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Metrics of shoreline armoring impacts on beach morphology in the Salish Sea, WA

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By Hannah Drummond

Accepted in Partial Completion
of the Requirements for the Degree
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<u>**Master’s Thesis**</u>

Hannah Drummond

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A Thesis
Presented to
The Faculty of
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1. ABSTRACT

Coastal development, and the shoreline defenses that accompany it, makes it vitally important to understand the shoreline's response to anthropogenic modifications. Armoring, or shoreline erosion control structures such as seawalls or riprap, is found on an estimated one third of Salish Sea shorelines and has been shown to degrade nearshore habitat. We compared physical beach characteristics from adjacent sections of armored and unarmored shoreline at a variety of locations in the Salish Sea to assess the effects of armoring on beach morphology. Nineteen sites, each a minimum of 500 meters in length, were selected from ten reaches sampled with boat-based LiDAR by the WA Dept. of Ecology Coastal Monitoring and Analysis Program. To assess data quality and select the best methodology for further analysis, beach slope and width measurements were compared between the point cloud and corresponding digital elevation model (DEM). Differences in the two data formats were found to be insignificant and the DEM was selected as the input data because use of the DEM is more efficient than the point cloud. Cross-shore profiles were generated from each DEM for each reach at 10-meter intervals alongshore. Estimates of beach slope, width, and toe elevation were extracted from the DEM along each profile in both the foreshore and backshore zones. Parameters were tested for significant differences between the armored and unarmored sections both regionally and within each site. The relationship between bluff or armor toe elevation and beach width and slope was also tested. Locally, direct impacts from armor covering the backshore habitat were more prominent than parameters that are suspected to be controlled by geomorphic processes. For example, backshore width and bluff or armor toe elevation were significantly different between armored and unarmored sections and correlated with each other but parameters such as slope or foreshore width that were not in direct contact with shoreline armoring did not show strong differences between armored and unarmored sections. The relationship between backshore width and toe elevation was consistent across all shore types and geographies. These results can be applied to restoration efforts by prioritizing armor removal projects where the armor toe is the lowest elevation compared to adjacent unarmored shoreline in order to maximize potential habitat benefits.

2. ACKNOWLEDGEMENTS

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1. INTRODUCTION

1.1 Background

Increasing development in coastal regions has resulted in widespread anthropogenic shoreline modifications. Armoring is a term used to describe bulkheads, seawalls, riprap, and other hard structures placed on a beach to combat erosion, and is a popular technique used worldwide for protecting infrastructure and property from destructive waves (Griggs, 2010; Shipman and Brennan, 2000). The Salish Sea in northwestern Washington has armoring on approximately one third of its beaches (Shipman, 2010). Figure 1 shows images of a typical unarmored (A) and armored (B) beach in the Salish Sea.

Figure 1. Photos of two typical bluff-backed beaches in the Salish Sea. Point Whitehorn Park along the Point Whitehorn Marine Reserve (A) is an example of unarmored shoreline with naturally recruited woody debris and a location on the west shore of Whidbey Island (B) is an example of shoreline armoring which includes a wooden seawall and riprap at the base of the bluff (photos by author).

The addition of shoreline armoring has been linked to habitat degradation. Not only does the process of armor construction cause disturbance to the beach, but studies have shown armor can lead to decreased taxa richness, lower amounts of woody debris and wrack, and a truncated intertidal zone (Dethier et al., 2016; Morley et al., 2012; Sobocinski et al., 2010; Toft et al., 2013). Armor has also been observed to disrupt natural sediment transport processes, impacting spawning grounds for forage fish (Parks et al., 2013; Pentilla, 2007). In natural systems, bluff erosion adds new sediment to the beach, which is transported alongshore and deposited on accretionary beach features (Johannessen and MacLennan, 2007). When shorelines are armored, bluff material becomes trapped above armoring and the beach is starved of new sediments (Parks et al., 2013). Armor can deflect wave energy and cause scouring seaward of the armor toe, which lowers the overall elevation of the beach profile and narrows the beach face over time (Jackson et al., 2002).

To mitigate negative effects of armoring on nearshore fish spawning habitat, Washington Dept. of Fish and Wildlife (WDFW) implemented regulations for armoring as early as the 1970's (Carman et al., 2010). These restrictions, however, continue to be contested by contractors and other lobbyists, resulting in limited enforcement (Carman et al., 2010). Commonly, those opposed to tighter regulations on shoreline armor express concern about how erosion can otherwise be managed effectively and safely (Pulkkinen, 2020). As new management strategies are introduced, it will be necessary to develop an understanding of current sediment dynamics in the Salish Sea to best predict how shorelines will respond to changes in armor type or placement. With increasing numbers of armor removal restoration projects (Blue, 2016), methods of prioritizing, designing, and monitoring these projects should be defined. The goal of this research is to develop insight to these issues and help provide the best available science to guide planning for armoring in the future.

Sediment and beach dynamics in the Salish Sea have been studied on a site-specific scale (Miller et al., 2011; Parks et al., 2013; Toft et al., 2013; Weaver, 2013; Weiner and Kaminsky, 2018). The Elwha River delta is a popular location to track changes in sediment after two dams were removed upstream in 2011. Shoreline restoration sites also draw interest, as they present the opportunity to compare pre- and post- measurements (Toft et al., 2013; Weiner and Kaminsky, 2018). Recently, these processes have been observed on a regional scale. In 2016, Dethier et al. conducted a study using a set of "paired armored and unarmored beaches" at 65 locations throughout the Salish Sea region. The influence of armor was detected for many parameters that were tested, but there was not a significant difference in beach slope. It was suggested that their methodology may not have been optimized to detect sufficiently small changes in beach morphology because it relied on only one cross-shore transect at each location in a pair (Dethier et al., 2016). Weiner et al. (2018) collected high-resolution lidar data from select locations around the Salish Sea as a step towards developing a sediment budget, however, did not specifically examine differences in armored and unarmored shorelines.

The research presented here uses the data collected by Weiner et al. (2018) to measure physical beach characteristics of armored and adjacent unarmored sections of beach at a higher spatial resolution than Dethier (2016). Data was collected between 2013 and 2015, and processing was completed in part by the author of this paper. Remote sensing data provides the opportunity to more efficiently extract a higher density of measurements than is possible in the field. The extent that these parameters are sensitive to spatial scales and able to evaluate armoring affects to shorelines alongshore are examined below.

1.2 Study Area

Our research focuses on the Washington portion of the Salish Sea, which includes the Puget Sound, Strait of Juan de Fuca, and San Juan Islands region. Figure 2 shows locations of the ten reaches and nineteen sites of beach that were included in analysis. Reaches were selected based on data availability and total just under 100 kilometers of shoreline. Both high-resolution DEMs

Figure 2. Overview map of study sites included in this research. Sites were used to determine the data format and reaches were used in the geomorphic analysis.

and the corresponding un-gridded lidar point clouds were used for this study. The nineteen sites were selected upon meeting all criteria outlined in the methods section. Each reach contained between one and four sites.

1.3 Physical Environment

1.3.1 Geography

The Salish Sea is an inland waterway that extends from the Puget Sound in Washington to the Strait of Georgia in British Columbia, and includes the Strait of Juan de Fuca, San Juan Islands, and Gulf Islands. The Washington portion of the Salish Sea in the Puget Lowlands is bound by the Olympic Peninsula to the west and Cascades to the east (Jones, 1999; Terich, 1987). The region is made up of a series of bays, estuaries, islands, and inlets extending from Olympia to the Canadian border. Seventeen major rivers flow into Washington's Salish Sea with the largest being the Skagit River (Czuba et al., 2011).

The most developed shorelines are in the southern Puget Sound where there are major population centers including Seattle, Tacoma, and Olympia. In the north, coastal areas near Bellingham and Anacortes are developed while Island County and the San Juan Islands region have lower population density and fewer armored shorelines (Shipman, 2010).

1.3.2 Geology and Geomorphology

The contemporary geomorphology of the Salish Sea and Puget Lowland region was shaped by a series of glacial advances and retreats throughout the Quaternary period (Jones, 1999). The most recent advance of the Cordilleran ice sheet sent a lobe between the Olympic and Cascade mountains with the terminus just south of Olympia 14,500 years ago, followed by a retreat to the

Canadian border (Booth, 1994). Each glacial advance and retreat deposited new glacial, glaciomarine, lacustrine, and outwash material in the lowlands. Subsequent advances carved troughs in the thick layer of deposited sediment primarily through subglacial fluvial processes resulting in the long channels oriented in the north to south direction that make up the present-day Puget Sound (Booth, 1994; Terich, 1987). Glacial deposits found in the Puget Lowlands tend to alternate between coarse and fine-grained and are loosely consolidated (Jones, 1999). Presently, bluffs eroding by wind and water processes expose the layers of poorly sorted glacial sediment. Shallow landslide material from bluffs is transported and deposited along beaches (Finlayson, 2006; Shipman, 2008). Sediment from both Quaternary glacial outwash and present-day glaciers in the Cascades is transported by major rivers and deposited on river deltas and adjacent beaches (Czuba et al., 2011). Because of the glacial origin, Salish Sea beaches are composed of mixed lithology outwash material with sediments ranging from fine sands to boulders (Shipman, 2008; Weiner et al., 2018).

Though Salish Sea shorelines are very complex and diverse, Shipman (2008) classified them into four general categories based on their geomorphology: beaches, rocky coasts, embayments, and large river deltas. Beaches are defined as gently sloping stretches of loose sediment along the shoreline and occur in coastal locations that have both a sediment supply and a mechanism of sediment transport (Johannessen and MacLennan, 2007; Marshak, 2009). In the Salish Sea, beaches line most of the shoreline and are either bluff-backed, barrier (accretionary), or developed (Shipman, 2008; *Figure 3*A). Historically accreting beaches take a variety of forms including spits, points, and tombolos. Rocky coasts are abundant in San Juan and northern Island Counties. Exposed bedrock is composed of metasedimentary deposits with igneous intrusions and volcanic rocks in smaller amounts (Schuster, 2005; *Figure 3*B). Rocky coasts can be identified by their irregular shape and slow change rates, and often lack sediment (Shipman, 2008). Embayments include any area on the coast where there is an indentation of the shoreline from its general trend (Woodroffe, 2002). The classification of these features is difficult because of the range of scales, however in the Salish Sea, these are generally considered as smaller scale estuaries and lagoons with low angle profiles and finer sediments (Nordstrom, 1989; Shipman, 2008; *Figure 3*C). Lastly, river deltas are the loose sediment platforms that form at the mouth of large rivers (Wright and Coleman, 1973). Delta shorelines are typically accretionary and dynamic with sediment delivery changing throughout the year (*Figure 3*D). The major delta-forming rivers that flow into the Salish Sea generally drain from the Cascade or Olympic mountains and include the Skagit, Nooksak, Snohomish, Stilliguamish, Nisqually, Puallup, Duwamish, and Skykomish Rivers (Czuba et al., 2011; Shipman, 2008). This is not a comprehensive list of shore types in the Salish Sea, but encompasses most coastal landforms found in the region.

