Controls on wave runup and coastal storm impacts on mixed-sediment beaches for coastal evolution modeling
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1. Introduction
1.1 Project Summary
This project aims to refine models used to forecast coastal hazards, impacts, and change in mixed-sediment (sand and gravel) beach systems characteristic of the Pacific Northwest. Field investigations will evaluate the extent that intertidal complexity (slope, roughness, substrate complexity) influence coastal processes like wave runup, sediment transport, and bluff erosion at three field sites in the Salish Sea (Figure 1). Data to be gathered will be used to calibrate runup model parameters and quantify their relative influence on runup along complex, varying shorelines. Cobble transport data will be used to quantify the frequency of mobility for different clast sizes under specific wave conditions. Results will feed the United States Geological Survey’s (USGS) Puget Sound Coastal Storm Modeling System (PS-CoSMoS) that currently projects the impending hazards, impacts, and risk of Puget Sound and the Salish Sea coastal ecosystems, infrastructure, and industry to sea-level rise (SLR) and coastal climate change (USGS PS-CoSMoS, 2018).

1.2 Problem Statement
Within the Salish Sea, relative sea level is projected to rise between 10-143 cm by 2100 (NRC, 2012). This change is expected to increase the frequency and intensity of extreme water levels and storm surges, causing formerly century water-level extremes (100-year high water events events) to become decadal (10-year high water events) by mid-century (Tebaldi et al., 2012). The combination of SLR and more intense storm surges is anticipated to increase the risk of inundation, erosion, and changes of shorelines within the Salish Sea posing costly effects to property, infrastructure, and ecosystem functions (Adelsman & Ekrem, 2012). To promote preservation and resiliency in the face of expected changes, a fundamental understanding of how shorelines and beach sediment will respond to hydrodynamic forces is necessary.

Predicting wave runup and shoreline change within the Salish Sea is difficult because of the high diversity of wave and wind exposure, shoreline morphology, and coastal landforms in this region. The general shore types include rocky coasts, coastal bluffs, deltas, spits, lagoons, and salt marshes with roughly half of the ~4,000 km shoreline consisting of heterogeneous mixed-sediment beaches (Johannessen & MacLennan, 2007). Existing literature covering beach geomorphology largely focuses on open coast fine grained sandy beach environments with limited tidal ranges (Finlayson, 2006). Relatively few studies have quantified sediment dynamics on mixed-sediment beaches characteristic of the Salish Sea (e.g., Miller et al., 2011; Weaver, 2013). Therefore, much less is known about the coastal processes that influence the geomorphology of mixed-sediment beaches (Shipman et al., 2014) and many models used to predict the interaction between the ocean and shorelines are largely derived from sandy low angled dissipative systems (e.g., Stockdon et al., 2006) rather than mixed-sediment steep reflective systems.

I propose to investigate the relationship between beach face characteristics (e.g., substrate complexity, roughness, slope) and, wave energy transformations that lead to runup
Figure 1. Map of Puget Sound and eastern Salish Sea showing the location of the three proposed study sites and bluff recession rates (ft/yr) from MacLennan et al., 2017. Sites 1 and 2 include some of the highest bluff recession rates within the Salish Sea. Site 1 located on west Whidbey Island, is exposed to both long-period ocean swell and short-period wind generated waves. Site 2, Tulalip Bay is adjacent to Tulalip Tribal Reservation and exposed to short-period wind generated waves. Site 3, Lone Tree Point is adjacent to the Swinomish Tribal Reservation and also exposed to short-period wind generated waves. Modified from MacLennan et al., 2017 Figure 11.
and sediment transport, in order to help refine numerical models of coastal change. Data characterizing wave runup relative to variation in beach face characteristics will be gathered then used to evaluate the skill of published wave runup models. Secondarily, data relating sediment transport of different clasts sizes to incoming wave energy, runup, and beach characteristics will be collected and analysed to assess conditions that drive sediment movement. I hypothesize that (1) wave runup, which drives sediment transport and movement, varies significantly across small spatial scales (10s to 100s of meters) in response to beach face slope and roughness, (2) models calibrated using data from sandy low sloping beaches (e.g., Stockdon et al., 2006) will overpredict wave runup on coarser grained beaches of the Salish Sea, and (3) cobble mobility will be lower along rougher transects with similar incoming wave energy and slope. These efforts intend to help improve our understanding of and ability to predict rates and drivers of shoreline change in mixed-sediment beaches characteristic of the Pacific Northwest and many similar steep, complex coastlines around the world.

