Healthy Beaches for People and Fish:

Protecting shorelines from the impacts of armoring today and rising seas tomorrow

Sea Level Rise Vulnerability in San Juan County, Washington

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FRIENDS
OF THE SAN JUANS

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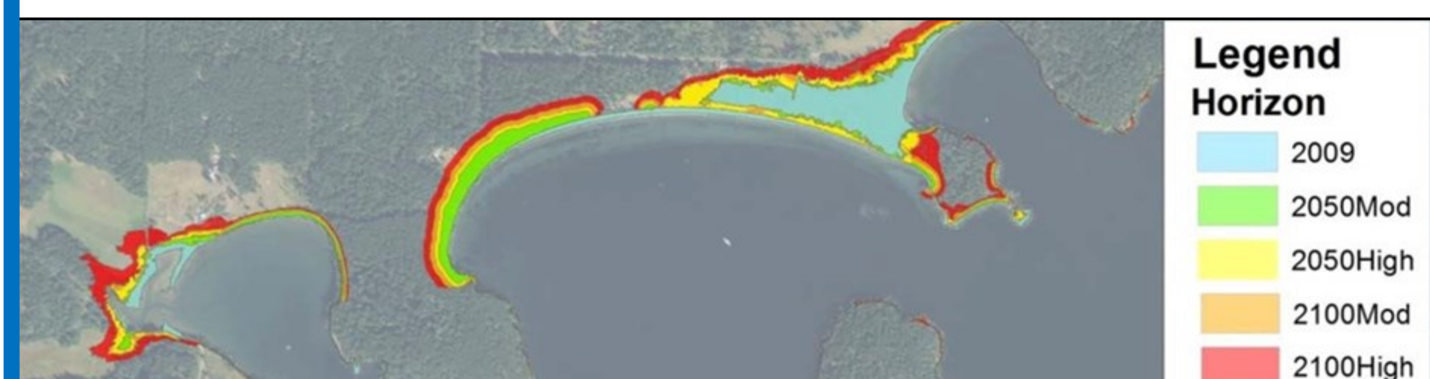

Healthy Beaches for People and Fish

The goal of the *Healthy Beaches for People and Fish*: *Protecting shorelines from the impacts of armoring today and rising seas tomorrow* project is to improve the long-term protection of nearshore marine ecosystems by developing new technical tools and identifying management strategies that specifically address sea level rise and the cumulative impacts of shoreline armoring.

The *Healthy Beaches for People and Fish* project was completed by Friends of the San Juans in partnership with Coastal Geologic Services, Salish Sea Biological and the Washington Department of Fish and Wildlife in 2014. Project approach and work was guided by a technical advisory group, which included representatives from The University of Washington, United States Geological Survey, Puget Sound Partnership, Skagit River Systems Cooperative, Samish Indian Nation, San Juan County Public Works, San Juan County Salmon Recovery Lead Entity, The Tulalip Tribes, Padilla Bay National Estuarine Research Reserve and the Washington State Departments of Ecology, Natural Resources and Fish and Wildlife.

The project contained four distinct areas that informed management recommendations:

- A legal review of existing local, state and federal shoreline regulations and their ability to address sea level rise and cumulative impacts;
- Sea level rise vulnerability assessment for San Juan County;
- Forage fish spawning habitat research; and
- Surveys of coastal managers, regulators and researchers.

Reports and data products associated with this project can be found online at www.sanjuans.org/NearshoreStudies.htm and include:

Friends of the San Juans. 2014. Healthy Beaches for People and Fish: Protecting shorelines from the impacts of armoring today and rising seas tomorrow. Final Report to WDFW and the U.S. EPA. Friday Harbor, Washington.

Loring, K. 2013. Addressing Sea Level Rise and Cumulative Ecological Impacts in San Juan County Washington Through Improved Implementation and Effective Amendment of Local, State, and Federal Laws. Friends of the San Juans. Friday Harbor, Washington.

MacLennan, A., J. Waggoner and J. Johannessen. 2013. Sea Level Rise Vulnerability Assessment for San Juan County, Washington. Prepared by Coastal Geologic Services for Friends of the San Juans.

Whitman, T., D. Penttila, K. Krueger, P. Dionne, K. Pierce, Jr. and T. Quinn. 2014. Tidal elevation of surf smelt spawn habitat study for San Juan County Washington. Friends of the San Juans, Salish Sea Biological and Washington Department of Fish and Wildlife.

Whitman, T. and S. Hawkins. 2013. The impacts of shoreline armoring on beach spawning forage fish habitat in San Juan County, Washington. Friends of the San Juans. Friday Harbor, Washington.

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Glossary

Accretion	The gradual addition of sediment to a beach or to marsh surface as a result of deposition by flowing water or air. Accretion leads to increases in the elevation of a marsh surface, the seaward building of the coastline, or an increase in the elevation of a beach profile (the opposite of erosion) (Shipman 2008).
Adaptation	The adjustment of natural or human systems in response to actual or expected phenomena or their effects such that it minimizes harm and/or takes advantage of beneficial opportunities.
Adaptive capacity	A community's ability to respond to actual or expected phenomena or their effects, including the moderation of potential damages caused by them, taking advantage of opportunities presented by them, and coping with the consequences associated with them.
Anthropogenic	Caused or produced by humans.
Backshore	The upper zone of a beach beyond the reach of normal waves and tides, landward of the beachface. The backshore is subject to periodic flooding by storms and extreme tides, and is often the site of dunes and back-barrier wetlands (Clancy et al. 2009).
Barrier beach	A linear ridge of sand or gravel extending above high tide, built by wave action and sediment deposition seaward of the original coastline. Includes a variety of depositional coastal landforms, including spits, tombolos, cuspate forelands, and barrier islands (Shipman 2008).
Beach	The gently sloping zone of unconsolidated sediment along the shoreline that is moved by waves, wind, and tidal currents (Shipman 2008).
Bluff	A steep bank or slope rising from the shoreline, generally formed by erosion of poorly consolidated material such as glacial or fluvial sediments (Shipman 2008).
Conceptual model	A model, either numerical or diagrammatic, that summarizes and describes the relationships and interactions between specified model components.
Drift cell	A littoral [drift] cell is a coastal compartment that contains a complete cycle of sedimentation including sources, transport paths, and sinks. The cell boundaries delineate the geographical area within which the budget of sediment is balanced, providing the framework for the quantitative analysis of coastal erosion and accretion. See Johannessen and MacLennan (2007) for further description of drift cells.
Embayment	An indentation of the shoreline larger in size than a cove but smaller than a gulf.
Equilibrium profile	A "statistical average beach profile' which maintains its form apart from fluctuations including seasonal effects at a particular water level.
Erosion	The wearing away of land by the action of natural forces. On a beach, the carrying away of beach material by wave action, tidal currents, littoral currents,

	or deflation (wind action) (opposite of accretion) (Shipman 2008).
Habitat	The physical, biological, and chemical characteristics of a specific unit of the environment occupied by a specific plant or animal. Habitat is unique to specific organisms and provides all the physical, chemical and biological requirements of that organism within a specific location (Fresh et al. 2004).
Longshore transport	Transport of sediment parallel to the shoreline by waves and currents (Shipman 2008).
Morphology	The shape or form of the land surface or of the seabed and the study of its change over time (Clancy et al. 2009).
Progradation	Occurs on a shoreline that is being built forward or outward into a sea or lake by deposition and accumulation as in a delta.
Protection	Safeguarding ecosystems or ecosystem components from harm caused by human actions.
Resilience	The ability of an entity or system to absorb some amount of change, including extreme events, and recover from or adjust easily to the change or other stress.
Risk	A combination of the magnitude of the potential consequence(s) of climate change impact(s) and the probability or likelihood that the consequences will occur. The magnitude of the potential consequence(s) is the result of the climate change impact(s) and the system's vulnerability to the changes.
Sediment transport	Bedload and suspended transport of sediments and other matter by water and wind along (longshore) and across (cross-shore) the shoreline. The continuity of sediment transport strongly influences the longshore structure of beaches.
Sediment Input	Delivery of sediment from bluff, stream, and marine sources into the nearshore. Depending on landscape setting, inputs can vary in scale from acute, low-frequency episodes (hillslope mass wasting from bluffs) to chronic, high-frequency events (some streams and rivers). Sediment input interacts with sediment transport to control the structure of beaches.
Shoreform	A term often used in Puget Sound to describe a coastal landform. The term is generally used to describe landscape features on the scale of hundreds to thousands of meters, such as coastal bluffs, estuaries, barrier beaches, or river deltas.
Vulnerability	The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.
Vulnerability assessment	Risk-based evaluation of the likely sensitivity and response capacity of natural and human systems to the effects of expected phenomena..