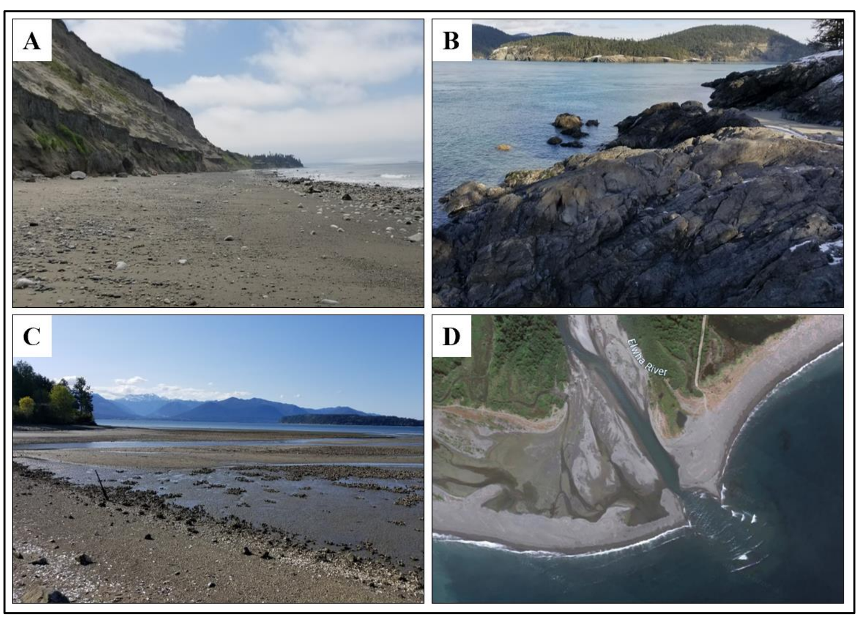

Figure 3. Images of the four major coastal types found in the Salish Sea. Photo A shows a bluff-backed beach with mixed sediment from the west shore of Whidbey Island. B is an example of a rocky coast in Deception Pass State Park. C shows and estuary type embayment near Seabeck. D is Google Earth imagery of the Elwha River delta.

1.3.3 Climate

Climate in the Salish Sea is complex but predominately controlled by the Pacific Ocean moderating temperatures year-round and contributing to strong seasonality in precipitation (Mass, 2008). Winters are mild with significant rainfall and generally less than 10 inches of snowfall at sea level annually, and summers tend to be cool and dry (Mass, 2008). Precipitation varies throughout the region due to local topography. Locations within the rain shadow of the Olympic Mountains can receive less than 24 inches annually while the southwestern Puget Sound can receive over 50 inches of rain per year (Shipman, 2008). The sites included in this research represent a variety of annual precipitation with Dungeness and West Whidbey falling within the rain shadow and Edgewater Beach and Seahurst Park both receiving almost 50 inches of rain annually (Mass, 2008).

Prevailing wind direction is westerly in the summer and south or southwestern during the winter months (Finlayson, 2006). Generally, stronger winds occur in the winter and light to moderate winds in the summer, however both wind direction and speed can differ due to local topography (Finlayson, 2006). Multiple storms producing winds up to 70 mph are common each winter (Mass, 2008). These infrequent, large magnitude windstorms create intense waves depending on exposure to open water or length of fetch and can result in significant shore erosion.

1.3.4 Tides, Waves, and Longshore Current

Waves and tides are two dominant factors controlling Salish Sea beach morphology. Geographic constraints make wave energy generally low to medium depending on fetch (VanArendonk et al., 2019). The Salish Sea is largely protected from Pacific Ocean swells by the

Olympic Peninsula and Vancouver Island, so most waves within the sea are generated from local winds. Winter windstorms result in larger waves, with smaller waves in the summer when storms are less frequent and lower intensity (Mass, 2008; Shipman, 2008).

Wind direction and fetch often generate waves at an angle to the shore that are then reflected away perpendicularly from the beach. This pattern occurs with each subsequent wave, creating a longshore current that runs parallel to the shoreline (Ritter et al., 2011; Wallace, 1988). Waves pick up sediment and depending on their strength to drive currents either transport it directly or it can be entrained by any alongshore current. The movement of sediment is called littoral or longshore drift and is responsible for accretionary beach features such as bars and spits (Wallace, 1988; Figure 4).

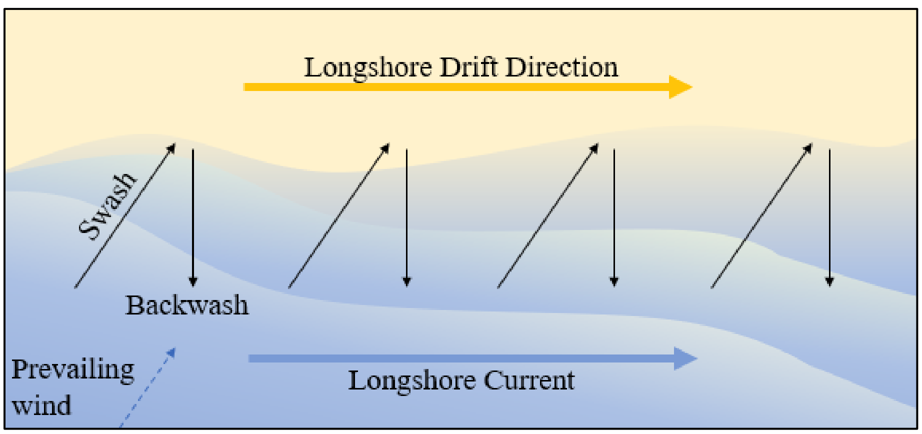

Figure 4. Schematic of longshore current and longshore drift development with waves hitting the shore at an angle.

Sediment transport largely occurs in both the surf and swash zones along mixed sediment beaches like those in the Salish Sea (Finlayson, 2006). Most beaches in the study region have a predominant longshore drift direction, with longshore current becoming stronger during storm events when wave energy is higher (Terich, 1987). The entire shoreline is divided into drift cells that reflect sections of shore that share a similar principal drift direction, sediment source, and accretionary feature (Wallace, 1988). Specific drift cell information for each of the reaches included in this research will be provided in the results section of this paper.

Tides are another factor that play a role in shaping the shoreline. The region has predominantly mixed-semidiurnal tides with two similar high tide elevations and two different low tide elevations within a day. The strongest tidal currents are in narrow straits and lesser currents in open areas or bays (Mofjeld and Larson, 1984). Because tides ebb and flood from the Pacific Ocean through the straits, the tidal range varies with distance from the ocean (Mofjeld et al., 2002). Tides are also influenced by bathymetry as water is pushed through trenches and over shelfs (Davies and Furnes, 1980). The tidal range, or vertical difference between mean lower low water (MLLW) and mean higher high water (MHHW), can be up to four and a half meters at the southern extent of the Puget Sound near Olympia and only two and a half meters near Port Townsend in the north of the Puget Sound (Finlayson, 2006). Topographic and bathymetric constraints also cause an approximate two-hour phase shift (e.g., lag) between southern areas and locations along the Straits, and an even larger phase shift from the outer coast of Washington (Mofjeld and Larson, 1984). Though tidal currents are significant in the Salish Sea, they are thought to be a small factor in shaping most shorelines compared to the influence that waves have (Shipman, 2010).

1.4 Research Questions and Objectives

The goal of this research is to quantify differences in physical shoreline characteristics between armored and adjacent unarmored sections and apply them to develop data driven recommendations for policy decisions and restoration planning. Beach slope, width, and bluff or armor toe elevation were used as the primary geomorphic indicators and were compared between shore types and between reaches with the armor updrift versus those where armor was downdrift. The study was guided by two sequential research questions:

1. Is extracting beach slope from a high-resolution digital elevation model (DEM) as accurate as extracting beach slope from a lidar point cloud? The lidar point cloud is assumed to be more accurate than the DEM.
2. Do armored beaches exhibit significantly different morphological characteristics including slope, width, and bluff or armor toe elevation?

The first question was used to assess the quality of the input data and select the best methods for answering the second question. Appendix A outlines the selection of the input data format and the main body of this thesis will address the approach to answer the second question. Findings here offer a first step towards optimizing armor removal actions in a way that best protects infrastructure while restoring essential forage fish habitat.

2. METHODS

2.1 Sites and Reaches

Ten reaches from around the Washington portion of the Salish Sea (Puget Sound, Strait of Juan de Fuca, and San Juan Islands) and were chosen based on the availability of high-resolution boat-based lidar from the WA Dept. of Ecology (Weiner et al., 2018). The reaches total just over 100 km of shoreline and encompass a range of shore types but are predominantly bluff-backed beaches.

Within these reaches, 19 sites of armored and adjacent unarmored sections of beach were identified, and a total of 1505 profiles were generated for geomorphic analysis. Each site was fully contained within a drift cell and one of three shore types: bluff-backed, accretionary, or transition zone. Drift cell boundaries and shore types were selected based on the 2019 Beach Strategies drift cell dataset (MacLennan et al., 2017). Sites were a minimum of 500 meters in length alongshore with approximately equal parts armored and unarmored shoreline. An armored section was defined as greater than 80% armored and an unarmored section was greater than 80% unarmored. The position of the armored section relative to the drift direction (updrift or downdrift) was recorded. Table 1 summarizes the conditions for each reach.

Table 1. Summary of conditions for each reach included in analysis, organized from north to south. Included is the individual site identifier (site code) and its respective reach and drift cell information based on data from MacLennan et al. (2017).