2. Background

Non-deltaic, beach shorelines of the Salish Sea are largely fed by the erosion of coastal bluffs composed of glacially-derived till, outwash sediments, glacial marine, and glaciolacustrine deposits. The resulting mixed-sediment beaches are comprised of a wide variety of grain sizes including cobbles, gravel, sand, silt, and clay (Figure 2). The shorelines of the Salish Sea consist of fetch-limited settings with exposure to short-period locally wind generated waves isolated from Pacific Ocean swell and shorelines that are exposed to both locally generated waves and long-period ocean swell. The majority of waves in the Salish Sea are therefore generated by winds blowing over local basins and narrow troughs creating an environment where waves are tightly connected to local wind patterns (Finlayson, 2006). The Salish Sea is a macrotidal estuary with large tidal ranges (1.9 m at the south end of Vancouver Island to 4.4 m near Olympia (Mofjeld & Larsen, 1984; Mofjeld et al., 2002)).

2.1 Influences on Coastal Morphology

Recent Geologic History of the Region

The significant variability and irregular shape of the Salish Sea landscape is dominantly a result of its glacial history. During the Pleistocene epoch, the Puget Lowland was repeatedly occupied by advances of the Puget Lobe of the Cordilleran ice sheet from ice sourced in the southern Coast Mountains of British Columbia (Booth, 2003). The most recent advance of the Puget Lobe during the Vashon Stage of the Fraser Glaciation (~18,000-15,000 BP; Porter & Swanson, 1998) deposited an extensive plain of poorly consolidated glacial drift across the region. During the maximum extent of glaciation, a series of deep troughs were carved into the glacial drift attributed primarily to subglacial fluvial incision. These troughs eventually became the major arms of the Salish Sea, which form the main shape and morphology of the modern coastline (Booth & Hallet, 1993).

Sediment Source and Characteristics

Glacially derived coastal bluffs are the main source of sediment for shorelines in the Salish Sea (Figure 2). These coastal bluff sediments are generally heterogeneous mixes of poorly sorted clay, silts, sand, and cobbles that have a high spatial variability, resulting in mixed-
sediment beaches (Finlayson, 2006). Mixed-sediment beaches have been defined as beaches with highly variable mixture of medium to moderately sorted gravel with 15-30% moderately sorted coarse sand and predominantly gravel in the upper foreshore and coarse sand in the lower foreshore (Taylor et al., 2004, Pontee et al., 2004).

**Bluff Recession**

Long-term bluff recession rates largely reflect the interaction of wave and tidal energy, geology of the bluffs, and beach characteristics, although other factors contribute to bluff erosion (e.g., groundwater seepage, rainfall and runoff, devegetation, and earthquakes) (Keuler, 1988). A recent report, by Coastal Geologic Services (2017) examined bluff recession under a wide range of conditions at a regional scale. By compiling historical bluff recession rates, field measurement, and aerial photographs of 186 bluffs they found an average long-term recession rate of -0.09 m/yr within the Salish Sea. The western shores of Whidbey Island show some of the highest rates, which vary from ~0.1 m/yr to -0.34 m/yr (MacLennan et al., 2017).

*Figure 2.* (a) Aerial photograph of a characteristic mixed-sediment beach backed by glacially derived bluffs on west Whidbey Island, WA. Image from the Department of Ecology State of Washington Shoreline Viewer ([https://fortress.wa.gov/ecy/shorephotoviewer/Map/ShorelinePhotoViewer](https://fortress.wa.gov/ecy/shorephotoviewer/Map/ShorelinePhotoViewer)). Photographs (b) and (c) from the same location, highlighting the complexity of beach substrate composition and roughness in mixed-sediment beach environments.
Wind and Wave Conditions in the Salish Sea

In addition to sediment sources, beach morphology is affected by exposure to wind and wave energy. Shorelines along and in line with the Strait of Juan de Fuca are exposed to both long-period ocean swell and locally wind-generated waves and are expected to experience greater shoreline changes from waves and projected SLR (NAS, 2012). Beaches sheltered from Pacific Ocean swell are shaped by fetch-limited local wind-generated waves as a result of the narrow troughs of the Salish Sea. Fetch driven energy generates sufficient bottom shear stress to move sediment across certain beaches, but overall a quantitative understanding of the spatial and temporal variability and importance of waves to shorelines processes is limited by few wave studies and models.