Acronyms and Abbreviations

BAB	barrier beach
CC	climate change
CGS	Coastal Geologic Services
DEM	digital elevation model
DOE	Washington Department of Ecology
FOSJ	Friends of the San Juans
GIS	geographic information systems
HOWL	highest observed water level
IPCC	intergovernmental panel on climate change
LWD	large woody debris
MHHW	mean higher high water
MHW	mean high water
MLLW	mean lower low water
NA	not applicable
NAD	no appreciable drift
NRC	National Research Council
PB	pocket beach
PSNERP	Puget Sound Nearshore Ecosystem Restoration Project
SCAPE	soft cliff and platform erosion
SMP	Shoreline Master Program
SLR	sea level rise
SJC	San Juan County
TAG	technical advisory group
USGS	United States Geological Survey
VLM	vertical land movement
WDFW	Washington Department of Fish and Wildlife
WDNR	Washington Department of Natural Resources (also noted as DNR)
USFWS	United States Fish and Wildlife Service

1.0 Introduction

Coastal areas are among the most heavily populated areas in the world. Shoreline development and population growth are expected to continue into the future. Regional projections of population growth in the Puget Sound region have estimated close to half a million more people will move to the region by 2030. Similar to regional projections, population growth projections for San Juan County predict that several tens of thousands of people will move to the area in the coming decades.

Waterfront property, whether along high bluffs or on low sandy spits, constitutes the highest value real estate in the region. Recent research has reported that millions of Americans live on land below approximately 3 feet (1 meter) above high tide. No similar research has been conducted in the Salish Sea region that aims to clearly outline areas of heightened vulnerability to implications of climate change, despite the population density across thousands of miles of shoreline. Beaches and bluffs in the Salish Sea are not only valued waterfront real estate but also provide critical habitat functions such as beach sediment supply for wildlife and fish including ESA listed salmon populations, spawning areas for species central to the marine food web, and shellfish harvesting. Additional human values associated with nearshore areas include recreation, aesthetic, and spiritual values.

The objective of this study is to attain greater understanding of the areas within San Juan County that are vulnerable to implications of sea level rise with the goal of providing better tools to resource managers and planners in this coastal county. San Juan County has more shoreline than any other county in the contiguous United States of America, and is comprised of almost all major coastal landform types (shoretypes) found in the region (excluding large delta systems). The range of shoretypes found in the county provides an opportunity to explore the variable climate change impacts across different landforms and how different areas may require different management approaches. Management strategies and planning recommendations will be proposed based on results in the forthcoming stages of this project to reduce, avert and mitigate vulnerability associated with sea level rise. Together these tools can form the foundation of a SLR adaptation strategy for San Juan County and increase the effectiveness of existing management approaches. In addition, these results can be used to identify additional long-term restoration and conservation targets throughout the County.

Several technical elements of this project were developed in collaboration with the technical advisory group (TAG) for the project. The project TAG provided much needed guidance and input on critical decisions that formed the foundation for the technical approach that was developed. TAG members are listed in Table 1.

Table 1. Members of the TAG and the entities they represent. Tina Whitman of Friends of the San Juans managed the greater project.

Last Name	First Name	Entity
Shipman	Hugh	Shoreline Geologist, WA State Department of Ecology
Grossman	Eric	Geologist, USGS
Williams	Terry	Tulalip Tribes
Mumford	Tom	Marine Biologist, DNR
Dethier	Megan	University of Washington Friday Harbor Labs
Lowry	Dayv	WDFW
Wenger	Barry	Shoreline Policy and Planning
Walsh	Stan	Skagit River System Co-op
Hardison	Prescott	Tulalip Tribes
Shull	Suzanne	Padilla Bay National Estuarine Research Reserve
Rawson	Kit	Tulalip Tribes
Rosenkotter	Barbara	WRIA 2 Salmon Recovery
Vekved	Dan	San Juan County Public Works Engineer

2.0 Background

Sea level rise will produce a range of impacts from increased erosion of coastal bluffs, the inundation of low lying coastal areas, and the landward translation of beach profiles, among other impacts (Huppert et al. 2009). San Juan County is comprised of a wide variety of shoretypes (also referred to as shoreforms) which will respond to the rise in sea level in different ways. Certain shoretypes are likely to be more vulnerable to erosion, others to inundation, and some will be vulnerable to both. Certain shoretypes, such as plunging bedrock shores, are unlikely to incur considerable impacts outside of a vertical rise in the mean high water mark. Table 2 displays the projected risk by shoretype for the shoretypes that occur in San Juan County (adapted from Shipman 2009).

Table 2. Shoretypes description, response to climate change and potential impacts.

Shoretype	Description	Geomorphic Response	Potential Impact
Rocky	Bedrock, resistant to erosion	Limited geomorphic response	Low vulnerability, shifts in ecological zonation
Feeder bluff	Steep, erodible slopes	Increased erosion, mass wasting, accelerated bluff retreat	Landslides and erosion, modified habitats, increased sediment delivery to beaches
Barrier beach	Low lying spits and barrier beaches, often with back-barrier wetlands, dunes	Erosion, overwash, barrier migration, breaching, shifting tidal inlets	Erosion, flooding, storm damage, altered backshore habitats, possible encroachment on back barrier wetlands
Estuaries & lagoons	Sheltered estuaries and lagoons, salt marshes, often found landward of barrier beaches	Marsh erosion/accretion, changes in tidal prism, altered inlet dynamics	Marsh/habitat loss, channel erosion, shoreline erosion, sedimentation, changes to wetland configuration
Deltas	Broad, low elevation alluvial features at river mouths	Marsh erosion/accretion, sedimentation changes, altered riverine influence, inundation, salinity intrusion	Increased flood vulnerability, damage to dikes and levees, marsh loss, vegetation shifts, decreased drainage
Artificial	Areas of extensive landfill, usually low elevation, engineered and hardened.	Limited geomorphic response.	Storm damage, flooding

2.1 Coastal Erosion

Coastal erosion is anticipated to increase in association with SLR and CC as a result of increased storm frequency and intensity, increased precipitation, increased wave heights, and high water events (storm surges, National Academy of Sciences 2012). Variables such as substrate (geology), slope, fetch, and shore orientation are likely to increase the vulnerability to erosion of certain shoreforms over others (Huppert et al. 2009, Shipman 2009). For example, bluffs comprised of outwash sands are likely to recede more rapidly than those comprised of more consolidated glacial till. Similarly, shores that are orientated to the south directly face the predominant and prevailing wind and wave approach in the region, resulting in greater vulnerability to increased wave heights and storm frequency, which are each additional implications of climate change. Shores with greater fetch are also more vulnerable to storm events, with more exposure to increased wave heights and high water events that exacerbate marine-induced erosion. Increased precipitation, another local implication of climate change (Mote et al. 2008), will result in the added probability of landslides along coastal bluffs, which are known to have a precipitation threshold (Chleborad et al. 2006).

Coastal erosion is a natural process that occurs along coastlines throughout the world. Each coastal landform type exhibits different forms and rates of erosion based on local drivers, such as beach and upland substrate composition and geology. Coastal bluffs and cliffs are typically classified as erosional landform types where erosion is driven primarily by sea level rise, large storms, and wave energy.