Site Code	Reach	Shore Type	Armor Position	Percent Armor in Drift Cell	Location Within Drift Cell
PR1	Point Roberts	Accretionary	Updrift	17%	First third
PR2	Point Roberts	Feeder-Bluff	Downdrift	28%	Middle third
PW1	Point Whitehorn	Transition Zone	Updrift	18%	Middle third
PW2	Point Whitehorn	Accretionary	Downdrift	18%	Middle third
GU1	Guemes	Accretionary	Downdrift	34%	Last third
WH2	Whidbey	Feeder-Bluff	Updrift	20%	First third
WH1	Whidbey	Transition Zone	Updrift	8%	Middle third
LE1	Ledgewood	Feeder-Bluff	Downdrift	14%	Middle third
LE2	Ledgewood	Feeder-Bluff	Downdrift	14%	Middle third
LE3	Ledgewood	Feeder-Bluff	Updrift	14%	Middle third
LE4	Ledgewood	Feeder-Bluff	Updrift	14%	Middle third
DU1	Dungeness	Feeder-Bluff	Updrift	6%	First third
CA1	Camano	Feeder-Bluff	Updrift	56%	Last third
US1	Useless Bay	Accretionary	Downdrift	15%	Middle third
SE1	Seahurst	Feeder-Bluff	Updrift	91%	First third
SE2	Seahurst	Feeder-Bluff	Downdrift	91%	First third
ED1	Edgewater	Transition Zone	Downdrift	55%	Last third
ED2	Edgewater	Feeder-Bluff	Updrift	55%	Middle third
ED3	Edgewater	Feeder-Bluff	Updrift	55%	First third

Selected sites were in drift cells containing between only 6% armoring near the Dungeness Spit and over 90% armoring near Seahurst Park south of Seattle. Thirteen sites had armoring on less than one third of the drift cell and only six sites were in drift cells with more than 50% armoring. Percent of armoring per a drift cell was noticeably higher in reaches in the south and further from the Strait of Juan de Fuca (Figure 2). Six sites were in the first third of the drift cell, ten sites were in the middle third, and three were towards the end of their drift cells. Seven sites had at least one stream outlet in either the armored or unarmored section (MacLennan et al., 2017). In some cases, local changes in beach parameters such as increased beach width and decreased slope along a small delta were obvious directly at a stream mouth. Results may be skewed because these external factors appear to exert a stronger control on beach parameters than the presence or absence of armor.

2.2 Data

Lidar data were collected by the WA Dept. of Ecology between 2013 and 2017 using an Optech ILRIS-HD-ER boat-based laser scanner. Overall average point density on the beach was 9 points per 0.5 m grid cell and on the vertical bluff face was 26 points per 0.5 m grid cell (Weiner et al., 2018). DEMs were generated by first interpolating the data using a Triangulated Irregular Network (TIN), then gridding the TIN at 0.5 m (Weiner et al, 2018). Lidar point returns were referenced to Washington State Plane (NAD 1983 2011) North or South coordinates depending on the study site location. Elevation values were referenced to NAVD88 and converted to local tidal datums using NOAA’s VDatum tool. Because the tool interpolates datums between tidal stations, the further a reach was from a tidal station, the larger the potential error.

2.3 Beach Parameter Extraction

Beach parameter extraction was completed using ArcGIS Pro. A set of cross-shore profiles at 10 m intervals alongshore was generated in each site to extract beach parameters for analysis. The foreshore was defined as the area between MLW and MHW, or between MLW and the bluff or armor toe where the toe elevation was lower than MHW, to best represent the active portion of the beach face (Ritter et al., 2011). The backshore was defined as the area between MHW and the bluff or armor toe (Figure 5) (Finlayson, 2006; Johannessen and MacLennan, 2007). MLW and MHW contours were extracted from the DEMs using the ArcGIS contour tool based on elevations for each site from NOAA's VDatum tool. The toe location was defined as the base of the bluff on unarmored bluff-backed beaches, base of the armor in armored sections, or where the riparian vegetation transitioned to terrestrial vegetation on low-angle accretionary shoreforms. The toe location was identified by using a combination of a least cost path analysis (Hardin et al., 2012) and the hand-digitizing method outlined by Hapke and Reid (2007). The least cost path analysis connected two points on either end of each site by automatically selecting the "most likely" toe location based on the most prominent slope break for each site, usually between 20 and 30 degrees. The generated least cost path was edited wherever necessary by viewing a hillshade layer in conjunction with NAIP imagery and photos taken at the time of data collection. The toe, MHW, and MLW contours were combined to create foreshore and backshore masks and used to clip profiles to.

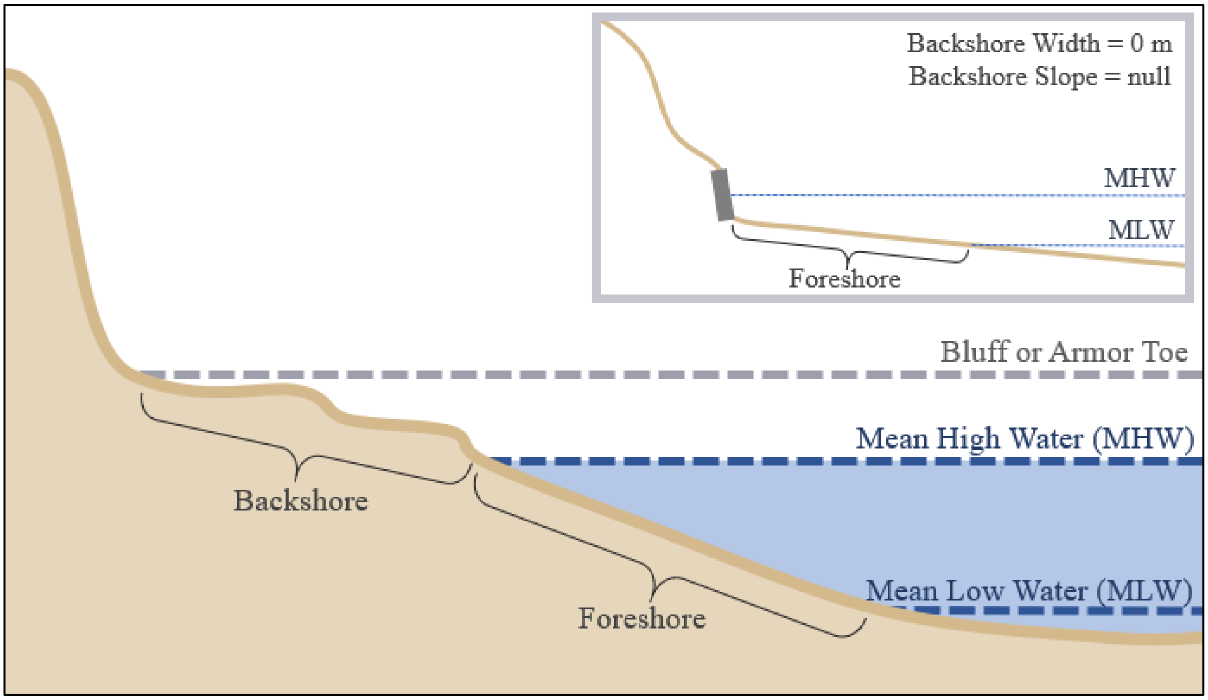

Figure 5. Schematic of how the backshore and foreshore was defined on each profile.

Beach width for the foreshore and backshore was calculated as the length of the profile, and the "endpoint method" described by Doran et al. (2015) was used to calculate an average slope. If the backshore or foreshore were completely truncated by armoring or the bluff toe, values of zero were given as the width, and slope was given a null value. The endpoint with the highest elevation on each profile became the "toe" elevation value (Figure 5). The resulting dataset included foreshore and backshore profiles in all sites, and each profile included an associated beach width, slope, toe elevation, reach, section, and armor position within the site. Note profiles that were in an armored section but did not actually have armoring present in that location were still coded as "armored" because they were assumed to have geomorphic processes dominated by the adjacent armoring.

2.4 Analysis

Mean differences between sections were not spatially correlated between reaches based on the calculated Global Moran's I and a traditional two-sample paired t-test was sufficient for the pooled regional analysis that included measurements across all sites. Paired t-tests were completed in R using average values for each section of each site. Measurements of each parameter from most sites were not normally distributed and the regularly spaced profiles were spatially autocorrelated, so permutation tests for difference in means between armored and unarmored profiles were conducted for each site, shore type, armor position group, and the entire dataset for both the foreshore and backshore profiles. Testing for differences in means using permutation is a non-parametric alternative to traditional t-tests and produces a p-value based on a data generated normal distribution instead of a mathematical normal distribution (LaFleur and Greevy, 2009). Though this method of testing may not completely solve the issue of spatial autocorrelation (Dale and Fortin, 2002), results were used to supplement the paired t-test results because the permutation tests drew from individual profile measurements, greatly increasing the sample sizes. Testing was completed in R with 1000 permutations and significance was based on a 95% confidence interval, however p-values were considered on a sliding scale and multiple levels of significance were considered when interpreting results (Dahiru, 2008).

The relationship between toe elevation and beach width and slope was described using a t-test modified for spatially correlated data (Dutilleul et al., 1993). Corrected degrees of freedom, p-values, and correlations were generated using the modified t-test function in R, which follows the methods outlined by Clifford et al. (1989). Correlations with toe elevation were completed for the backshore and foreshore width and slope, and the combined width (MLW to toe). Interpretations were applied to the context of armor removal restoration efforts. Stronger statistical test results represent a higher likelihood of restoration success for that parameter and test group.

3. RESULTS

3.1 Site Variability

Beach characteristics varied significantly between sites likely due to differences in geologic history and substrate throughout the study region (Dethier et al., 2016). Though these factors were not considered during analysis, it is important to note because geographic location has been described as a major factor in observed variations in beach parameters (Dethier et al., 2016; Shipman 2008). Figure 6 displays one armored and one unarmored transect from each site between MLW and 30 m landward. The array of widths, slopes, and variability within a profile is indicative of the variability between sites. Steeper and narrower beach profiles tended to be in southern sites including those near Edgewater Beach and Seahurst Park, and the widest and flattest profiles displayed are from multiple locations on Whidbey Island.