Locally, forecasted SLR may change wave conditions reaching shorelines. Higher sea level will reduce the friction between waves and the sea floor causing less dissipation of wave energy. This allows more frequent high energy wave events to reach shorelines (Tabaldi, 2012). A notable increase of offshore wave heights related to increases in both the magnitude and frequency of storms in the North Pacific has occurred over the last 60 years (Bromirski et al., 2003). Deep-water wave buoy data since the mid-1970s offshore of the Pacific Northwest has documented that the annual averages of deep-water significant wave height have increased at a rate of approximately 0.015 m/yr (Ruggiero et al., 2010). This wave energy penetrates and affects portions of the Strait of Juan de Fuca and Whidbey Island shorelines. In addition, the frequency and intensity of atmospheric rivers originating from the south-central Pacific is expected to increase, influencing local wave generation (Mauger et al., 2015; Warner et al., 2014).

2.2 Wave Runup Dynamics and Modeling

Wave runup occurs within the swash zone where waves encounter the shore and break, causing an upsurge of water. Runup is measured as the vertical height above the still water elevation attained by the extremity of up rushing water (Figure 3a). Runup is important to guidance of flooding and coastal erosion hazard planning because total water level, an estimation of the elevation where the ocean meets the coast, is the combination of tides, storm surge, and wave runup (“Total Water Level and Coastal Change Forecast Viewer”). Wave runup is complex and depends on several factors including wave characteristics (wave height, period, steepness, direction) as well as the nature of the beach (slope, reflectivity, height, permeability, geometry, roughness). Since runup is sensitive to many factors, it can vary significantly alongshore over short distances (FEMA, 2005).

A number of wave runup-models (Figure 3b) have been used to calculate wave runup on beaches to guide planning for coastal inundation from storms and rising sea levels (e.g., NHC, 2005; Stockdon, 2006; Waal et al., 1992; Van Gent, 2001; Hedges & Mase, 2004; Ahrens et al., 1988; Ruggiero et al., 2001). These models have typically been formulated based on empirical field measurements at sandy low angle open coast beaches or in laboratory experiments. The Federal Emergency Management Agency (FEMA) created the RUNUP 2.0 model which uses wave runup formulas based on small-scale laboratory runup tests with regular waves on smooth, impermeable, uniform slopes (Stoa, 1978). FEMA’s Wave Runup and Overtopping report (FEMA, 2005) suggests that RUNUP 2.0 may not be directly transferrable to the Pacific.
Figure 3. (a) Simplified beach profile illustrating runup defined as the maximum vertical extent of wave uprush on a beach above the still water level. (b) Table of runup formulations to be tested in this study.

Coast without revision and modification for areas like the Pacific Coast that are more complex than the open coast Atlantic and Gulf of Mexico. They recommend identifying the appropriate runup guidance for the Pacific Coast as a high priority and that testing should include evaluation of the sensitivity of runup models to specific parameters such as beach slope, roughness, and incident wave characteristics (FEMA, 2005).

Stockdon et al. (2006) devised one of the most widely used parameterizations of maximum runup elevation pertinent to storm impact models. They defined the maximum runup elevation as the 2% exceedance value, or the maximum runup elevation that is exceeded by 2% of incoming waves. They collected runup data using an Autonomous Real-Time Ground Ubiquitous Surveillance (ARGUS) video techniques developed at the Coastal Imaging Lab at Oregon State University at 10 field sites to refine formulations of runup. Time stacks of pixel intensity were sampled at 1 or 2 Hz (1 or 2 photos per second) over 17 to 120-minute periods where runup and rundown are shown as a white edge moving in the swash.