Bluffs typically recede through a combination of (bluff) toe erosion and subsequent mass wasting (commonly referred to as landslides). The effect of surface water and groundwater often exacerbates (Gerstel et al. 1997) bluff instability and triggers landslides. The rate at which a bluff retreats is dependent on several interacting variables (Shipman 2004). First order factors include climate and sea level rise. Second order drivers of erosion are more site-specific and are commonly categorized as marine, subaerial or human induced erosion. Each driver of erosion may occur independently or simultaneously upon the bluff throughout time (Johannessen and MacLennan 2007). Marine-induced erosion is the dominant type of erosion along coastal bluffs, which works in combination with bluff geology to shape the overall bluff profile. Bluff recession results in the landward migration of the shoreline which commonly results in structures becoming closer in proximity to the bluff crest and shoreline, often putting them at greater risk than either owners or insurers recognize. The Heinz Center (2000) estimated that over the next 60 years, erosion may claim one out of four houses within 500 feet of the shoreline. To the homeowners living within this narrow strip, the risk posed by erosion is comparable to the risk from flooding along low lying shores.

Coastal bluff retreat tends to be episodic, with much of the long-term bluff failure taking place during a few severe storm events that occur every 15-40 years (Johannessen and MacLennan 2007). The arrival of storm waves concurrent with higher high tides, along with elevated water level due to low atmospheric pressure associated with storm fronts is a common cause of bluff toe erosion. However, it is often major precipitation events which trigger or cause mass wasting events (Tubbs 1974). The combination of these conditions commonly occurs during major El Nino events and over extended periods (months) can result in dramatic coastal erosion throughout the region (Chleborad et al. 2006, Johannessen and MacLennan 2007, Russell and Griggs 2013). The frequency of El Nino events are likely to increase as an additional implication of climate change.

Although long-term bluff retreat rates are low for most San Juan County shores, the episodic nature of bluff retreat can lead to considerable instantaneous recession, followed by little change for several decades. Therefore short-term recession rates should be viewed with caution and are often a source of fear to new owners of coastal bluff properties. Little data is available on the variable retreat rates of bluffs throughout the Salish Sea and San Juan County.

2.2 Coastal Flooding

As sea levels rise, the lowest lying areas will be regularly flooded by high tides. This gradual process of sea level rise exhibits considerable spatial variability due the combined effects of global (eustatic) sea level rise and vertical land movement (isostatic uplift or subsidence), the net effect of which is referred to as relative sea level rise.

Relative sea level rise in Washington is variable due to spatial variability in vertical land movement throughout the state. Western Washington sits on the western edge of the North American continental plate which is converging with the (subducting) Juan de Fuca oceanic plate. This subduction zone, commonly referred to as the Cascadia subduction zone, generates many of the region’s largest earthquakes and far more subtle, locally variable vertical land movement. The northwestern Olympic Peninsula is gradually uplifting, while south Puget Sound gradually subsides. San Juan County is located at the hinge point between these two contrasts resulting in minimal vertical land movement. Therefore local relative sea level rise rates in San Juan County are anticipated to be in line with global (eustatic) sea level rise rates.

Water levels in San Juan County are variable at time scales ranging from daily tides (spring tide range of approximately 12 ft) to decadal cycles (El Nino – Southern Oscillation, Shipman 2009). Elevated mean sea level occurs several times a year, but is consistently much higher during El Nino events (on the order of 0.5 – 1 ft or more). Shipman reports that a one foot rise in water level leads to an increase in the number of high water events at a given elevation by roughly an order of magnitude, turning a 10-year event into an annual event, or a 100-year event into a 10-year event.

Inundation of low lying coastal areas is likely to occur episodically in association with storms that coincide with high water events (storm surges). These will be determined by factors largely unrelated to climate change – for example, the joint probability of large wave-producing wind storms and unusually high astronomic tides (Shipman 2009). Events such as this would result in overtopping of spits and barriers by wave run-up, the increased likelihood of breaches or formation of new tide channels and barriers, the erosion of high marsh by wave action, and the inundation of low lying areas (Shipman 2009). Changes in the seasonal pattern of rainfall or increased peak run-off from snow melt could exacerbate flooding near rivers and streams (Huppert et al. 2009).

An increase in maximum wave heights has been documented along the coast of Washington and Oregon (Ruggerio and Allen 2010). It is unlikely that this trend will result in a change in wave regime within the more protected shores of San Juan County. The west shore of San Juan Island and the south shore of Lopez Island are the only areas in which ocean swell persists and where increased wave height associated with climate change is likely to occur.

2.3 Coastline Response to SLR

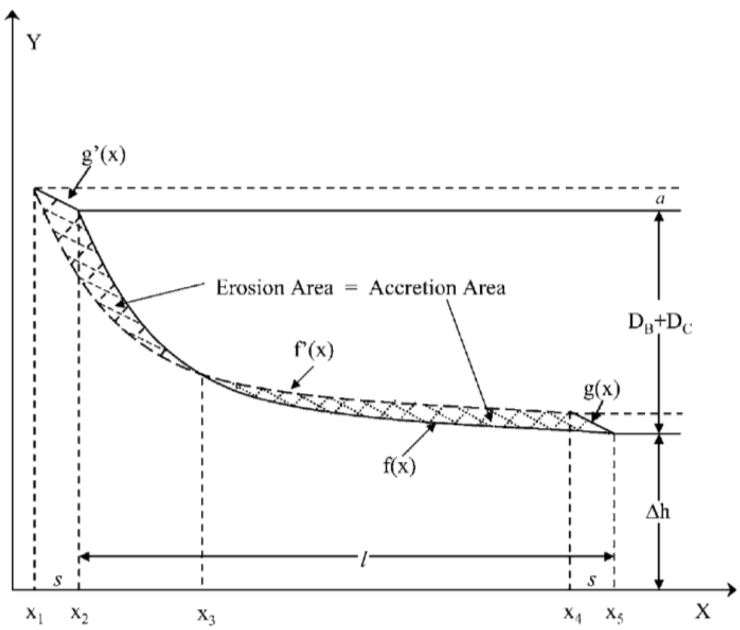
Coastal response to SLR has been a complex and intriguing area of research in the field of coastal geomorphology since the 1960s. More recently, the widespread acceptance of the acceleration of sea level rise and anthropogenic climate change by scientists has led to concern worldwide. Planners and managers in coastal countries are developing a wide range of approaches to address these issues. Leatherman (1990) and Cooper and Pilkey (2007) stressed that understanding shoreline response to sea level rise is essential to inform policy makers, the coastal management community, and stakeholders (Defeo et al. 2009). The following section is comprised of a brief review of different approaches that have been used to understand how shorelines will respond to sea level rise and an analysis of which approach(es) would be appropriate for application or could inform the tools developed as part of this effort.

Several different approaches ranging from models to indices have been developed and applied at a range of scales to assess the vulnerability and response of different shores to sea level rise. Because coastal systems operate on a range of scales in space and time, understanding coastal response to SLR clearly requires an appropriate scale of investigation. The spatial scale of the most commonly applied models range from countywide assessments of variable resolution, to high-resolution site-specific modeling. The level of detail applied in each study is typically a function of data availability and the purpose of the study. Most models incorporate some measure of background (historic) retreat rates, topography (LiDAR), and regional SLR projections. Higher resolution models might also include shoretype (shoreline classification), geology (bluff lithology), wave data, bathymetry, and rate of sea level rise. Although site-specific, high resolution models are not appropriate for use in this study due to the county-wide scale and data limitations, however the fundamental principles and relationships driving the models can shed light on the most relevant variables to incorporate into this study.