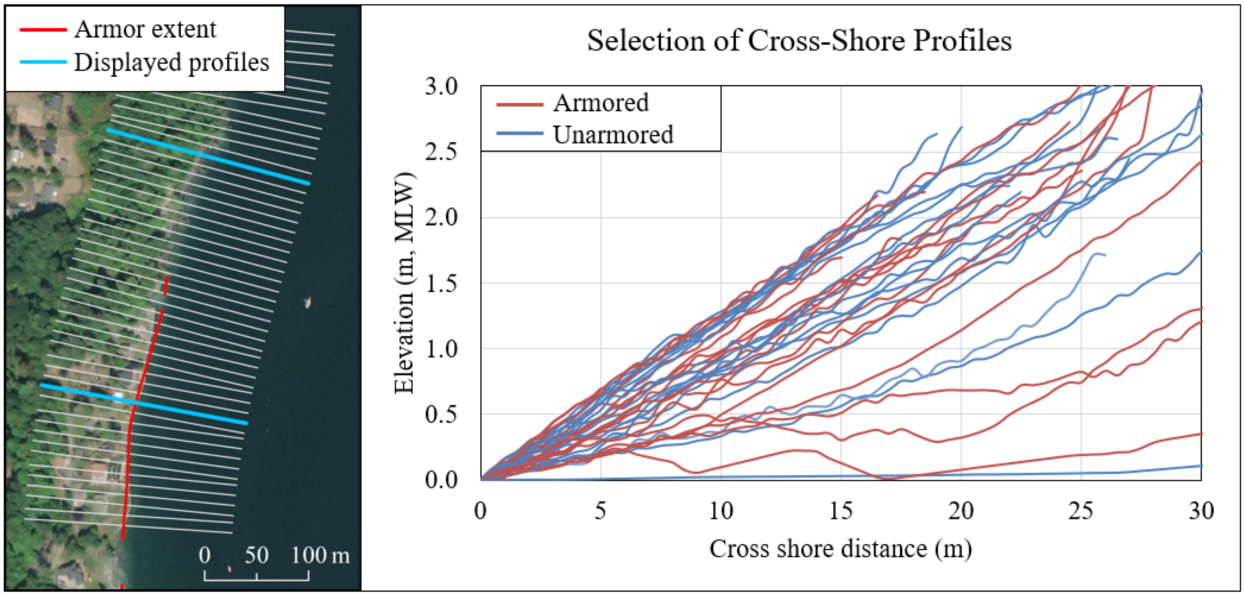

Figure 6. Example showing generated transects for one site (left) and selected armored and unarmored profile from each site (right).

Average beach foreshore width per a site ranged from 7.3 m near Point Whitehorn, where much of the foreshore is completely truncated by armoring, to 83.8 m in Useless Bay, which is dominated by low angle mudflats. Average backshore width ranged from less than 1 m near Edgewater Beach in the south Puget Sound to 18.3 m on west Whidbey Island. In all but two sites, one on west Whidbey and one near Point Whitehorn, the average foreshore width was greater than the average backshore width. Standard deviation of foreshore width within a site ranged from 0.5 to 14 m (backshore standard deviation ranged from 1 to 12 m), average foreshore slope ranged from 2.4 to 14.2 percent (average backshore slope ranged from 11.9 to 20 percent), and average toe elevation relative to MHW ranged from -0.8 m to 2.3 m. Beach parameters also varied between shore types, however this shore type variation was minimal between sites within a single reach. This suggests broader scale shoreline conditions such as waves and tides may be a better indicator of geomorphic beach conditions than local shore type.

3.2 Armored and Unarmored Comparisons

3.2.1 Region-wide comparisons

Despite the range of geographic conditions between sites and reaches, some differences between parameters in armored and unarmored sections were detected at a regional scale with measurements from all sites pooled. Figure 7 shows distributions of measurements from all profiles included in analysis. Average foreshore width was similar between armored and unarmored profiles (armored mean = 24.4 m, unarmored mean = 25.3 m, p-value = 0.139), however the backshore was significantly narrower in armored sections (armored mean = 4.8 m, unarmored mean = 6.8 m, p-value = 0.007). It is unsurprising that toe elevations were also significantly lower in armored sections (armored mean = 0.4 m above NAVD88, unarmored mean = 1.1 m above NAVD88, p-value = 0.004) because armoring is often placed on top of a portion of the backshore zone. Since the toe was defined as the base or the bluff on unarmored beaches or base of the armor on armored beaches, the toe elevation is likely to be artificially lowered by the seaward location of the armoring.

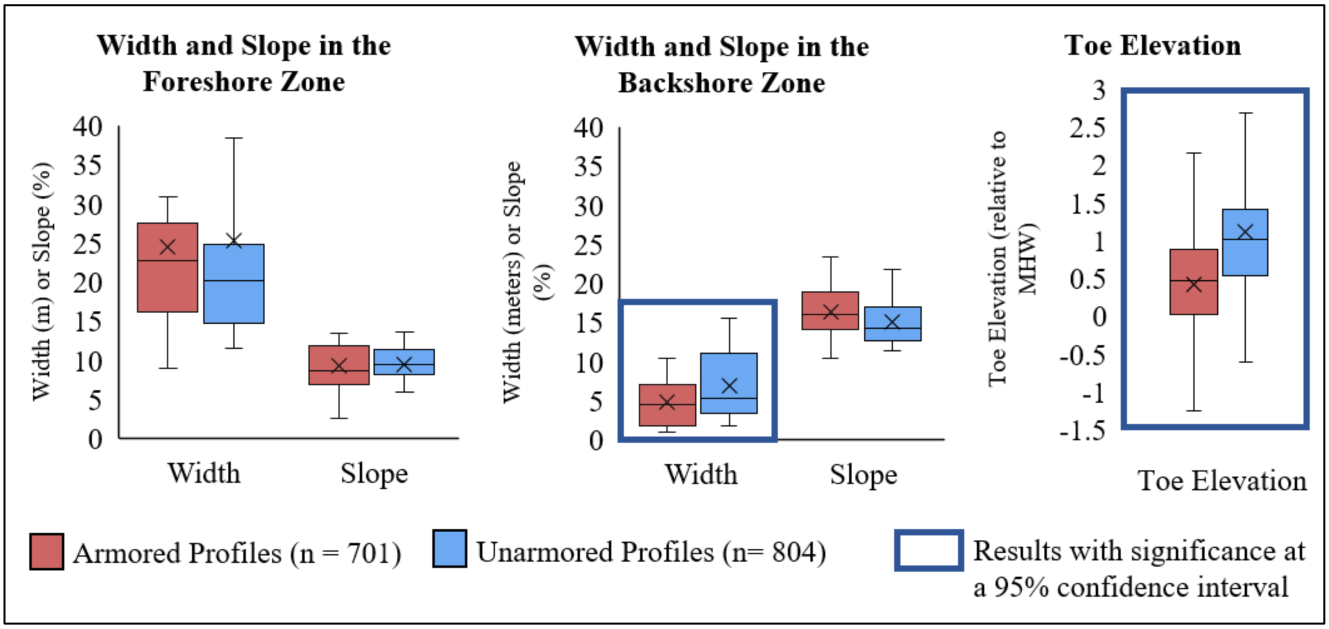

Figure 7. Distributions of all measurements included in analysis with armored profiles in red, unarmored in blue, and x marking the mean for each group. The blue box indicates results that are significant at a 95% confidence interval.

When sites were separated by shore type, armored sections in bluff-backed beaches had significantly narrower backshores (p-value = 0.006) and significantly lower toe elevations (p-value = 0.009) than unarmored sections, however there was no significant difference in backshore width or toe elevations in accretionary beaches (Figure 8). Armored sections in transition zones had narrower backshores at a 90% confidence interval (p-value = 0.085) and had significantly lower toe elevations (p-value = 0.044). These sites have similar results to bluff-backed beaches because most of the transition zone areas included here are backed by bluffs but did not show signs of active erosion at the time of mapping (MacLennan et al., 2017). Results from transition zone sites may also not be reliable because of the low number (n = 160 profiles from only three sites) included in analysis. The large interquartile ranges compared to accretionary and bluff-backed sites shown in Figure 8 are likely a product of a small sample of geomorphic conditions represented by the transition zone sites.

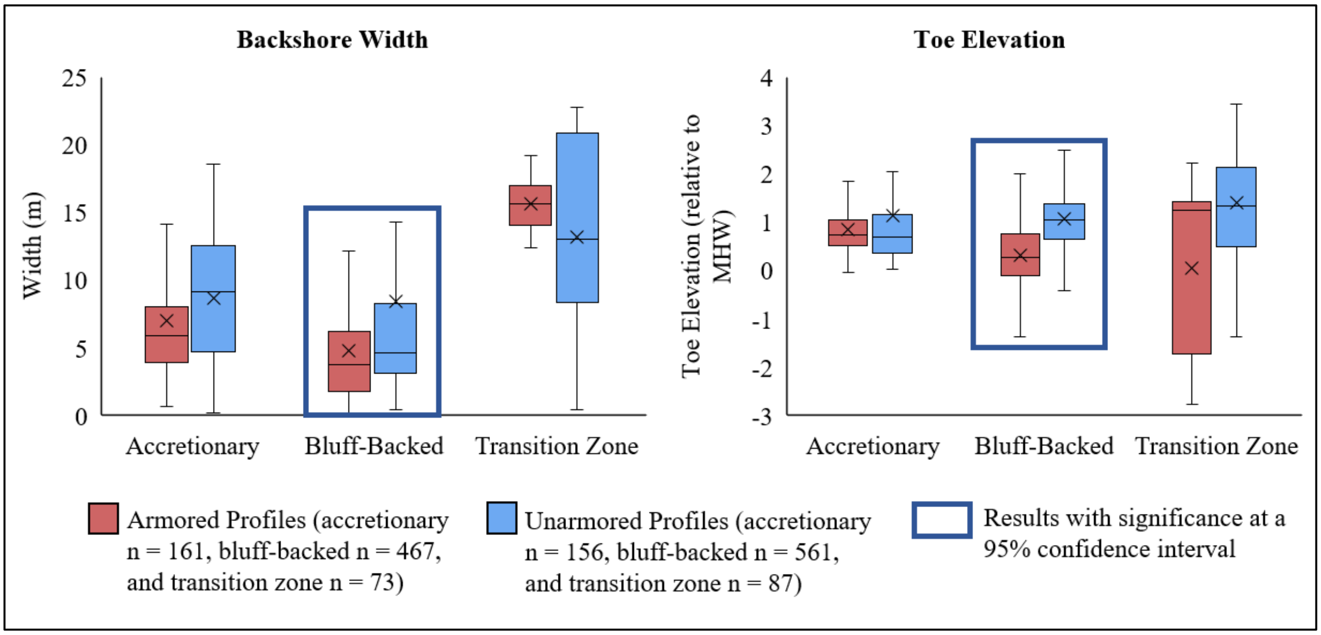

Figure 8. Distributions of backshore width and toe elevation by shore type with armored profiles in red, unarmored in blue, and x marking the mean for each group.