### Table of Runup Formulations

<table>
<thead>
<tr>
<th>Source</th>
<th>Equation</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stockdon et al. (2006)</td>
<td>$R_{2%} = 1.1(0.35)(H_bL_o)^{1/2} + \frac{1}{2}(H_bL_o(0.565\beta^2 + .004))^{1/2}$</td>
<td>$R_{2%}$ = runup 2% exceedance elevation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\beta$ = average beach slope</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$H_b$ = deep water wave height</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$L_o$ = deep water wave length</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma_r$ = reduction factor (rf) for shallow foreshore</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma_f$ = rf for roughness of slope</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma_o$ = rf for oblique wave attack</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma_b$ = rf for a berm</td>
</tr>
<tr>
<td>Van der Meer &amp; Janssen (1994)</td>
<td>$R_{2%} = H_sL_o\tan(\beta)\sqrt{2gH_s/gH_o}$</td>
<td>$R_{p} = H_sL_o\tan(\beta)\sqrt{2gH_s/gH_o}$</td>
</tr>
<tr>
<td>Van Gent (2001)</td>
<td>$R_{2%}/H_{ave} = 2.3(\xi_{ave})^{0.3}$</td>
<td>$R_{p} = H_sL_o\tan(\beta)\sqrt{2gH_s/gH_o}$</td>
</tr>
<tr>
<td>NHC/FEMA (2005)</td>
<td>$R_{2%} = H_{ave}1.77\gamma_r\gamma_f\gamma_o\gamma_{ave}$</td>
<td>$\xi_{ave}$ = Irribaren number $= \sqrt{(H_s/L_o)^{1/2}}$</td>
</tr>
<tr>
<td></td>
<td>$0.5 \leq \gamma_r \leq 1.8$</td>
<td>$\xi_{ave}$ = Irribaren number $= \sqrt{(H_s/L_o)^{1/2}}$</td>
</tr>
<tr>
<td></td>
<td>$R_{2%} = H_{ave}4.7\gamma_r\gamma_f\gamma_o(4.3 - 1.6\sqrt{\xi_{ave}})$</td>
<td>$H_s$ = significant wave height</td>
</tr>
<tr>
<td></td>
<td>$1.8 \leq \gamma_r \leq 3.5$</td>
<td>$T_p$ = peak period</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$g$ = gravitational acceleration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$H_{ave}$ = spectral significant wave height at the structure toe, zero-moment wave height</td>
</tr>
</tbody>
</table>
zone. A generalized expression of runup on all beaches was created based on their entire data set (Figure 3b). Although their study includes a variety of environmental conditions, the bulk of their data (91%) were collected from Duck, NC, a fine grained, low-sloping-sandy beach. Given the typically steep angle and high reflectivity of mixed-sediment beaches in the Salish Sea and the Pacific Northwest, models using Stockdon’s runup equation would benefit from testing model skill and/or adding reflective-specific parameterizations and coefficients.

2.3 Sediment Transport Studies on Mixed-Sediment Beaches

Mixed-sediment beaches are relatively rare worldwide compared to homogeneous fine sand or gravel beaches (Zenkovich et al., 1967) and occur at high latitudes where glaciation has left an abundance of poorly sorted unconsolidated sediment (e.g., New Zealand, the United Kingdom, the Pacific Northwest). This has led to a limited understanding of the rates and drivers of sediment transport compared to less complex environments (i.e., homogeneous-environments like fine sand or gravel beach environments) where the majority of nearshore research is focused (Curtiss et al., 2009).

In the Pacific Northwest, several studies have focused on the drivers of sediment movement in mixed-sediment systems (e.g., Miller et al., 2011; Curtiss et al., 2009; Weaver, 2013; Osborn et al., 2010; Allan et al., 2006). Studies found high seasonal fluctuations and dominant seasonal transport directional patterns as well as a range of transport magnitudes and directions at different elevations of the beach. Miller et al. (2011) tracked cobbles using Radio Frequency Identification (RFID) tag techniques and found that cobbles can approach average long-shore velocities of 100 m/day under winter wave conditions. Weaver (2013) resolved significantly different rates of cobble movement with respect to elevation on the beach and wave regime, with greater rates of sediment transport high on the beach and in response to slight increases in wave period. Other studies focused on anthropogenic forcing on mixed-sediment beaches including vessel wake and dam removal (Osborn et al., 2010; Warrick et al., 2009; Curtiss et al., 2009). Overall, research on mixed-sediment beaches suggests that different forcing conditions affect sediment transport throughout the year, indicating the need for longer term observations for both forcing and responses.

