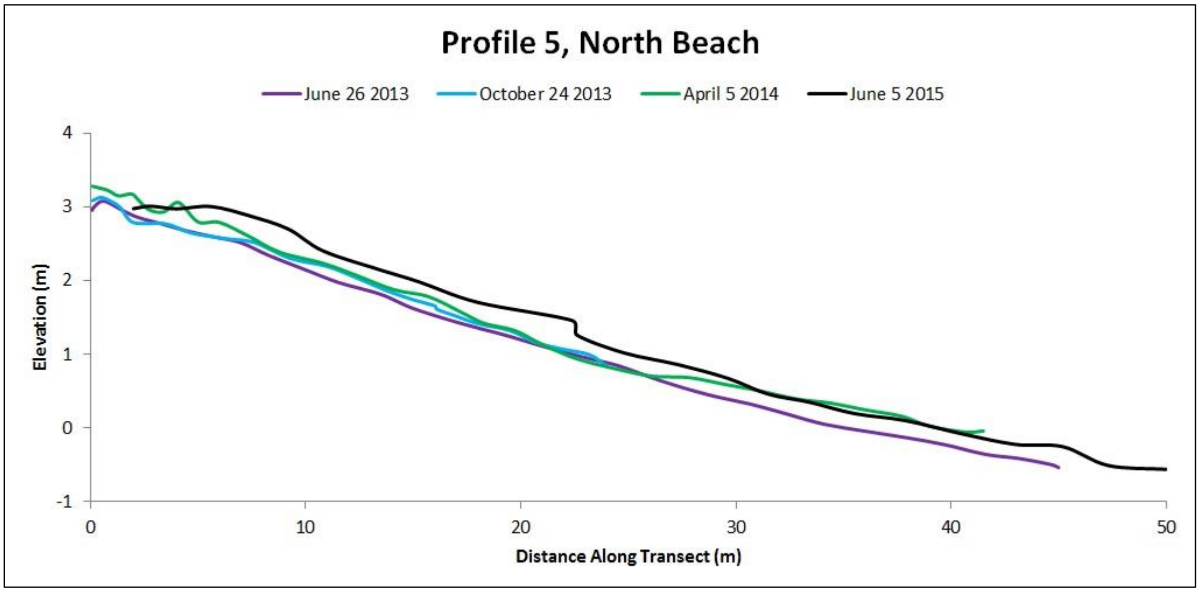

Figure A-5. Profile of Transect 5.

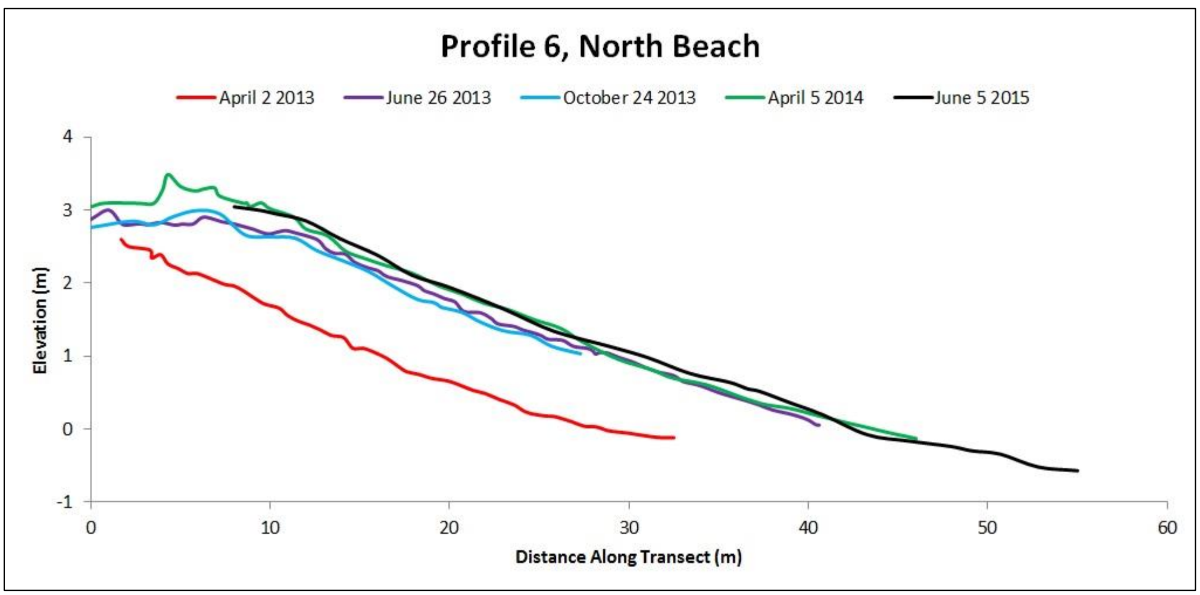

Figure A-6. Profile of Transect 6.