The Bruun Rule (Bruun 1962, Schwartz 1967) has long been used to predict the effects of sea level rise on coastal recession. Based on conservation of mass principles, the Bruun model is used to predict the horizontal translation of the shoreline associated with a given rise in sea level. It provides a plausible process through which sea level rise may drive beach erosion. Its application has been the subject of considerable debate as it has several limitations and fundamental assumptions. The Bruun Rule assumes that the observed shoreline recession is controlled primarily by SLR and is not subsumed by other factors such as reduced sediment supply (Cooper and Pilkey 2007, Davidson-Arnott 2005). The Bruun Rule has been adapted by several researchers (Figure 1) to better predict SLR and account for additional variables or limitations in the assumptions (Dean 1990, Davidson-Arnott 2005, Leatherman, Zhang and Douglas 2000, Zhang, Douglas and Leatherman 2004, Stive 2004, Esteves et al. 2009, and Lymbery, Wisse, and Newton 2007) and generally includes the following assumptions:

- a two dimensional, equilibrium profile
- sandy substrate
- height and limit of the onshore boundary (of the beach profile) should not include any significant change or increase in the elevation
- does not account for cross-shore or alongshore sediment transport
- shoreline recession is controlled primarily by SLR and is not subsumed by other factors such as reduced sediment supply (Cooper and Pilkey 2007 and Davidson-Arnott 2005)

An adapted Bruun model (Nicholls 1998) was recently applied to several pocket beaches along the west shore of San Juan Island (Grilliot 2009). The SLR projections used in this application were from the IPCC's Fourth Assessment Report and are now considered to be outdated as they under-estimate future SLR. Results showed only the high sea level rise scenario will result in large transgression and erosion of the backshore. Data limitations, resource constraints, and the model's assumptions preclude appropriate application of the Bruun Rule throughout San Juan County.



$$s(D_B + D_C) = al \text{ or } a = \frac{(D_B + D_C)}{l}s = (\text{active profile slope}) \cdot s\,,$$

Figure 1. Active cross-shore beach profile geometry for derivation of the two-dimensional Bruun Rule of beach erosion and Bruun Rule equation. DB is the elevation of the shore above sea level, DC is the depth of closure, a is the rise of sea level, and l is the distance from the shore to the ‘closure point’ (Schwartz 1967).

Many studies have projected beach response to sea level rise by integrating historic trends derived from air photo analysis with SLR projections. One approach developed by Leatherman (1990) and recently (built upon and) applied to the coast of California (Revell et al. 2011) links shoreline response with historic trends and local sea level change during a specified time period (e.g. through 2100). Historic trends were integrated into Revell et al.’s work from Hapke and Reid (2007) and other rigorous studies of erosion along the coast of California. Change rates were classified by shoreline type, wave exposure and other variables (e.g. bluff lithology). Additionally, a general hypothesis based on the relationship between SLR and shoreline recession is proposed and applied as a multiplier; therefore this model accounts for inherent variability in shoreline response based on differing coastal processes, sedimentary environments and exposure (Leatherman 1990). For some cases shoreline change rates were multiplied by the ratio between the historic and projected SLR rates.

Another commonly applied approach is the Coastal Vulnerability Index (CVI). This index incorporates six variables into the Index score, which rates the relative vulnerability of a reach of shore to SLR. The variables include geomorphic shoretype, coastal slope, relative SLR rate, erosion or accretion rate, mean tidal range, and mean wave height. This model has been applied at a very coarse resolution to much of the coast of the United States by the US Geologic Survey (Hammar-Klose and Thieler 2001). The rates of shore change were based on dated, low resolution data sets. The study area did not include most of the shores of the Salish Sea and appeared to stop west of Dungeness Spit in the Strait of Juan de Fuca, thereby excluding San Juan County.

Sea level rise inundation models are commonly applied using the "bathtub model" or "single-value surface model", whereby digital elevation data (typically LiDAR data) and tidal surfaces are used to create future shorelines representing different SLR projections. This type of mapping has only two variables, the inundation level and the ground elevation. Upland slope is the controlling variable. This method is preferred for immobile substrates such as rocky or armored shorelines, especially along sheltered coasts with very low wave energy (Leatherman 1990). This method has been applied as part of several efforts to understand SLR implications in the Salish Sea including MacLennan et al. (2010), Glick et al. (2007), Peterson (2007), and City of Seattle Public Works (2012), among others.

Recently a geomorphologic model, SCAPE (Soft-Cliff and Platform Erosion), was developed, which provides mesoscale outputs for informed coastal management (Figure 2, Walkden and Hall 2005, Dickson et al. 2007, and Walkden and Hall 2011). This processed-based numerical model incorporates feedback mechanisms (such as colluvium buffering wave attack or decreasing slope resulting in less recession), which enables dynamic equilibrium forms to emerge and brings model stability (Dickson et al. 2007). Similarly, positive feedback also exists such as where the beach profile is excessively steep, positive feedback drives change toward more gentle slopes again (Walkden and Hall 2011). The model is designed for beaches with a low volume of sediment; on the order of 30 m^3/m or less, which is generally the case for San Juan County shores.

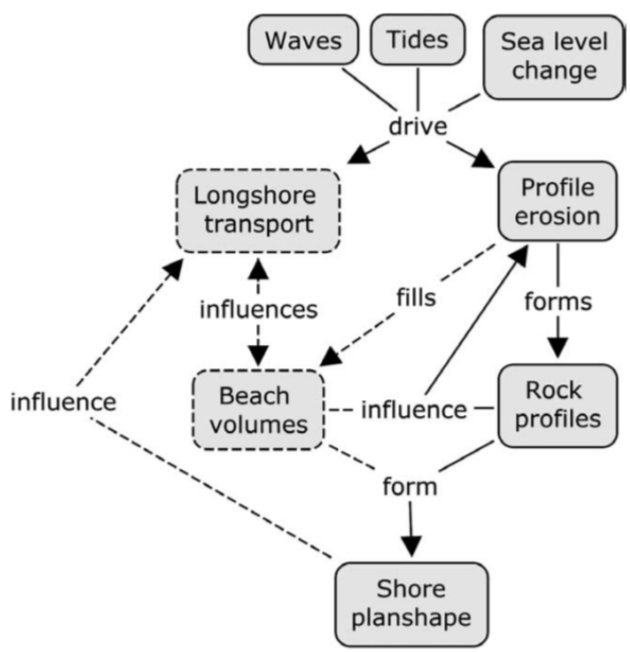


Figure 2. Flow-chart illustrating interactions of quasi-three-dimensional model (all lines) and a two-dimensional model (solid lines only, Walkden and Hall 2011).

Analyses of SCAPE model results have documented a strong relationship between the rates of bluff retreat and SLR. SCAPE model outputs differ from those of the Bruun model, which proposes an equilibrium profile that is migrated upward and landward, maintaining its shape relative to still water.

The SCAPE model outputs result in new equilibrium profiles that become increasingly steep under higher rates of SLR. Increased beach slope can be explained by the zone of wave attack moving landward faster than the beach can equilibrate under drastically accelerated SLR (Ashton et al. 2011, Walkden and Hall 2011). Where a bluff is present lesser areas of the beach are available to be flattened by wave action, resulting in profile steepening (Ashton et al. 2011). These results are not contradictory, but show the assumption of an unchanging equilibrium form under drastically accelerated SLR may be unrealistic for bluffs that are resistant enough to erosion and mass wasting that recession cannot keep pace with rapid SLR (Walkden and Hall 2011). However, the bluffs are locally less resistant to erosion then those of most European and other areas researched. The geology of the majority of the lower bluffs in San Juan County would likely not hinder profile adjustment; however there is little data on this topic.

In contrast to the Bruun model, the SCAPE model predicts that in the absence of SLR the bluff will recede at a lower velocity while the Bruun model suggests that no coastal recession will occur. The SCAPE model assumes that time required for the beach profile to reach equilibrium is associated with the rate of sea level rise. Although that time required for the new equilibrium profile to form may also be dependent on storm frequency and time lags in shore response are likely to occur (Walkden and Hall 2011, Ashton et al. 2011, Brunsden 2001). Comparison of SCAPE predictions with those made using the modified Bruun Rule show that SCAPE predicts a complex suite of responses and lower overall sensitivity of soft-rock shores to SLR (Dickson et al. 2007).