3. Methods

My proposed research is part of an interagency study led by the USGS to improve PS-CoSMoS and long term (e.g., 50-100 years) predictions of beach and bluff dynamics in mixed-sediment systems. I will integrate in-situ field measurements, remote sensing, and modeling to assess wave runup and sediment mobility at three mixed-sediment beaches in the Salish Sea (Figure 1) over timescales of individual waves, storms, and storm seasons. Complimentary efforts by the USGS will measure and model offshore wave conditions (e.g., wave period, wave height) for each field site. Additionally, an ARGUS video system will measure time-averaged runup, water level, and wave heights at two of the field sites. I will make several measurements (Table 1) throughout this study to determine necessary boundary conditions for runup equations (e.g., Stockdon et al., 2006; NHC, 2005; Meer et al., 1994; Van Gent, 2001; Adelsman et al., 2012; Ahrens et al., 1988; Waal et al., 1992). In-situ wave runup measurements will be used to test how well published formulations predict runup for the mixed-sediment systems studied. I will also refine roughness and friction coefficients using both boundary conditions and
measured runup. Secondarily, coarse sediment transport data will be collected and analyzed to assess the frequency that cobbles are mobilized in the swash zone under specific wave conditions. Together, these data and refined models will help predict the influence of changes in wave conditions to mixed-sediment beaches and coastal change.

**Table 1.** Survey measurements and methods.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Measurement Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave runup</td>
<td>RTK-GPS, ARGUS</td>
</tr>
<tr>
<td>Beach slope (profile)</td>
<td>RTK-GPS</td>
</tr>
<tr>
<td>Beach face roughness</td>
<td>Structure-from-Motion</td>
</tr>
<tr>
<td>Grain size distribution</td>
<td>Cobble Camera</td>
</tr>
<tr>
<td>Wave climate (water level,</td>
<td>Acoustic Doppler Velocimeter (ADV), USGS models</td>
</tr>
<tr>
<td>breaking wave heights, wave period,</td>
<td>and offshore instruments, ARGUS</td>
</tr>
<tr>
<td>wave set-up, current velocities/directions, wave orbital velocities)</td>
<td></td>
</tr>
<tr>
<td>Cobble transport rate</td>
<td>Cobble Transport Camera, RFID</td>
</tr>
<tr>
<td>Geomorphic features</td>
<td>RTK-GPS</td>
</tr>
</tbody>
</table>

### 3.1 Field Site Selection

The beach and bluff systems to be studied are characteristic of many Pacific Northwest coastal areas and are intended to capture a variety of shoreline settings present in the Salish Sea. Sites were selected based on the following criteria:

1. Variations in wave exposure.
2. Diversity in beach face complexity/roughness.
3. Site specific importance (cultural, ecological, hazards).

Site 1 is a ~1-3 km stretch of bluff-backed beach north of Fort Ebey State Park on Whidbey Island. This site includes a narrow shoreface (<50 m) with highly variable (mud to cobble) mixed-sediment beaches and variable slope. It is exposed to long-period ocean swell that penetrates the Strait of Juan de Fuca and locally generated wind waves. Bluffs range in height from a minimum of a few meters to a maximum elevation of 80 meters, with slopes that vary from nearly vertical to roughly 45°. This site includes some of the highest rates of historical bluff recession in the Salish Sea (MacLennan et al., 2017) that is leaving homes (some <20 m from the bluffs edge), parks, and infrastructure (roads) vulnerable. This study site is part of a principle USGS study that includes an online video system, ARGUS, that will continually monitor water levels, wave heights, and wave runup along ~500 meters of beach and bluff.