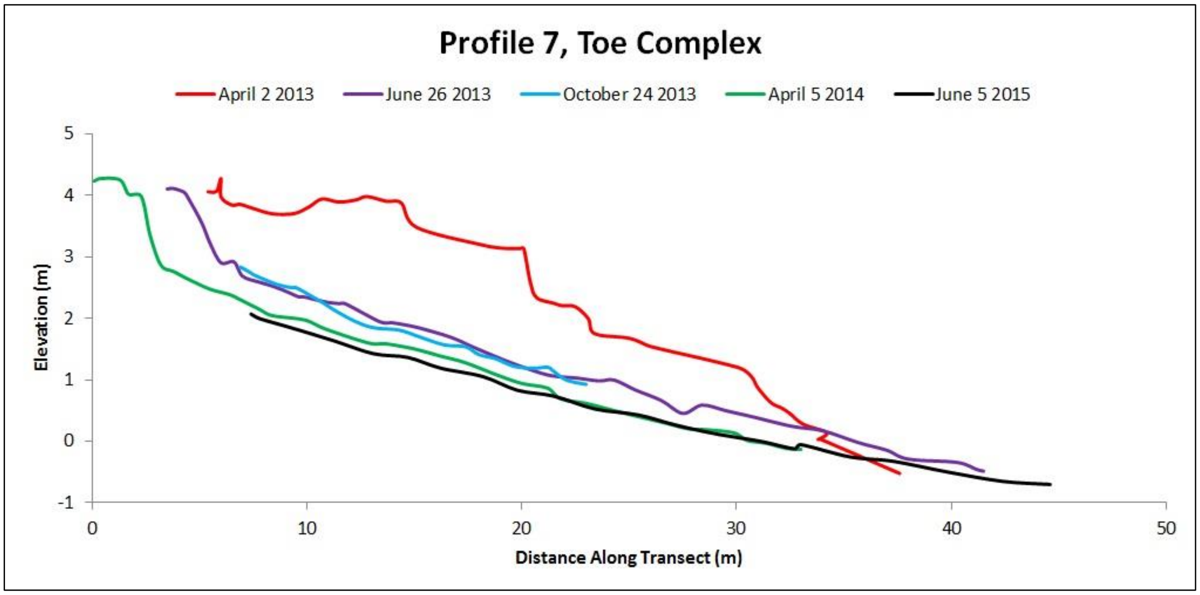

Figure A-7. Profile of Transect 7.