Sites where armor was updrift from the unarmored sections were not significantly different from sites where armor was downdrift from unarmored sections, however those with armoring updrift had stronger differences between sections in backshore width and toe elevation. When armor was updrift, armored sections had significantly narrower backshores (p-value = 0.042) and lower toe elevations (p-value = 0.026). This pattern was present but weaker in sites where the unarmored sections were updrift, showing significantly narrower backshores and lower toe elevations only at a 90% confidence interval (Figure 9). Since this study does not formally consider conditions updrift from the defined site boundaries, it is possible that armor does significantly affect the beach downdrift but is not detectable in our data or at this scale of analysis. To aid in interpretations, the armoring status 200 meters updrift of the defined reach was recorded as predominantly armored (>66% armored), predominantly unarmored (<33% armored), or mixed (between 33% and 66% armored).

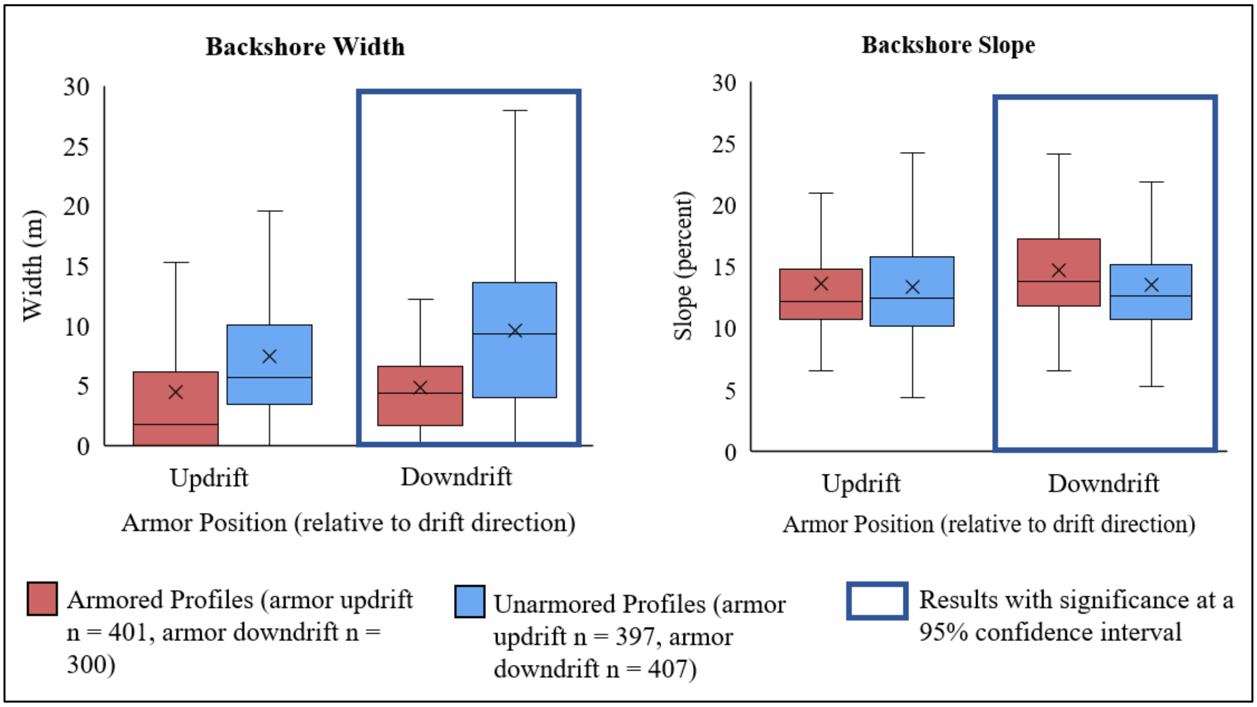

Figure 9. Distribution of backshore width and backshore slope separated by groups where armor is updrift and where armor is downdrift with armored profiles in red and unarmored in blue.

Few significant differences between slopes in armored and unarmored sections were detected, and there was no significance within a 95% confidence interval. Since our toe locations were selected based on a major slope break in the DEM, it is possible that some backshore slope measurements are higher than the true slope because they may include bluff or armor material that sits above a minor slope break, but below the major slope break. Additionally, the "toe" has three different definitions depending on the geomorphic setting. Results for upper beach slope, width, and toe elevation shown here may be a product of how the toe was defined and not necessarily indicative of geomorphic conditions. Future work that draws from remote sensing data should consider redefining the toe location to minimize the potential error associated with choosing the major slope break.

The range of unarmored foreshore slope shown in Figure 7 is noticeably narrower with both a smaller overall and interquartile range than backshore slopes and armored foreshore slopes. This suggests that Salish Sea beaches in their natural state have uniform foreshore slopes. Table 2 summarizes the paired t-test results for all reaches combined and for subgroups with significant results highlighted in green.

Table 2. Summary of paired t-test results including all reaches combined, reaches separated by shore type, and reaches separated by the updrift section. Darker green cells show strongest significance, lighter green shows weak significance, and grey shows no significance.

Significance (α = 0.01) Significance (α = 0.05) Significance (α = 0.1)		FORESHORE Width	FORESHORE Slope	BACKSHORE Width	BACKSHORE Slope	Toe Elevation
ALL		0.139	0.107	0.007	0.255	0.004
Shore Type	Feeder-Bluff	0.215	0.054	0.006	0.295	0.009
	Accretionary	0.096	0.438	0.348	0.347	0.264
	Transition Zone	0.101	n/a	0.085	n/a	0.044
Armor Position	Armor Updrift	0.428	0.162	0.042	0.741	0.026
	Armor Downdrift	0.113	0.254	0.062	0.229	0.058

3.2.2 Comparisons by site

More significant differences between armored and natural sections were found when comparing profiles within a single site. These results are summarized in Table 3, which shows the percentages of sites in each group with significantly narrower beaches, steeper beaches, or lower toe elevations in armored sections. The foreshore in armored sections was significantly narrower than their adjacent unarmored sections in nine of the nineteen sites analyzed. However, the foreshore was significantly wider in armored sections in eight sites, and two additional sites showed no significance, mirroring the mixed results of the region-wide analysis outlined in the previous section. The difference in backshore width for pooled regional results between sections was clear with significantly narrower backshore zones in armored sections of fourteen sites and only five showing no significance at a 95% confidence interval. Thirteen sites had significantly lower toe elevations in armored sections, all of which also had narrower backshores. There was no significant difference in armored and unarmored slopes at the pooled regional scale, but armored foreshore zones were significantly steeper in just over one third of the sites and backshore zones significantly steeper in less than a quarter of sites. Though our data does not show that slope is consistently higher in armored sections, steeper slopes may be detected on certain beaches. Slope could not be measured on profiles with a width of zero and reaches with less than 10 transects per a section were omitted from testing. This included two sites from the Edgewater study site and both locations from the Point Whitehorn reach. Eliminating the four sites with the lowest armor toe elevations may have contributed to the lack of significance because we hypothesized that lower toe elevations would be correlated with higher slopes. Redefining the slope measurement interval to accommodate armor with toe elevations below MHW would offer opportunity to test for these patterns in locations with more encroachment than the sites included here.

Though literature consistently describes armor to cause beaches to narrow and steepen and toe elevations to lower (Nordstrom and Jackson, 1992; Shipman, 2010), only three of the nineteen sites, all from the Edgewater reach, had significantly narrower and steeper foreshore zones in armored sections compared to their adjacent unarmored sections. Only one site at Point Roberts had a significantly narrower and steeper backshore zone and lower toe elevation in armored sections. Three sites had no significant difference between armored and unarmored for any beach parameters in both the foreshore and backshore zones and the remaining sites had some combination of significant and insignificant differences. Though most sites within the same reach had results similar to each other, this was not true for all reaches. For example, the four sites in the Ledgewood site on the west side of Whidbey Island sat directly adjacent to each other, all had the same shore type, and all were located within the same drift cell (Table 1), however none of these sites shared the same set of results. External factors such as sediment size, local sediment sources, or variations in fetch could be contributing to local variability. Mixed results from the site-scale analysis may reflect the diverse and unpredictable nature of shorelines in the entire study region.

Table 3. Summary table of site-scale with percentages of sites showing significantly narrower or steeper beaches, or lower toe elevation in armored sections at a 95% confidence interval.

≥ 75% of reaches in subset; ≥ 50% of reaches in subset		FORESHORE		BACKSHORE		
		Width	Slope	Width	Slope	Toe Elevation
ALL	ALL	50%	41%	78%	20%	68%
Shore Type	Feeder-Bluff	33%	50%	75%	90%	67%
	Accretionary	75%	33%	50%	25%	50%
	Transition Zone	67%	50%	100%	0%	100%
Armor Position	Armor Updrift	45%	30%	82%	11%	90%
	Armor Downdrift	50%	43%	63%	22%	63%

3.3 Toe elevation correlations

At a pooled regional scale, bluff or armor toe elevations were correlated backshore width, but were not correlated with foreshore width, foreshore slope, or backshore slope (Figure 10). This is reflected in the site-scale analysis with all shore types and sites showing some correlation between backshore width and toe elevation. Correlation coefficients ranged from 0.60 to 0.99, with correlations in eight sites greater than 0.90. The scatterplot is wedge-shaped, where there appears to be a minimum width associated with a given toe elevation, but not a clear maximum width (Figure 10B). Toe elevation and foreshore width was not correlated unless the toe elevation was lower than MHW (Figure 10A). In all sites where armor was consistently lower than MHW, the foreshore width was correlated with toe elevation, but was not correlated in any other sites. Of the profiles included in this analysis, the toe elevation was lower than MHW on 26.6 percent of profiles in armored sections (34.6 percent lower than MHHW) but only 4.4 percent of profiles in natural sections (13.0 percent lower than MHHW). Toe elevations lower than MHW in armored sections occurred in all three shore types, however toe elevations in natural sections were only lower than MHW if the bluff or bluff deposits extended lower on the beach. At both scales of analysis, toe elevations were not correlated with beach slope in the foreshore or backshore.