The Scientific Committee on Ocean Research (SCOR) Working Group 89 (1991) recommended a number of guidelines for use when employing coastline response models. SCOR (1991) suggested an application of an order-of-magnitude assessment to the model output; meaning that results of the model are not absolute. As with any predictive model, error associated with each variable incorporated into the model calculations can be compounded or magnified in the final outputs.

2.4 SLR in San Juan County

Data

A number of oceanographic and meteorlogical processes can elevate regional sea level leading to high water events and coastal flooding. El Ninos, low atmospheric pressure, and storm surge caused by strong wave forcing in enclosed areas can all elevate sea levels above the standard tidal range for hours to months. Recorded water level data shows eight extreme high water events that exceeded the 10% annual exceedance probability levels at the Friday Harbor NOAA tide station (station 9449880, benchmark sheet published 2003). Storm and high water events are likely to result in the greatest flooding and inundation hazards to coastal communities, rather than the more gradual long term rise in sea level (Russell and Griggs 2013). Mean higher high water (MHHW) at Friday Harbor is +7.76 ft MLLW. The highest observed water level at Friday Harbor was measured at 3.4 ft above MHHW or + 11.1 ft MLLW. However, this is a still water level and does not account for wave run-up.

A recent guidance document for assessing SLR vulnerability recommended assessing regional sea level trends from the closest tide gauge. The Friday Harbor station, run by NOAA records, indicates a relative rise in sea level of 1.13 mm/yr with a 95% confidence interval of +/- 0.33 mm/yr between 1937 and 2006. This is equivalent to a change of 0.37 ft in 100 years. This is only slightly lower than global SLR trends as tide gauge measures have documented a 1.7 mm/yr (+/- 0.5) rise in sea level. These data contrast more recent SLR measures from satellite altimetry since 1993, which shows an increased rise to 3.1 mm/yr.

SLR Projections

A recent review of regional sea level rise projections was reported by the National Research Council for the coasts of California, Oregon, and Washington (National Academy of Science 2012). Standard projections and ranges were reported to capture the range of model outputs from multiple emissions scenarios across three planning horizons; 2030, 2050, and 2100.

The NRC projections are generally rooted in IPCC projections based on multiple numerical models forced by different emission scenarios, as well as simple climate models. IPCC data was augmented, updated and applied to the Pacific Coast the by the NRC and included the following refinements:

- local steric and wind-driven contributions to SLR were estimated using general circulation models,
- the land ice contribution was adjusted for gravitational and deformational effects and extrapolated,
- sea level finger printing, and
- contributions from VLM data (at the state scale) estimated.

The Technical Advisory Group (TAG) supporting this study recommended early in the research design process that two sea level rise scenarios be applied in this study: a moderate and a high projection. The TAG also recommended that the SLR projections be applied for two planning horizons (2050 and 2100). The NRC scenarios were specifically created for Seattle, Washington, but did not include vertical land movement data specific to Seattle (per Mote et al. 2008) that would preclude appropriate translation for San Juan County (without VLM data the Seattle SLR projections work well for San Juan County). The moderate projection reported represents the IPCC A1B scenario, and were adapted to the Pacific Coast from gridded data by Pardaens et al. (2010). The high projections used the averaged values for the A1FI model outputs. All NRC- regional SLR projections were originally reported in cm relative to year 2000, but have been translated to feet for use in this study. Table 3 shows these values. Unmitigated CO2 emissions may generate greater warming than what has been estimated. Since 2000 the growth rate of actual CO2 emissions has tracked the most pessimistic (i.e. the fastest growth rate for CO2 emissions or the High SLR scenarios) of the IPCC scenarios (Pew Center on Global Climate Change 2009).

Table 3. Moderate and high sea level rise projections by the National Research Council (NAS 2012). Moderate scenario = mean SLR for the Pacific Coast from Pardaens et al. (2010) for the A1B scenario. High scenario = upper extent of the means for B1 and A1FI.

SLR Projections	Year 2050	Year 2100
Moderate (IPCC A1B) Scenario	0.54 ft1	2.03 ft
High (IPCC A1FI) Scenario	1.57 ft	4.69 ft

2.5 Data Availability

Although considerable data is available for San Juan County, data sets relevant to this specific application are somewhat limited. Valuable data sets for this application include: geomorphic shoretypes, shore orientation, previously georeferenced historic air photos (from MacLennan et al. 2010), San Juan County structures and roads (vector data), and recent (2009) LiDAR data. High quality mapping of geomorphic shoreforms that integrates data from several local and regional mapping efforts (Whitman et al. 2012) is a valuable data set for this utility. Georeferenced vertical aerial photography covers a large portion of the county at scales ranging from 1:6,000-1:12,000. Structure and road vector data created by San Juan County Public Works Department can be used to identify threatened infrastructure. LiDAR data is available for much of the county from 2009.

Several data limitations exist that precluded the application of a more detailed transgression model. These data shortages include: wave data, higher resolution geologic mapping, complete LiDAR coverage flown at a low tidal height, and bathymetric data. There is a general absence of wave data for much of the Puget Sound/Salish Sea region. Wave data could help develop a model that would account for wave run-up, although some might argue that run-up is not a major driver of beach morphology in the fetch-limited environment of San Juan County. A fetch model was created for this project, and the outputs were linked with shoreform mapping. Geology mapping for San Juan County is coarse (1:100,000) and only represents surface geology. Surface geology is typically not consistent with the geology of the base of the bluff or overall bluff stratigraphy, both of which are relevant to bluff recession rates. Higher resolution geology data could also aid in the identification of pocket beaches (and other shoretypes) that may be naturally limited in their ability to transgress due to bedrock exposures. The current LiDAR data set does not include the northernmost portion of the County, and omits Stuart, Johns, and Waldron Islands. In addition, it was flown at a tidal height that precluded slope measures across approximately half of the county shores. Bathymetric mapping (multibeam sonar) in combination with wave data, would be an optimal data set for helping to fully understand the variable wave environments of San Juan County, as well as understanding how beaches will translate.

3.0 Methods

The SLR model for SJC entailed six major steps each of which entailed detailed analysis, and applied concepts and calculations from best available science documents, most of which was applied in GIS. The six steps listed below and shown in Figure 3 are described in detail in the following section of the report:

1. Digitize shoreline features from current and historic georeferenced air photos from a stratified sample of geomorphic shoretypes across the county.
2. Calculate shoreline change rates for each shoreform and statistically analyze the results.
3. Apply a multiplier for increased erosion based on shoretype and stratification variables (as necessary).
4. Project the future position of the shore by integrating the vertical change in sea level (based on the most current projections for the region) with the extrapolating background (historic) erosion rates to each shoretype.
5. Create erosion and inundation vulnerability polygons for both a moderate and a high SLR scenario across two planning horizons (2050 and 2100).
6. Apply spatial queries to identify potentially at risk infrastructure (structures and roads) within each of the hazard polygons and highlight areas from which specific management strategies should be applied.

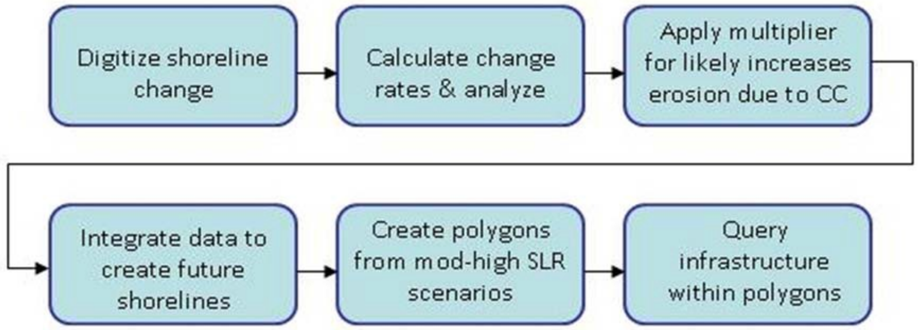


Figure 3. Sequence of the major tasks of the sea level rise model for San Juan County.