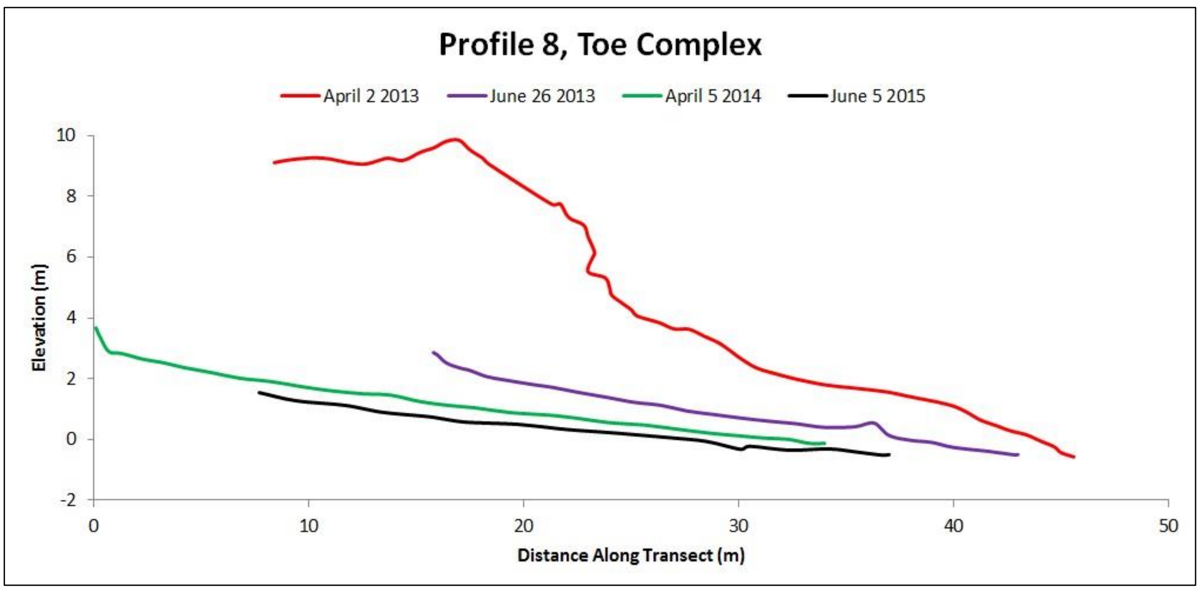

Figure A-8. Profile of Transect 8.

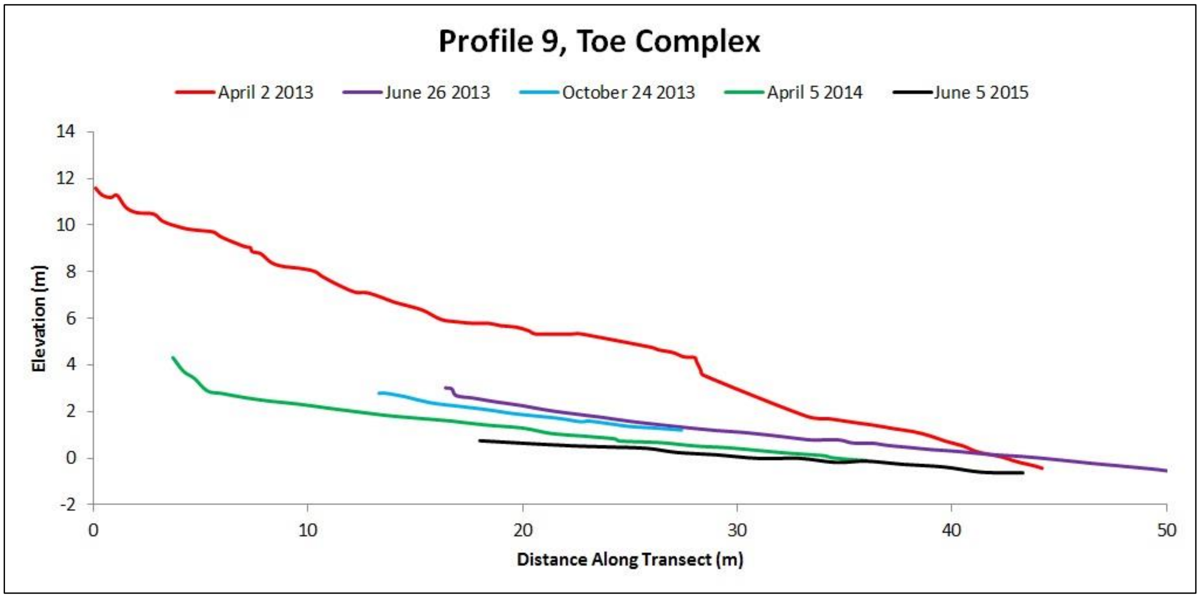

Figure A-9. Profile of Transect 9.