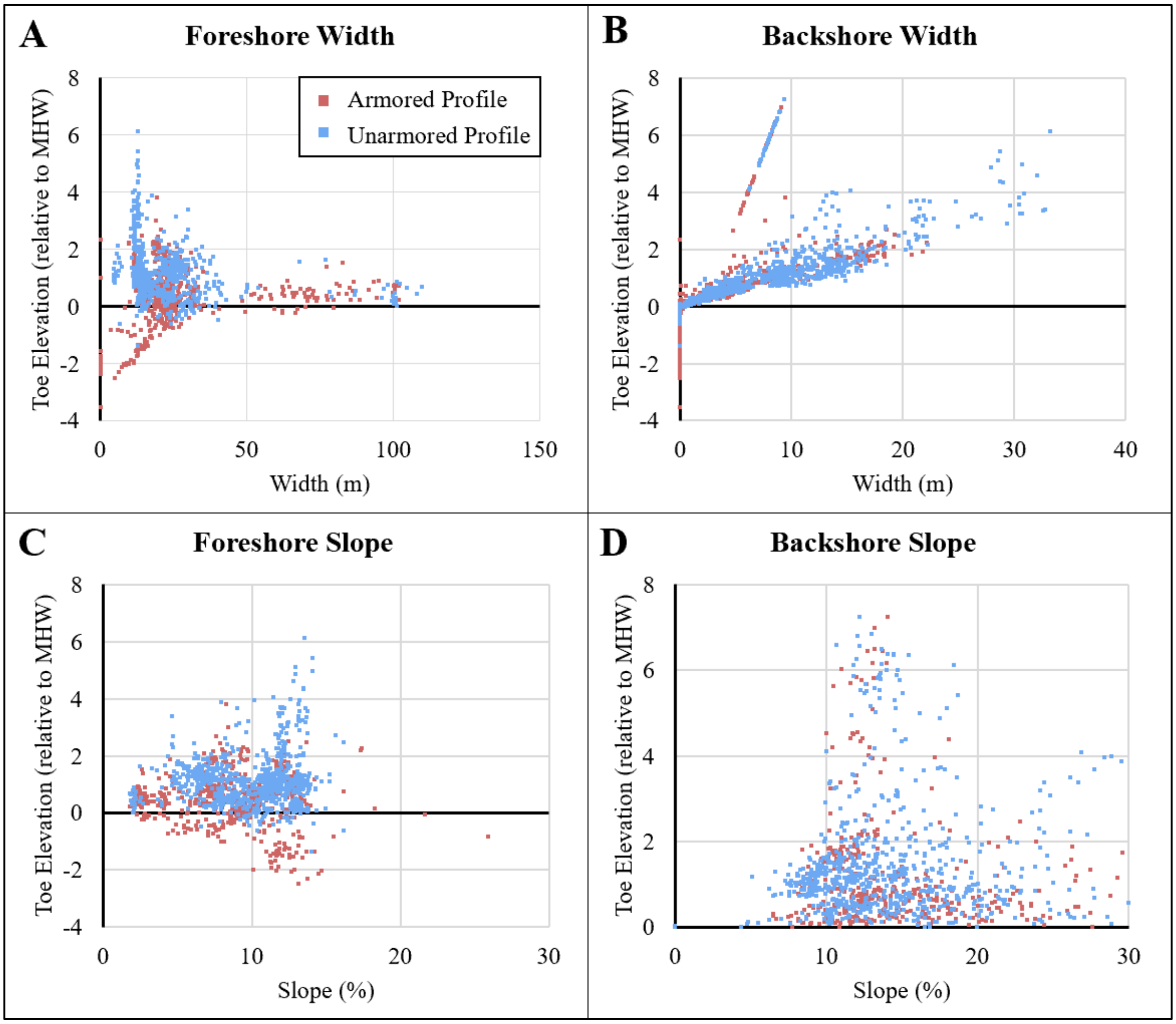

Figure 10. Scatterplots showing the relationship between toe elevation relative to MHW and beach parameters. Red represents armored profiles and blue shows unarmored.

There was not a noticeable difference in correlations between toe elevation and slope or width between shore types or armor position, suggesting the relationship between toe elevation and beach morphology may be responding to factors other than shore type. However the plots in Figure 11 can give some insight to the nature of relationships for each shore type. The plot on the left displays toe elevation relative to MHW on the y-axis and the combined beach width, or width between MLW and the toe location, along the x-axis. The concentration of bluff-backed profiles between 10 and 50 m combined width displays the narrow range of parameters that bluff-backed beaches display compared to the sprawling distribution of accretion areas. The band of accretionary profiles with relative toe elevations between 0 and 1 meters, but widths ranging from 50-120 reflects the wide, low-angle nature of accreting shorelines where low toe elevations can still correspond with high beach widths. This is also shown in the plot on the right by the cluster of accretionary profiles with slopes under 5% (Figure 11).

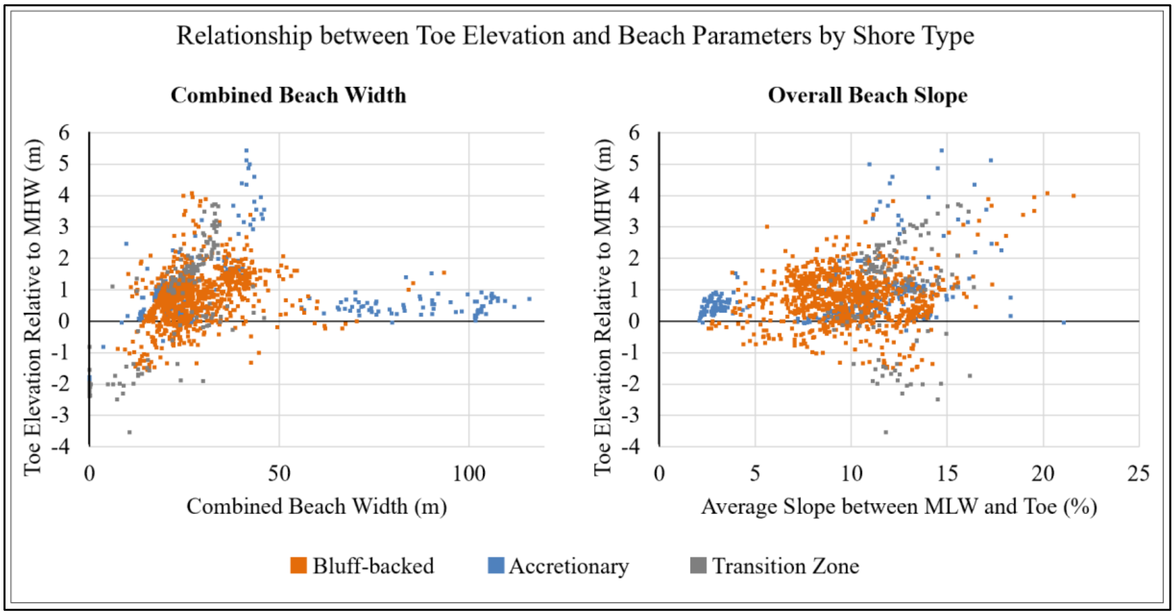

Figure 11. Scatterplots showing the relationship between toe elevation and beach parameters separated by shore type with bluff-backed profiles in orange, accretionary in blue, and transition zones in grey. Toe elevation relative to MHW is on the y axis with combined beach width (MLW to bluff or armor toe) or average slope (between MLW and bluff or armor toe) on the x axis.

4. DISCUSSION

4.1 Direct Geomorphic Impacts

Analyses show that armoring does impact geomorphic parameters on the beach, particularly backshore width. This is consistent with previous work that has shown armoring to cause a decrease in the availability of upper beach habitats that are required to accumulate wrack and woody debris (Dethier et al., 2016; Sobocinski et al., 2010). Our data suggest this decrease in backshore width to be closely related to armoring toe elevation. When armor is placed on top of part or all the backshore zone and the toe elevation is artificially moved lower and seaward, the armor directly truncates the backshore area. This is also reflected by results from the foreshore zone, where all four of the sites where foreshore width and toe elevation were correlated were the only four sites where armor was lower than MHW. Since the foreshore was defined as below MHW, the relationship between foreshore widths and toe elevation appear to be a direct impact of the armor encroaching into the foreshore zone.

Based on our selected sites, differences in backshore widths and toe elevations were strongest in bluff-backed sites but not significant among accretionary sites suggesting that shore type in some instances is a useful indicator of expected armoring impacts. With additional accretionary sites, however, differences in parameters may emerge as significant. Accretionary shoreforms often have wide backshore zones, and the low angle nature of these shorelines offer buildable substrate directly landward of the beach (Ritter et al., 2011; Shipman, 2008), therefore armoring does not need to be placed lower on the beach than the natural “toe” location. A site on an accretionary beach containing armor that encroaches into the backshore or foreshore zone may offer more gain than armor removal on bluff-backed beaches because accretion areas are often wider and gently sloping with a large backshore area (Shipman, 2008), however our data was unable to verify this. Bluff-backed beaches tend to have a narrow foreshore and buildable substrate is restricted by the bluff directly landward. High erosion rates of bluffs in the region also pose a threat to infrastructure on top of the bluff (Baum et al., 2005). For these reasons, it is possible that armor is built lower on the beach in bluff-backed areas for the purpose of maximizing property protection, and therefore covers the already narrow backshore. These factors on bluff-backed beaches also restrict armor removal efforts because the threat to infrastructure and property is higher without the shoreline protection. Our data suggests that backshore habitat gain from armor removal may be most effective on bluff-backed beaches where the toe elevation is lower than the adjacent bluff, and efforts should be focused in these areas wherever possible.

The strong correlation across all shore types between the toe elevation and backshore width supports findings from the paired t-tests. Since these parameters are directly related, preventing construction of new infrastructure that lowers the toe elevation will preserve the backshore. Working to remove beach structures that encroach on the backshore zone is likely to restore the backshore area. The lower the armoring toe elevation is relative to adjacent backshore areas, the more likely armor removal will result in habitat gain. When planning armor removal efforts, targeting and increase in backshore width should be a priority because it can increase the accumulation of beach wrack and woody debris and ultimately add ecological value. Additionally, our results suggest that targeting backshore width offers well-defined prioritization criterion that is consistent across all shore types and drift cell contexts.

4.2 Impacts to nearshore processes

Though previous work discusses armor's impact on beach morphology in terms of is effect on nearshore processes (Dethier, 2016; Weiner and Kaminsky, 2018; Nordstrom and Jackson, 1992), our results indicate that the local presence or absence of armor has a minimal effect on foreshore width or beach when compared to direct impacts from lowering the toe elevation with armor. A noticeable transition between sections would be expected if armor was affecting the beach downdrift, but each site revealed abrupt transitions with measurement changes occurring within one or two profiles from the armoring extent. Figure 12 shows an example of this transition between sections along a reach in the Point Roberts study site.