Sites 2 and 3 are exposed dominantly to short period (3-5 second) locally wind-generated waves and represent less overall exposure to wave energy than site 1. Site 2 includes relatively high bluff recession rates varying from -0.055 m/yr to -0.16 m/yr (MacLennan et al., 2017). Sites 2 and 3 are of considerable interest to the tribal reservations for habitat restoration (e.g., clams, oysters, crab, forage fish, eel grass). They are also the sites of important research on habitat availability and information needs to inform protection and habitat restoration (e.g., Barber et al., 2016), important to tribal treaty rights.
3.2 Pre-survey characterization

I will create maps of beach and bluff morphology and grain size differences from aerial imagery and LiDAR to define baseline conditions for each proposed study site. I will refine remotely generated maps to higher resolution using an RTK-GPS in order to measure change during subsequent surveys. Preliminary RTK-GPS surveys of water levels and wave runup heights will be observed and measured at each site in order to design a sampling protocol for focused runup and cobble transport studies during winter storm season. Initial 1D models of wave runup using shoreline profiles collected with RTK-GPS will be generated and tested for sensitivity to summer and storms season wave climate and to guide winter storm season sampling.

3.3 Summer and Storm Season Surveys

Summer surveys will be carried out for two main purposes. First to test and refine survey strategies during optimal weather conditions and daytime low tides and second to capture wave runup and sediment transport during lower energy conditions. Once data collection methods are refined, I will repeat surveys outlined below at each of the sites during the active storm season when sediment transport rates and wave runup is expected to be
greater. I will gather data during low, medium, and high wave events over a range of tidal stages at each field site. Wave runup and cobble transport surveys will be conducted on hourly time scales to understand the effects of specific wave/wind conditions. The following outlines the different surveys I will perform (Figure 4).

**Wave Runup Surveys**

Wave runup elevation and location data will be gathered along multiple transects with variations in beach substrate at each site. Transects will be located in close proximity (<50m) to each other where approaching wave energy is similar. Measurements will be taken by staking maximum wave runup locations and recording coordinates using an RTK-GPS over periods of 30 minutes to 3 hours. I anticipate being able to collect ~20-30 wave runup data points/hr.

A video camera system referred to as ARGUS, has been installed at site 1 which collects imagery across a 90-degree panorama and ~500 meters along the beach as part of the USGS Coastal Habitats in Puget Sound Project. I will install a second ARGUS system at either site 2 or 3. ARGUS records 5 sets of images every half hour during daylight hours to supply a snapshot, 10-minute time average, variance image (the variance of the light intensity signal), bright image (brightest pixel within time period), and a dark image (darkest pixels within time period). These images are used to continuously measure tide level, wave heights, and wave runup at lower cost than traditional oceanographic equipment. The runup time-series generated from the ARGUS will complement my study with runup data at several cross-shore transects in the ARGUS view and in turn will be validated by my RTK-GPS surveys of runup.

**Roughness Mapping**

To characterize roughness of the beach face where wave runup and sediment transport surveys are being conducted, I will use Structure-from-Motion photogrammetry techniques (Warrick et al., 2017) taken from a mast-mounted camera (~3 m above ground) (Figure 5). I will create high resolution (mm-cm scale resolution) digital elevation models (DEMs) from images using Agisoft Photoscan Professional software. High resolution DEMs including micro-texture of the beach substrate will be used to extract the rugosity (a quantification of roughness) of beach substrates, or the distance up and over cobbles and gravels relative to the straight-line distance (Figure 5d).

**Cobble Transport Surveys**

Cobble transport data will be collected by deploying labeled cobbles in a survey grid below a mast-mounted camera that will collect video of cobble movement during the experimental period. Surveys will be conducted in ~100-300m² region within the swash zone within the field of view of the camera. During each survey, I will deploy ~10-25 cobbles of 3-4 different sizes with each cobble size painted a unique color. Each cobble will be fitted with a Radio Frequency Identification (RFID) tag that allows tracking with an antenna (Miller et al., 2011; Weaver, 2013) to locate clasts that get lost or buried. To measure swash zone hydrodynamics including breaking wave heights, wave set-up, current velocities/direction, and wave orbital velocities during these surveys, I will temporarily deploy an acoustic doppler velocimeter (ADV) (Raubenheimer et al., 2004). These data will provide important boundary
conditions for forcing runup models and help relate observations of sediment transport and mobility to nearshore processes that drive sediment transport.