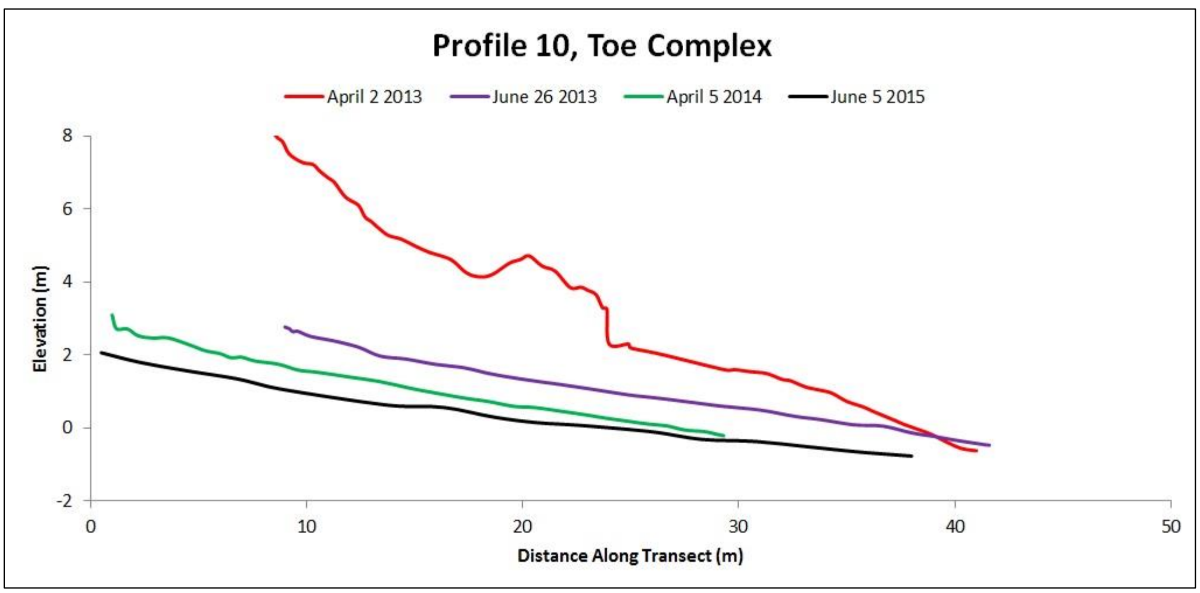

Figure A-10. Profile of Transect 10.

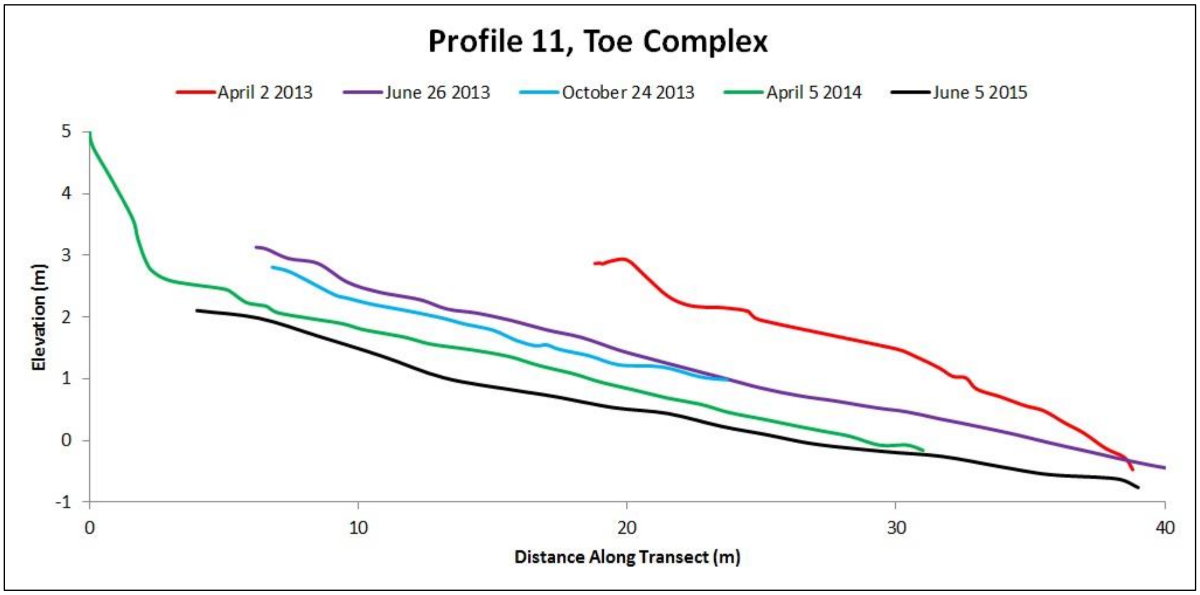

Figure A-11. Profile of Transect 11.