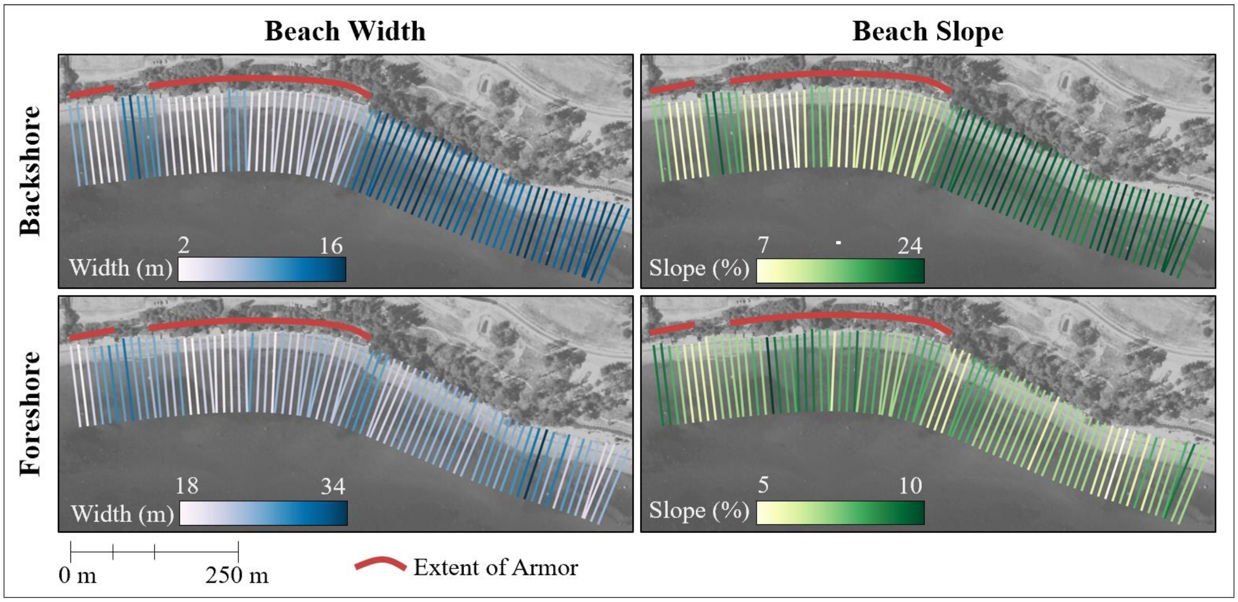

Figure 12. Map view of an example site on Point Roberts with backshore measurements displayed in the top row and foreshore measurements displayed in the bottom row.

At this site (PR2), the backshore was significantly narrower and steeper in the armored section, with beach parameters shifting directly at the beginning of the armor extent (Figure 12). The foreshore slope was also narrower in the armored section, but the transition is not as abrupt as changes in beach width and slope in the backshore, likely because coastal processes are able to average out the variability in the foreshore zone. Since slope does not seem to be affected by the local presence or absence of armor on a regional scale, this site-scale look at the profiles may reflect the influence of longshore drift.

Some work has suggested that the percentage of armor in the entire drift cell exerts more control on beach parameters than local conditions such as shore type or the local presence or absence of armoring (Shaffer et al., 2012). This could explain the lack of significance in the foreshore zone and backshore slope, which are in large part influenced by the drive-scale coastal processes rather than existing sediment and beach characteristics. It is also supported by the fact that variability within sites was much less than that within specific shore types or updrift sections, particularly in the foreshore zone.

There is some evidence in these data, though, of a geomorphic response to armor downdrift on our site-scale. The differences between backshore width and toe elevation were both stronger when armoring was updrift compared to sites where armor was downdrift. Though there was no significance within a 90% confidence interval, the large disparity in p-values between foreshore width and backshore slope when armor was updrift compared to when armor was downdrift may be an indicator of a pattern that would emerge with further sampling. The stronger results for sites where armor was downdrift could be a result of armor affecting the foreshore width and backshore slope both directly in front of it and downdrift, therefore those sites are more similar than when the unarmored sections were updrift.

More striking was a strong pattern of updrift armoring conditions predicting the outcomes of the backshore width difference in means tests. All five sites that did not have significantly narrower backshores in armored sections had a change in amount of armor directly updrift from the site boundaries. In other words, sites that had alternating sections of armor on the scale of about 200 m had more similar beach parameters between sections than sites that were at the end of a long stretch of armoring. This suggests that on locally mixed shorelines, beach morphology does not necessarily respond to individual sections of armor and on locally homogenous shorelines, a change from armored to unarmored contrasts more with the updrift conditions. This pattern may be the product of external factors such as more erosion resistant sub straight occurring at sites with mixed or alternating armoring. Based on our data, restoration site selection and monitoring should consider the spatial shift that may occur after armor removal from the end of a long stretch of armoring. Removing armor in locations with unarmored sections directly downdrift could result in higher potential gain because not only will the beach directly in front of the armor be restored, but the unarmored section downdrift that has been affected by the armor will have the opportunity to recover and be maintained by coastal processes. Areas with mixed or alternating sections of armor may be more likely to occur in locations where there is less active erosion and therefore coastal processes may not be as disrupted by armor in these locations. Initial site selection processes should consider potential sites at the end of a long stretch of armor before considering beaches with variable amounts of armor.

4.3 Sources of error

Potential error in our analysis include data quality, methods of toe extraction, error associated with tidal datum elevations, accuracy of shore-type data and potential biases from site and profile sampling methods. Our site selection was confined to available input data, and therefore a small number of accretionary and transition zone shore types restricted analysis. In most cases, transition zone analysis results were excluded from interpretations because the sample size was too small. Though sites represented a range of shore conditions and geographies, they do not encompass all conditions in the Salish Sea. Therefore, specific site conditions should be considered before using the prioritization criteria suggested here. It is recommended that a similar study with a more robust set of sites is performed to verify our results.

Sites included in analysis may be sensitive to temporal differences in data collection and age of the armoring. Since the DEMs were generated from data collected over the course of one week or less, they show a snapshot in time that may not be representative of the beach's equilibrium state. Most data collection occurred in the summer, however beach morphology can change significantly in response to just one storm event and has been observed to change seasonally with the weather patterns (Curtiss et al., 2009; Lee et al., 1998). At sites where seasonal morphology changes exist, data collected in early summer could exhibit different characteristics than data collected in late summer or early fall and may skew results. Additionally, the age of the armoring in each site affects how long the natural beach processes have been disrupted. Older armoring may cause larger differences in beach parameters because there has been more time that the sediment source is cut off from the beach, however this was not accounted for when choosing sites.

Using remote sensing products as the primary source to derive data offers challenges because measurements cannot be visually verified like they can with traditional field data collection methods. Our method of identifying the toe location, which directly related to backshore width, backshore slope, and toe elevation, was likely the largest source of error. Since it was based on the major slope break in each site, the selected toe location had three different possible locations relative to geomorphic features (base of the bluff, base of the armor, or transition in vegetation). Some of the significant results found in difference in means testing may be the product of how the toe location was defined. A more objective definition of the toe location in future research would produce more reliable results. In locations where a major slope break was not obvious, aerial imagery, shoreline photos, and a hillshade layer was used to determine the landward extent of the beach. This process was subject to the researcher's opinion and assumed there were no significant shoreline changes between the time the imagery was collected and the time the elevation data was collected. In some instances, the major slope break may not represent the actual toe location, for example when a berm or minor nearshore structure was misinterpreted. This semi-automated method of toe extraction has not been explicitly tested against traditional field methods, however, has been tested against the hand-digitizing method outlined by Hapke and Reid (2007) and there is an estimated ±3 meters error. Considering the overall average backshore width of only 6.7 meters, this potential error could greatly skew backshore width results. Based on this average backshore width and our average backshore slope of 13.8%, our estimated vertical error of toe elevation is ±0.41 meters. Again, this error has the potential to skew results given our toe elevation range of only 6.4 meters and most measurements falling within a couple of meters of MHW. These error estimates do not include the calculated error of the elevation data. The DEM's resolution restricts true elevation and location to the 0.5-meter grid size.

As discussed previously, the regular interval sampling method creates a spatial autocorrelation problem for the site scale analysis. It is possible that the tests performed here have wrongfully produced significant results. Cross-referencing the site scale analysis with the regional analysis can help to validate results. In most cases, these two sets of statistical tests mirrored each other. When disparities were found, the result from the paired t-test was used because our pooled data was not spatially autocorrelated and this is a more conservative approach to interpretation.

Lastly, important possible confounding variables including sediment size, local wave energy, sediment availability and transport, bluff type, tidal range, slope stability, armor age and type, and ongoing sea level rise were omitted from analysis. Many of these have been proven to be an important control on beach morphology (Kirk, 1980). Significant findings, particularly those we have described as process-based parameters, may not be a response from armoring if the effects of other variables are stronger. On the other hand, lack of significance could be the result of one of these external factors and may not necessarily mean that armor has no effect. These results should be used cautiously, as we acknowledge the complex nature of Salish Sea beach morphology.

5. CONCLUSION

Here we offer a first high-resolution look at the morphological effects of armor in the Salish Sea compared between foreshore and backshore zones and dominant shore types. Beach profile response to armor is complex and affected by more than just the presence or absence of armor. This study found that locally, the most predominant changes to the nearshore morphology from armoring are very direct impacts where armor actively impedes on backshore habitat. There was some evidence that this response varies with shore type, however the armor toe elevation relative to the adjacent unarmored shoreline had the strongest control on backshore width regardless of shore type, geographic location, or updrift conditions. Sites that were at a major transition from armored to unarmored beach had narrower backshore sections, however this difference was not present in alternating sections of shoreline. Beach morphology parameters that were suspected to be controlled by sediment transport processes such as slope or foreshore width were not affected by the local presence of armoring but may be affected by conditions over a larger spatial scale.

Assuming these findings are representative across most shorelines in the region, they can be applied in the context of armor removal prioritization, monitoring, and policy planning. Backshore width is both ecologically important and directly affected by the elevation of armor toe similarly across shore types, which offers a straightforward method for prioritizing restoration efforts. Armoring with the lowest toe elevation relative to adjacent natural beaches will offer the largest potential for backshore habitat gain. Policy should consider this relationship by restricting the replacement of armor where the toe elevation is lower on the beach than adjacent unarmored toe elevation. Removing sections of armor at transition areas, either the end of a long stretch of armor or beginning of a long unarmored stretch, may be more likely to result in backshore recovery than removing a section of armor in an area where armored and unarmored sections are alternating. The sites included in analysis may not be representative of all Salish Sea beaches, and therefore the prioritization criteria presented should be used in conjunction with individual restoration site characteristics. Future research that incorporates additional sites and beach parameters is recommended to verify the shore type differences found and to directly link beach morphology to forage fish usage and habitat features.