3.1 Shore Change Analysis

The first step in conducting the shore change analysis element of this study was to identify representative shoreforms of each geomorphic shoretype. The stratification structure of the sample of shoreforms required that half of the shoreforms of each type were exposed to less than 5 miles of fetch and half were exposed to 5 miles or more of fetch. Approximately half of each exposure category was oriented to the southern quadrants and half to the northern quadrants. Erosion rates were calculated from at least 12 of each shoretype, which represents approximately 2% of each shoreform type (Table 4). Shoreforms selected for shore change analysis were required to be primarily unarmored, and free of other potential sources of interference to change rates, such as bedrock islets directly offshore. Historic, vertical aerial photography of high resolution and with visibility of the upper beach and bluff with a low georeferencing error (root mean square (RMS) <5) were additional requirements. The shoreforms also needed to be located within drift cells that had not incurred a considerable loss of sediment supply. The spatial distribution of the sampled shoreforms is shown in Figure 4.

A personal geodatabase was created within which shoreline features from current and historic conditions were digitized for later analysis. The specific shoreline feature that was digitized, the year that feature represented and the scale of digitizing was documented in the attribute table. Features were heads-up digitized at a 1:500-1:700 scale across the length of each of the sampled shoreforms. The specific feature (or shoreline proxy) that was digitized was different based on shoreform type and what feature could be mapped across the length of the shoreform with the highest level of confidence. If multiple features were visible, then the more landward proxy was selected (e.g. bluff crest versus vegetation line), as the more landward the higher the accuracy (Ruggerio et al. 2003).The log line or vegetation line was typically the digitized feature for barrier beaches, while the toe of the bluff or the bluff crest was the feature digitized all other shoreforms. The shoreline proxy was consistent among shoreforms across years. Different historic aerial photographs were used for different areas, based on availability and the ability to clearly view the subject feature with a high level of confidence. Photos ranged in scale from 1:6000 to 1:12,000 and from 1960-1978. Features were digitized from the most recent vertical aerial photographs of high resolution (2008) or the LiDAR imagery (2009).

All of the original feature digitizing was completed by the same staff member to assure consistency in feature interpretation, and preclude unnecessary bias associated with multiple analysts. All digitizing was QA/QC'd by the project manager to ensure consistency. During the QA/QC process, areas in which bedrock exposures or shoreline armor could interfere with erosion rates were clipped from the geodatabase to prevent erroneous results.

Table 4. Sampling design displaying shoreforms, stratification of shoreforms by exposure and orientation, and hypothetical "likely acceleration rate".

Shoreforms	Exposure	Orientation
13 Feeder Bluffs **NOT occurring in drift cells with highly impacted sediment supply**	5 with <5 mi fetch	3 Southern quadrant
		2 Northern quadrant
	8 with >5 mi fetch	4 Southern quadrant
		4 Northern quadrant
12 Transport Zones	5 with <5 mi fetch	3 Southern quadrant
		2 Northern quadrant
	7 with >5 mi fetch	3 Southern quadrant
		4 Northern quadrant
12 Barrier Beaches	6 with <5 mi fetch	4 Southern quadrant
		2 Northern quadrant
	8 with >5 mi fetch	4 Southern quadrant
		4 Northern quadrant
21 Pocket Beaches	11 with <5 mi fetch	6 Southern quadrant
		5 Northern quadrant
	10 with >5 mi fetch	6 Southern quadrant
		4 Northern quadrant

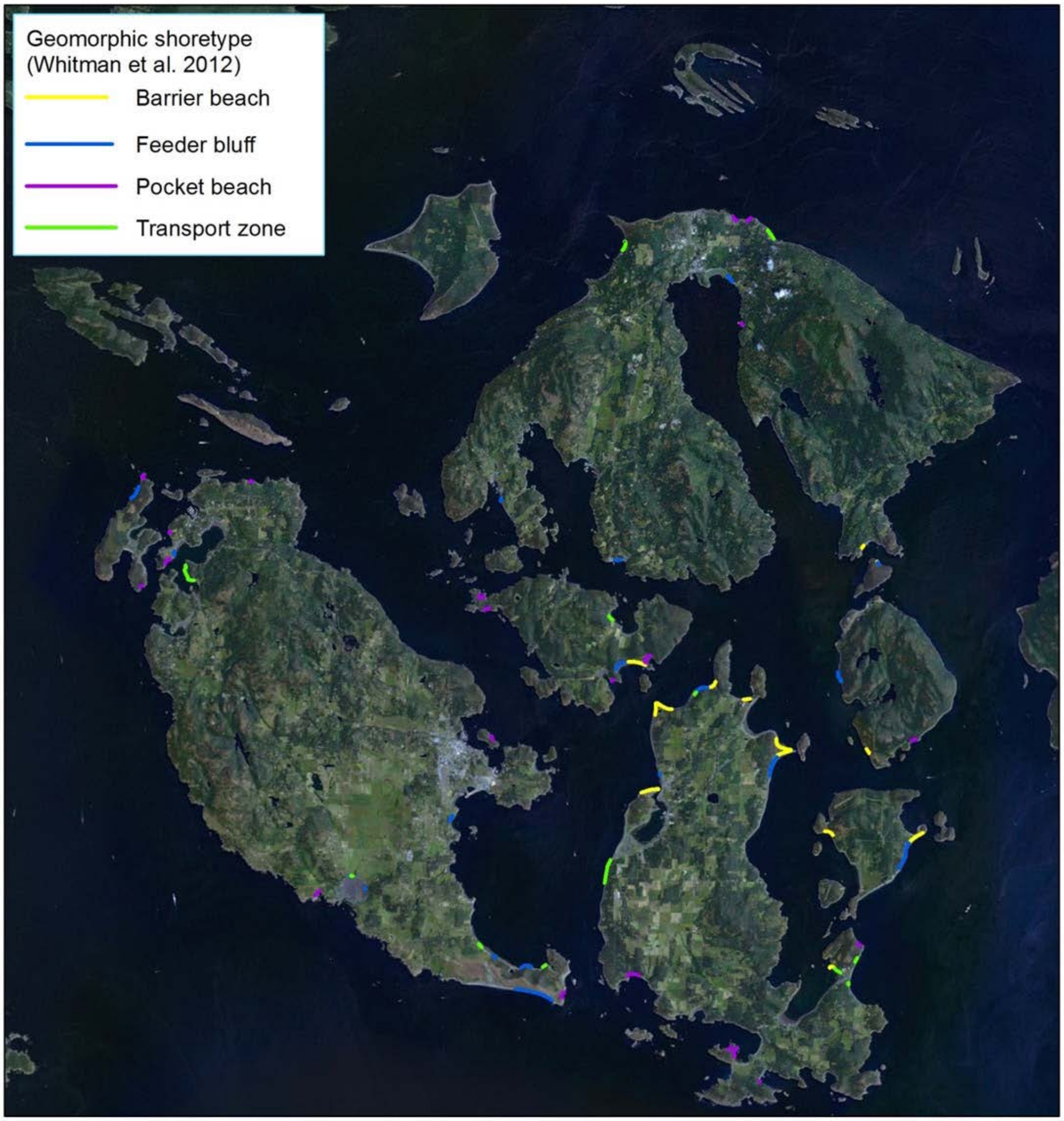


Figure 4. Shoreforms sampled for shore change analysis (from Whitman et al. 2012).

3.2 DSAS and Statistical Analysis

The Digital Shoreline Analysis System (DSAS) is a free software application that was developed by the Environmental Systems Research Institute (ESRI) and USGS. DSAS computes rate of change statistics for a time series of shoreline vector data. DSAS automates the shore change process allowing for greater efficiency and reduces the opportunity for error. Prior to running the software, baselines were created from which transects would be drawn perpendicular to the shoreline. Baselines were created by exporting sample shoreform reaches of the WDNR Shorezone shoreline (WDNR 2001) and buffering those reaches landward of the feature digitizing. Cumulatively over 300 transects were placed at 82-foot (25-meter) intervals across the sampled shoreforms. DSAS then calculated the distance between each shoreline feature and calculated an end point rate (EPR), which equates to the measured distance between the two features divided by the number of years between those features (e.g. 1960 and 2009). EPR measures were then analyzed within each individual shoreform and across each shoretype.