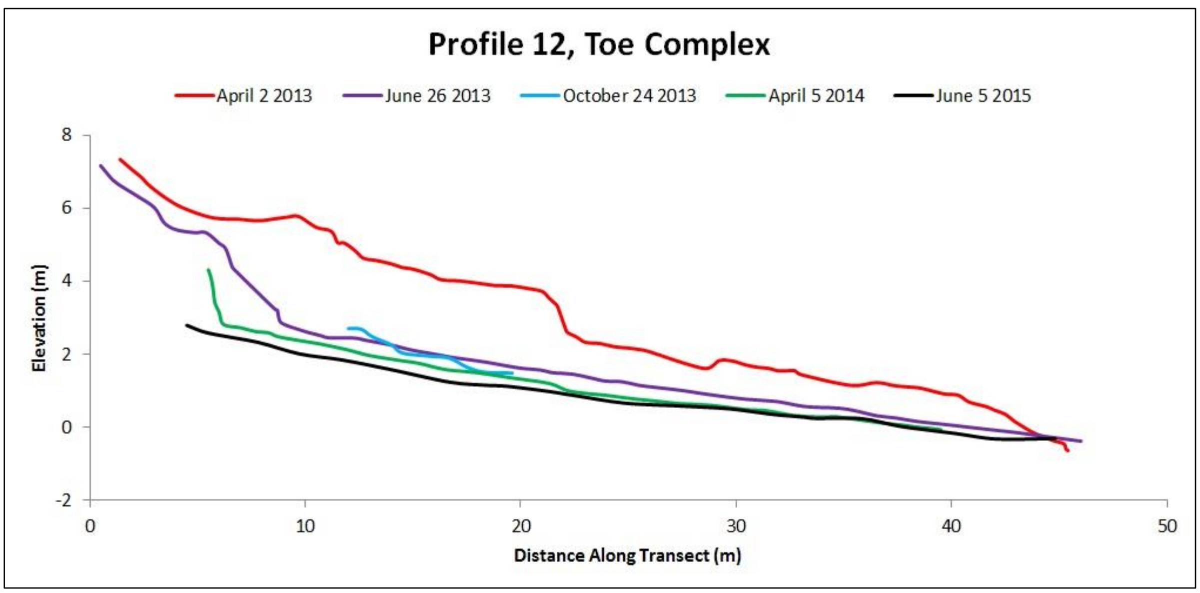

Figure A-12. Profile of Transect 12.

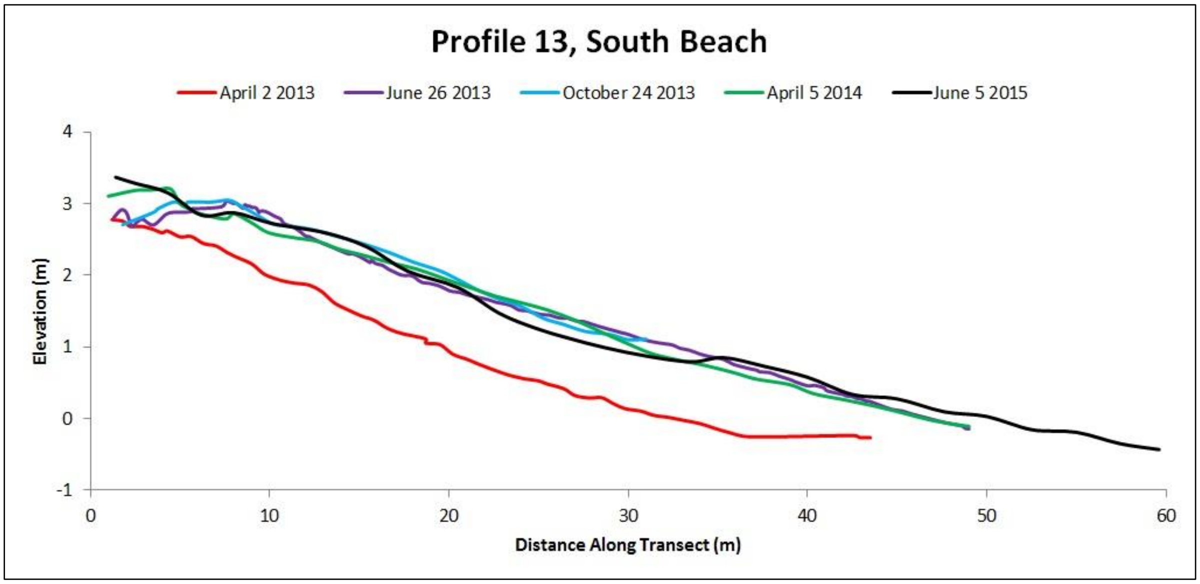

Figure A-13. Profile of Transect 13.