Figure 5. (a) Photograph showing Structure-from-Motion photogrammetry techniques using a mast-mounted camera. High resolution DEMs with micro-structures can be generated with this technique in Agisoft Photoscan Software shown in (b) and (c) (provided by Nate VanArendonk). The rugosity of the surface can be quantified by draping profiles over the DEMs. (d) visually demonstrates how rugosity, a way to quantify surface roughness, is measured.
**Substrate Composition**

I will take repeat surveys of grain size distribution on beach faces using cobble cam approaches developed by Warrick et al. (2009). I will conduct surveys in cross-shore transects collected using a camera mounted in a vertically down-looking position on a tripod approximately 1 m above the ground surface. Grain-size distribution for each photograph will be quantified during post-processing that employs automated (auto-correlation of pixels) and semi-automated (randomized manual measurements of grain sizes) classification techniques.

3.4 Analyses and Modeling

*Wave runup*

In-situ measurements of beach slope, beach face roughness, grain size, and wave climate will be used as boundary conditions to force several runup formulations (Figure 3). I will compare the outputs from these models to observed runup to evaluate the skill of each model. Importantly, I will test how well runup is modeled given the roughness parameters estimated from Structure-from-Motion and use the derived roughness if a better fit is determined between modeled and measured runup. This will be done by iteratively solving for the roughness and friction coefficients that minimize the misfit between predicted and observed runup to refine the reduction factors for the mixed-sediment systems studied. I will use the Root Mean Square Error (RMSE) to compare predicted and observed runup values and evaluate roughness and friction coefficients. Refined runup models will then be used to simulate runup for several SLR scenarios for 2050, 2075, and 2100. This will quantify the projected increase in frequency that total water levels will reach different elevations on the beach slope and the bluff toe.

*Sediment Transport*

Swash zone cobble transport distances, directions, and rates stratified by cobble sizes will be extracted from mast-mounted cobble transport camera imagery using open source object tracking code in MATLAB from several surveys. With these data I will characterize the frequency of mobility of different clasts sizes today and project mobility frequencies in the future with higher water levels and wave energy expected with SLR. I will also calculate the threshold of exceedance for the various particle sizes on the beach, assuming all clasts move when critical shear stress is exceeded. This will inform potential future rates of sediment transport and the fate of sediment generated from expected bluff erosion.

4. Expected Results and Implications

Quantitative data collected during summer and storm season surveys will characterize the morphologic and substrate complexity of the mixed-sediment beaches studied and the predominant coastal processes driving responses. Data collected will quantify and refine published runup model skill including roughness parameters for varying conditions at mixed-sediment beaches. I will produce maps and plots of the frequency that runup or total water level reach different levels of the beach (e.g., along several profiles at each field site) as well as the frequency that different cobble sizes are mobilized. Additionally, I will project runup and cobble mobilization frequencies for multiple SLR scenarios for 2050, 2075, and 2100.
Refined runup models to better capture nearshore processes in steep, complex coastal settings will improve projections of impending shoreline change and hazards as well as habitat restoration and resilience planning efforts. Maps and plots of sediment mobilization will guide erosion estimates and erosion potential and intend to help inform potential changes to important habitats and species dependent on intertidal beaches. These plots are identified as priority information needs to identify preservation and restoration opportunities for many values species within the Salish Sea and specifically address complex habitats beings tested for importance to biomass and diversity as part of a parallel study. Results from this study will provide essential boundary conditions for planned coupled beach-bluff dynamics modeling (USGS-PS-CoSMoS) and help inform coastal managers and policy makers of spatial considerations when planning for future shorelines change and risks.
5. Timeline

Spring 2018
- Literature review
- Apply for grants
- Meet USGS collaborators, help georeference ARGUS camera system
- Learn how to generate DEMs from Structure-from-Motion techniques and Agisoft Photoscan Professional software and use RTK-GPS
- Write thesis proposal

Summer 2018-Winter 2019
- Test and refine survey strategies
- Collect data
- Test several runup formulations skills
- Develop initial runup models with Matlab
- Generate DEMs of beach substrate
- Write

Winter 2019-Fall 2019
- Analyze data
- Run model simulations
- Generate plots and maps
- Write

Fall 2019
- Table thesis
- Defend and graduate
6. References