3.3 Estimating the Future Position of the Shoreline

This element of the vulnerability assessment is complex and although considerable uncertainties exist regarding *when* shorelines will reach the predicted locations, they will inevitably retreat to the vicinity of the predicted locations. The estimated future position of the shoreline for each planning horizon is the cumulative product of the background rate of erosion, the predicted degree of acceleration resulting from the increasing rate of sea level rise, combined with the vertical change in sea level across the number of years in that planning horizon.

Modeling Inundation

The first step in applying this approach was to transpose the shoreform mapping from the WDNR best available science high water shoreline (2001 WDNR) to a shoreline that is linked with a vertical datum. This was conducted by first creating a MHHW digital elevation model (DEM) using VDatum (v 3.1 Spargo et al. 2006) with grid-spacing of 100 ft. Each portion of the grid represented the difference between NAVD88 and MHHW at that location. The grid size (100 ft) was selected to both maximize processing time while also minimizing the different between adjacent grids. Very little difference (< 0.01 ft) was seen between grids at this resolution. Since VDatum only performs conversions for in-water locations, portions of the grid on land were not calculated. An interpolation of nearby in-water values was used to "extend" the conversion grid over the land. The conversion values were then applied to the LiDAR data to produce a new digital elevation model (DEM) in MHHW datum.

The MHHW shoreline was then linked to shoreform data by applying a mapping technique referred to as a euclidian allocation to accurately transpose the shoretype boundaries so as to pair shoreform data with other variables such as fetch.

The inundation areas for each SLR horizon where created from the MHHW DEM. The lower limits of the inundation polygons were the highest observed water level (HOWL) for 2009, which was +3.4 ft above MHHW (for Friday Harbor, http://tidesandcurrents.noaa.gov/data_menu.shtml?stn=9449880%20Friday%20Harbor,%20WA&type= Bench%20Mark%20Sheets). A contour line was generated using GIS for that elevation and additional contours to represent the upper boundary of the inundation polygons from both the moderate and high scenarios for 2050 and 2100. The lines were then converted to polygons that represent all regions between successive inundation steps (2050 moderate, 2050 high, 2100 moderate, and 2100 high). The contours were retained for further use in determining erosion hazard zones.

Modeling Bluff Recession

Accelerated erosion rates were calculated using an equation well-cited in peer reviewed literature and was also described in the background section of this report. Recent research conducted by Ashton et al. (2011) and Walkden and Hall (2011) documented a strong relationship between SLR rate and bluff recession rate. This equation was used to predict future erosion based on future rates of SLR. SCAPE simulations run across a wide range of model parameter space including variations in wave height, period, tidal range and rock strength revealed that a simple expression could be used to relate the rate of SLR and the equilibrium recession rate (Ashton et al. 2012, Walkden and Dickson 2008).

$$\varepsilon_2 = \varepsilon_1 \, ? \, \frac{\square\square}{\square\square} \qquad \text{Equation 1}$$

Where (ε_2) is the future erosion rate and (ε_1) is the current erosion rate, and the prior and future rates of sea level rise are S_1 and S_2, respectively. This expression was found to hold for profiles that included a beach whose volume was below a threshold level appropriate for San Juan County (determined to be <30 m^3/m for the base model parameter).

To produce accurate model outputs this model required sea level rise rates at a resolution that goes beyond the reported projections from the NRC (NAS 2012). Therefore a quadratic spine that adheres to the combined curve of the current rates of SLR reported at the NOAA Friday Harbor tide station and the NRC SLR projections for 2030, 2050 and 2100 (Figure 5), were integrated (for both moderate and high scenarios) to produce SLR rates at ten year time intervals. The integration was created using the software on the following website: http://science.kennesaw.edu/~plaval/applets/QRegression.html .

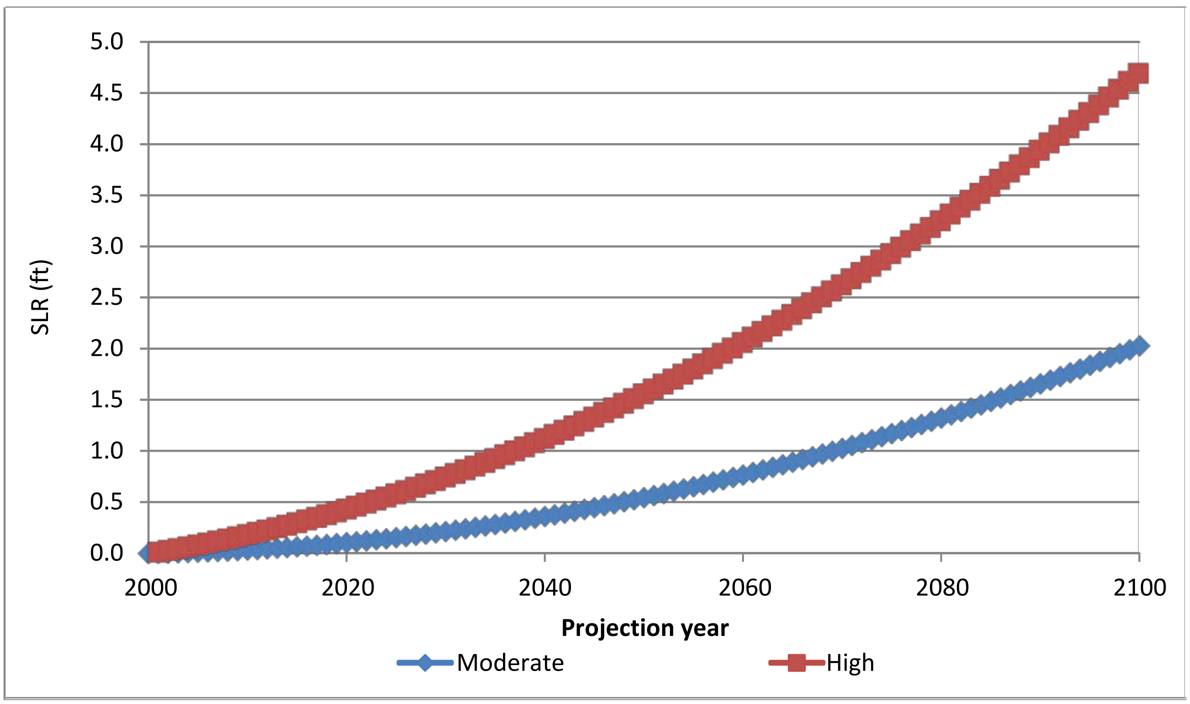


Figure 5. Quadratic spline integration of SLR rates at 10-year intervals for each scenario using data from Friday Harbor NOAA tide station and NRC SLR projections (NAS 2012).

As previously stated, this method of predicting shoreline change is only applicable for eroding shores and therefore is not appropriate for barrier beaches, which are characteristically depositional shores. Little research has been conducted on how barrier beaches in the Salish Sea will respond to SLR. Considerable research has been applied on this concept elsewhere, however predominantly along sandy beaches with incomparably greater wave exposure in addition to aeolian processes. Accelerated erosion rates were not estimated for barrier beaches, which are much more likely to be threatened by inundation and are in need of further research to elucidate their response to SLR.

For shoretypes with considerable upland relief (such as transport zones, feeder bluffs and some pocket beaches) inundation polygons appear as narrow bands that simply move vertically up the toe of the bluff, and clearly do not depict the landward recession of the bluff. To fully display the likely transgression of the beach profile, the position of the bluff crest needed to be delineated from which projections of bluff recession could be applied.