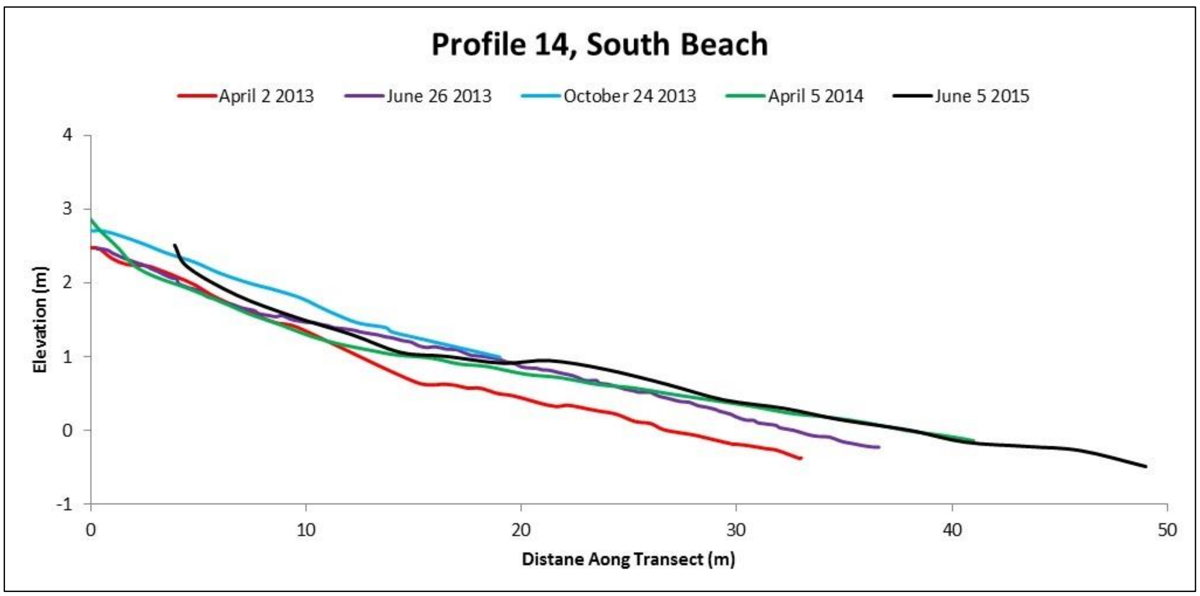

Figure A-14. Profile of Transect 14.

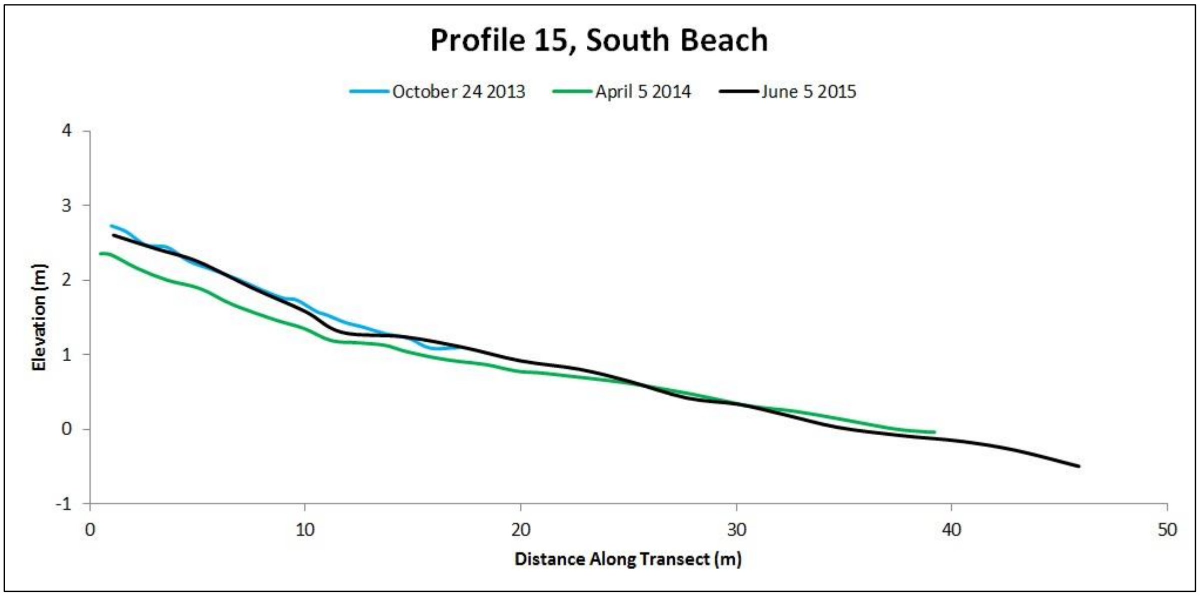

Figure A-15. Profile of Transect 15.