APPENDIX A: CHOOSING THE INPUT DATA FORMAT

To determine the most appropriate data format to use for this study, measurements from un-gridded lidar point clouds and corresponding DEMs were compared. The point cloud was assumed to be more accurate than the DEM because it contains actual point location and elevations collected in the field while the DEM is a smoothed model of the beach surface and does not always represent actual data points. Sources of error in DEMs have been shown to be a function of the smoothing that occurs with increasing grid size and in the process of averaging values into individual grid-shaped cells (Wolock and McCabe, 2000). The DEM was the preferred data format because it takes less processing power and software to work with and there are well-defined methodologies for extracting geomorphic characteristics from them (Hapke and Reid, 2007; Hardin et al., 2012; Le Mauff et al., 2018). Additionally, DEMs are increasingly available and can be processed using ESRI ArcGIS software, an industry leading GIS software (Sweetkind-Singer and Williams, 2001; Wolock and McCabe, 2000). DEMs as the input data source would allow for future work to readily build on this research using similar data inputs and methods.

5.1 Data Format Comparison Methods

Foreshore width and slope measurements were extracted from both the lidar point cloud and DEM to test for significant differences between the two data formats. Three trials, each including 100 randomly selected profiles, were run and measurements from the point cloud were compared to measurements of the DEM. If measurements from any of the three trials were found to be statistically different at a 95% confidence interval, the point clouds would be used for its accuracy, but if none of the measurements were statistically different, the DEM would be used for its efficiency.

5.1.1 Extracting Profiles to Choose Data Format

Using ArcGIS Pro 2.3.1, profiles were generated perpendicular to the shore throughout the study sites at 10 m intervals. For each of three trials, one hundred of the generated profiles were randomly selected. These were visually evaluated and those that occurred in a stream mouth or where no foreshore was present were discarded. For the remaining profiles, the foreshore was defined as the area between MLW and MHW (Ritter et al., 2011). NOAA's VDatum tool was used to identify tidal datum elevations at the location of each profile. Fledermaus 7.7.8 and Excel 2013 were used to select two points from the point cloud along each profile: one at or nearest to the MHW elevation and one at or nearest to the MLW elevation. Profiles were visually inspected and in locations where MHW was higher than armor or bluff toe, a new point along the profile at the location of the toe was selected as the landward extent of the profile. Resulting points were used as foreshore profile endpoints to calculate width as distance between the two and percent slope using the width and endpoint elevations.

ArcGIS Pro was used to extract beach parameters from the DEM using the same profile locations of those used in the point cloud. Contours of MHW and MLW were converted to polygons to create foreshore masks. The same foreshore masks created for the second research question outlined previously were also used to extract parameters from beach parameters for determining the data format. Foreshore masks were created by extracting tidal datum elevations and a beach mask was created by semi-automated methods of extracting the toe location outlined previously. Profiles were clipped to both the foreshore masks and beach masks so they would represent the area between MLW and MHW, or the area between MLW and the toe if the toe fell lower on the beach than MHW in a profile location. ArcGIS Pro was used to calculate width and average slope values of the resulting clipped profiles.

5.1.2 Data Format Analysis

Two-tailed paired t-tests were used to compare width and slope measurements from the two data formats (Hill and Hinsley, 2015). The difference between the measurements from the point cloud and DEM at profiles were calculated and summarized for each trial and p-values were recorded. Significance was based on an alpha of 0.05. Global Moran's I was calculated for the width and slope measurements and difference values to check for any spatial autocorrelation in our data (Dale and Fortin, 2002).

5.2 Data Format Comparison Results

A total of 288 profiles from three trials were selected to use for comparing the point cloud measurements with DEM measurements. There was no spatial autocorrelation found in any of our three trials. Global Moran's I calculated from the profile offset values were -0.016, 0.253, and 0.003 for beach width and -0.069, -0.056, and -0.083 for beach slope, all of which represent a random distribution. The average offset between beach widths extracted from the two data formats (absolute value of point cloud values minus DEM values) was 17 cm and the average offset for beach slope was 0.4 percent. Figure 13 shows measurements from the two data formats from each of the three trials plotted against each other. Each point represents measurements from the same profile, and those that fall closer to the grey dotted line are most similar. From viewing these plots, it is apparent that width is most similar between data formats when considering the offsets in proportion to the average widths. The slope values are noticeably more different than width between the two formats, however they are not different enough to be statistically significant.

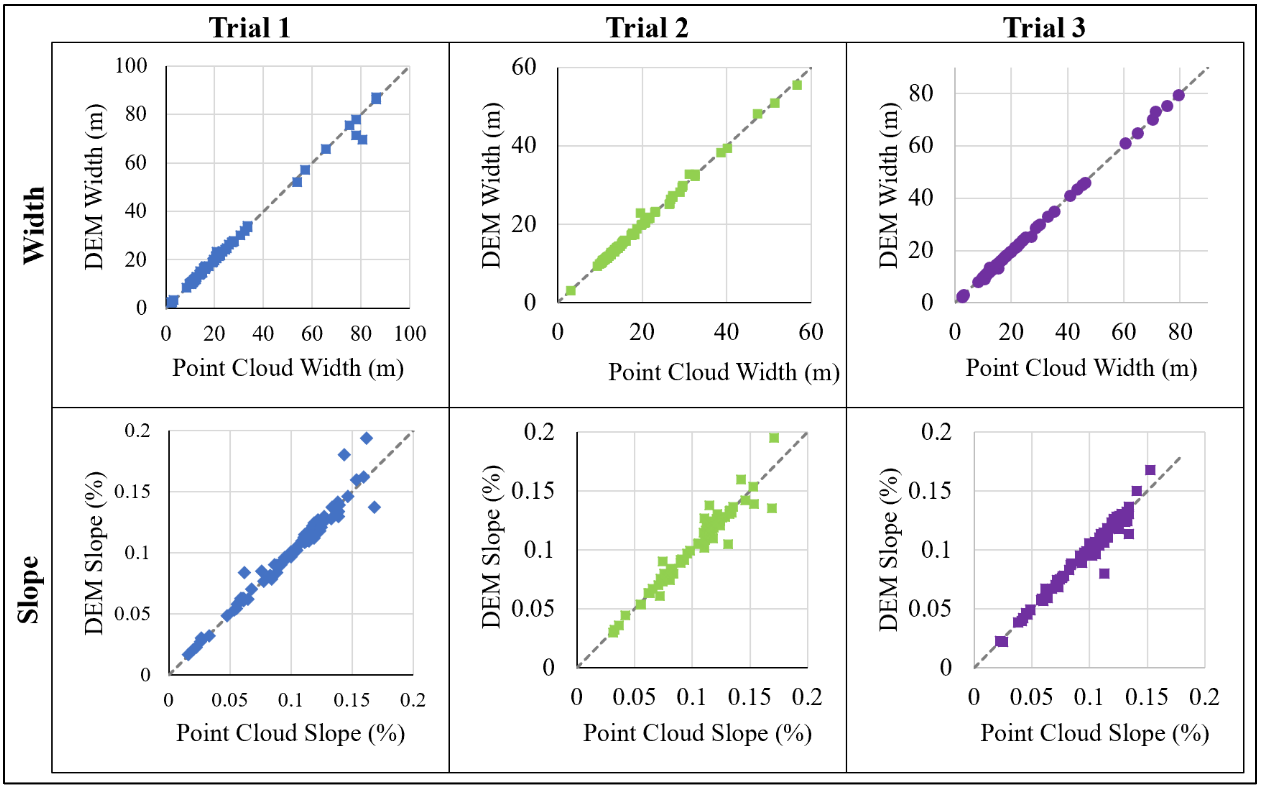

Figure 13. Plotted measurements from the DEM along the y axis and point cloud along the x axis. If the two data formats were the same, every point would fall on the grey dotted line in each plot.

Table 4 summarizes the results from the paired t-tests by trial number including the number of profiles used in each trial, p-values, difference mean (average offset of the DEM from the point cloud value), and standard deviation of differences (standard deviation of offsets of DEM from the point cloud). Comparison within each trial of beach width resulted in p-values of 0.446, 0.387, and 0.467 and slope p-values were 0.428, 0.336, and 0.450. Based on the selected alpha of 0.05, there was no significant difference between the point cloud or DEM in width or slope in any of the three trials.

Table 4. Summary table of results from the paired t-tests performed to compare beach profiles extracted from the point cloud vs. the DEM. Three trials were run, and tests were separated by beach width and beach slope.

Trial Number	Profile Count	Width			Slope		
		P-Value	Difference Mean	St. Dev. of Difference	P-Value	Difference Mean	St. Dev. of Difference
1	97	0.446	-0.125	1.457	0.428	0.064	0.737
2	93	0.387	0.055	0.520	0.336	0.426	0.633
3	98	0.467	0.033	0.421	0.450	0.322	0.459

5.3 Discussion and Conclusions of Data Format Selection

The DEM was found to be minimally different from the point cloud and the remainder of the study was completed using the DEM as the input data format. The high p-values and small average differences between the point cloud and DEM in all three of our trials suggest that a DEM gridded at 0.5 m is as accurate as the point cloud for describing beach width and slope along the foreshore. Though the differences between slope were more noticeable than those between width measurements, the two data formats were not significantly different and were still reliable enough to use in subsequent research. Since an averaged beach slope between two endpoints of a transect was used, it is possible that other morphological features occurring between the two endpoints such as boulders or berms may be smoothed out in the DEM and preserved in the point cloud, but was undetected by our testing method.

We hypothesized that the smoothing of sharp changes in elevation would contribute to differences in parameters at the base of armoring or steep bluffs. If this were the case, profiles where the toe elevation fell lower than MHW would have been the most different between data types however this was not apparent in the data. In fact, these profiles had some of the smallest differences in measurements from the two data formats. The noticeable disparities between measurements in the point cloud and DEM could all be explained by low data density. Profiles with large woody debris accumulation or those with extremely flat low tide terraces are two examples of this. Low angle beach profiles result in lower data density because of the side angle of the boat-based lidar. Since the major differences did not appear to be a product of gridding the DEM with the 0.5 m resolution, it was sufficient to test only the foreshore zone, not the backshore zone where gridding may have been a larger concern. Future work should test the effects of using coarser resolutions to better understand the needs of data quality inputs. Testing between field measurements and remote sensing measurements should also be compared to verify these results. Similarities between data collected in the field and lidar data would offer the opportunity to integrate historic monitoring data with these new data collection techniques.

These findings can be applied to future shoreline research. As DEMs become more publicly available and the ESRI software becomes more widely used, shoreline research may be greatly expanded to cover a wider range of shore types and geographies. Additionally, repeatable methods may be developed which could result in more collaborative efforts to address coastal morphology problems. In the case of the research presented here, additional sites could be added to these results as more data becomes available.

6. WORKS CITED

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