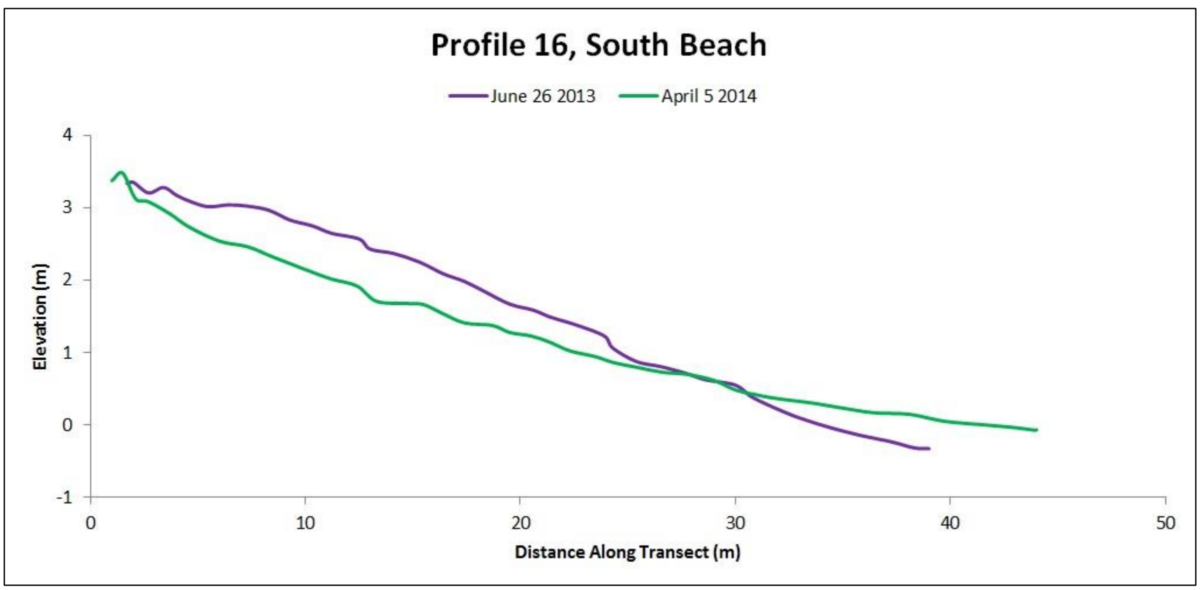

Figure A-16. Profile of Transect 16.

Appendix B: Grain Size Analysis

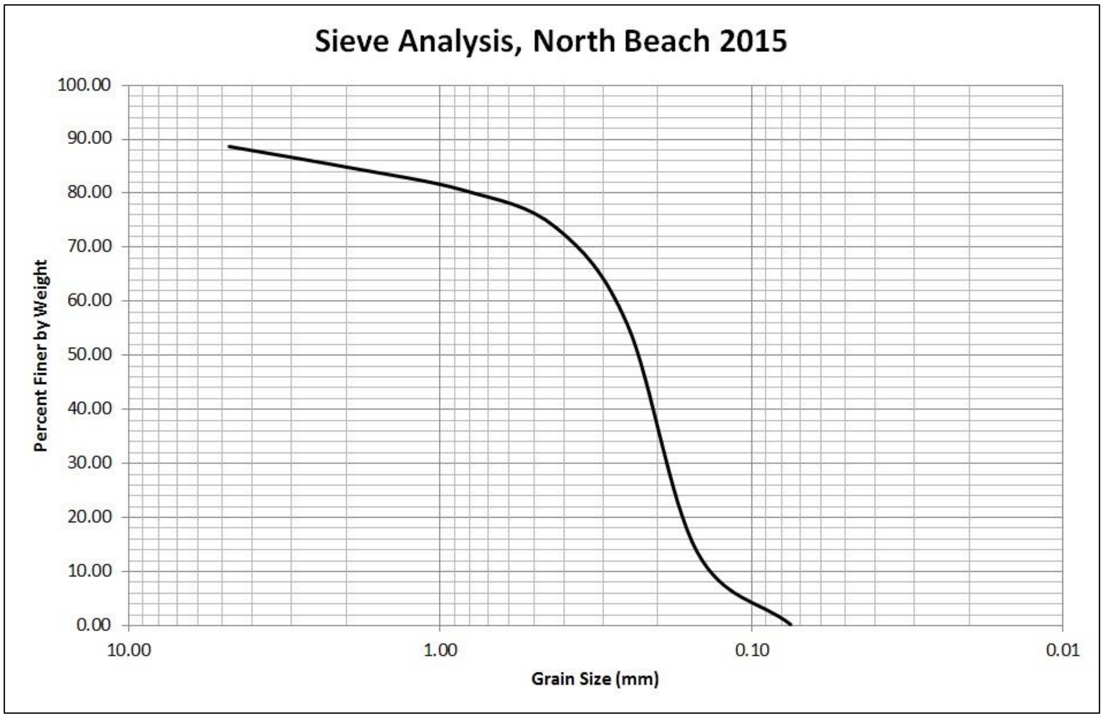

Figure B-1. Sieve analysis from mid-beach of Transect 6, North Beach. Note that sediment distribution is well-graded with the dominant sediment type being fine to medium sand.

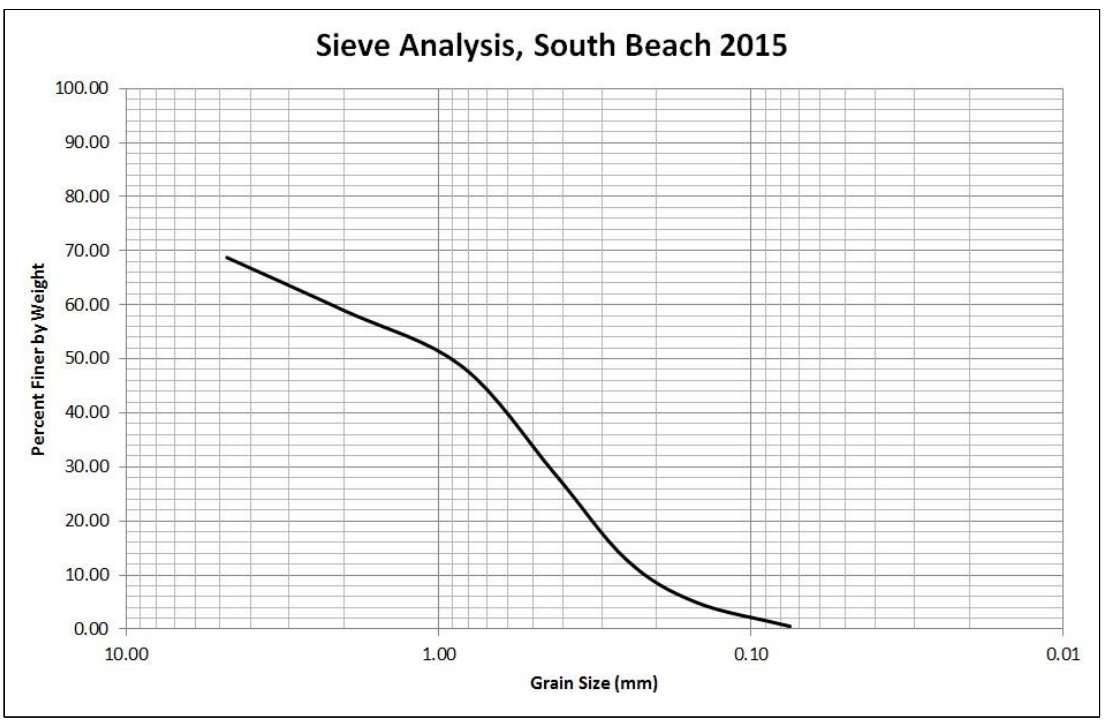

Figure B-2. Sieve analysis from mid-beach of Transect 13, South Beach. Note that fine gravels are the dominant sediment type with a distribution of well-graded sands.