The bluff crest was mapped using GIS and LiDAR imagery at the break line that marked the greatest change in relief (from high to low slope) closest to the shoreline. In certain areas there were multiple slope changes and/or dramatic changes in relief. Care was taken to consistently interpret the bluff crest that would be the first to incur wave induced erosion in these areas. Where uncertainty occurred, the original LiDAR data and high resolution vertical and oblique shoreline imagery were referenced. All digitizing was conducted at a fine scale on the order of 1:500 with a maximum of 1:700. Vertices were placed every 10-50 ft. Each shoreform was attributed with the shoreform ID, so it could later be linked with shoreform data including shoretype and fetch for forthcoming elements of model application. Figure 6 displays a screen capture of the digitizing process in which the waterward shoreform mapping was used to direct the alongshore boundaries of the digitizing area, as well as the slope data derived from LiDAR.

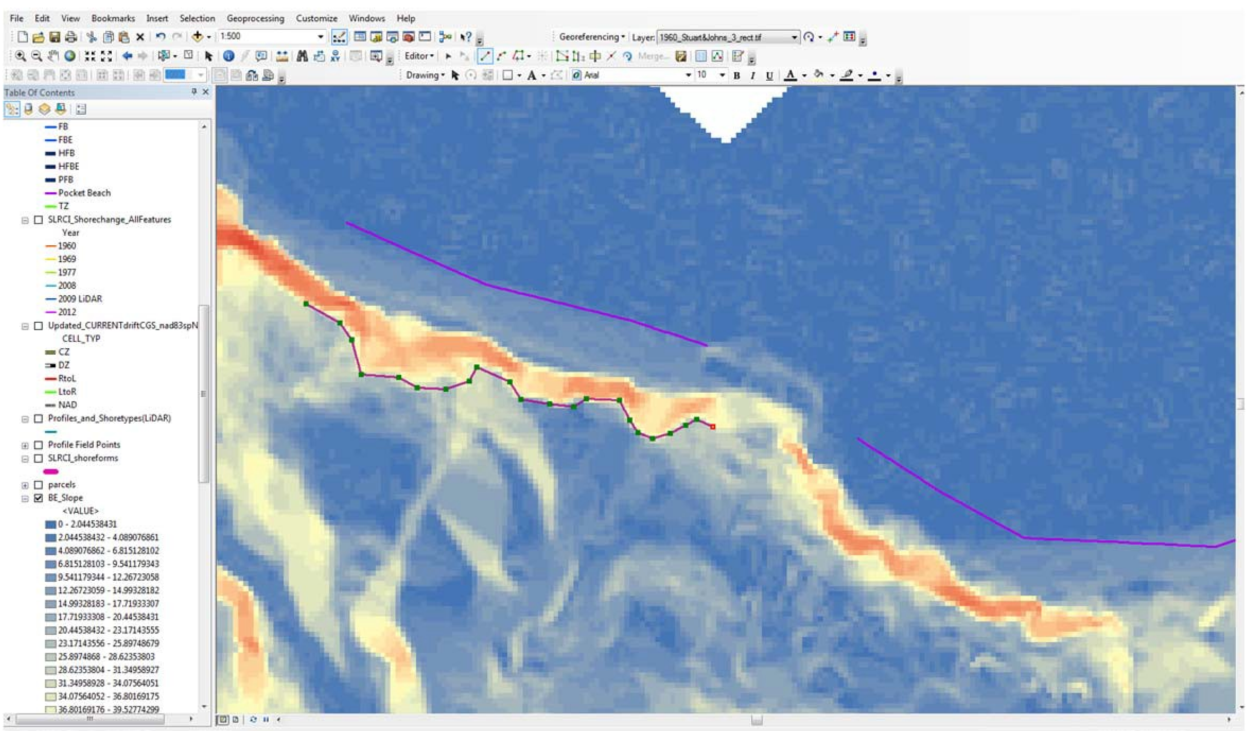


Figure 6. Screen capture of bluff crest digitizing process.

After bluff crests were digitized for all of the shoreforms (excluding bedrock, embayments, and barrier beaches), the bluff recession vulnerability polygons were generated using data described in each of the previously described steps (including: inundation contours, the background erosion rates, erosion acceleration rates based on equation 1, SLR projections, and planning horizons).

First, the bluff crest and inundation contours were separated into resistant and non-resistant surface geology based on available state-wide geology maps (WDNR 2010). Bedrock geology (in contrast to unconsolidated, Quaternary, sedimentary geologic units) was assumed to be completely resistant to erosion, and therefore no future erosion was applied to those areas. Erosion vulnerability areas were then generated as buffers that extended landward of the bluff crest and inundation areas based on the respective projections and planning horizons. Again, surface geology was used to separate out those areas resistant to erosion, which were then excluded from the hazard zones. Shoreline armor was not accounted for as it was assumed that shore protection would not entirely preclude profile adjustment, as wave-induced erosion is not typically the only driver of bluff erosion (Johannessen and MacLennan 2007), and most shore armor is not engineered to sustain the sea level rise.

4.0 Results

4.1 Shore Change Analysis

Results from the shore change analysis portion of this study offer an initial attempt at documenting the variability in erosion rates across shoretypes and the relative influence of specific variables on coastal erosion in the Salish Sea. These data have the potential to function as a baseline data set for similar studies of this nature in the region. Exploring the relative erosion rates across geomorphic shoretypes has not previously been conducted in the Salish Sea. This stratified sampling approach provides the opportunity to explore the relative influence of different variables on erosion rates. There is much more to explore and understand in these data and results, however the analysis presented in this report is limited to conclusions that will influence the forthcoming steps of the project.

Shore change analysis results exhibited considerable variability within and across geomorphic shoreforms (Table 5, Figure 7). Barrier beaches had significantly higher positive change rates (F=12.03, p=0.00), which is indicative of progradation or shoreline accretion. Overall the change rates at barrier beaches were considerably more variable than other shoreforms (Table 5, Figures 7 and 8). A number of barrier beaches incurred erosion over the period of study, while most exhibited accretion. The barrier beaches in which erosion occurred were primarily south-facing and often exposed to more than 5 miles of fetch (Figure 8). Pairwise comparisons showed that shoreline change rates along barrier beaches were significantly different from all other geomorphic shoretypes (Tukey HSD, FB: p=0.00, PB: p=0.01, TZ: p=0.00).

The lowest change values (indicative of shoreline retreat) across all geomorphic shoretypes occurred within feeder bluffs. Mean erosion rates across feeder bluffs ranged from -0.26 to -0.93 ft/yr and averaged -0.47 ft/yr (Table 5). Erosion was measured exclusively within feeder bluffs. Shoreline orientation did not appear to have a significant effect on the degree of erosion that was measured at a site.

Table 5. Descriptive statistics for change rates (ft/yr) across geomorphic shoreforms (1960-2009). Negative numbers are the lowest rates, if less than zero represents erosion (e.g. bluff crest recession).

Shoretype	Minimum	Maximum	Average	Std. Dev.
Barrier beaches	-0.34	0.61	0.07	0.32
Feeder bluffs	-0.93	-0.26	-0.47	0.19
Pocket beaches	-0.37	0.09	-0.17	0.11
Transport zones	-0.52	-0.07	-0.25	0.15

Transport zones and pocket beaches on average exhibited considerably less shoreline recession. A few pocket beaches exhibited minor accretion, while minor to moderate recession was documented along all transport zones. Shoreline change rates across all shoretypes were (significantly) inversely correlated with exposure or maximum measured fetch. In other words, sites with greater exposure or higher maximum measured fetch typically had higher erosion rates (measured as values less than zero, Regression: R^2=0.14, adjusted R^2=0.118, ANOVA F=4.68, p=0.013). On average, every mile increase in exposure is associated with a decrease the change rate (erosion) of -0.014 ft/yr (south orientation only). Based on the significance of the relationship between fetch and mean change rate, the authors concluded that fetch categories are a relevant variable to carry forward in to the later steps of this model.

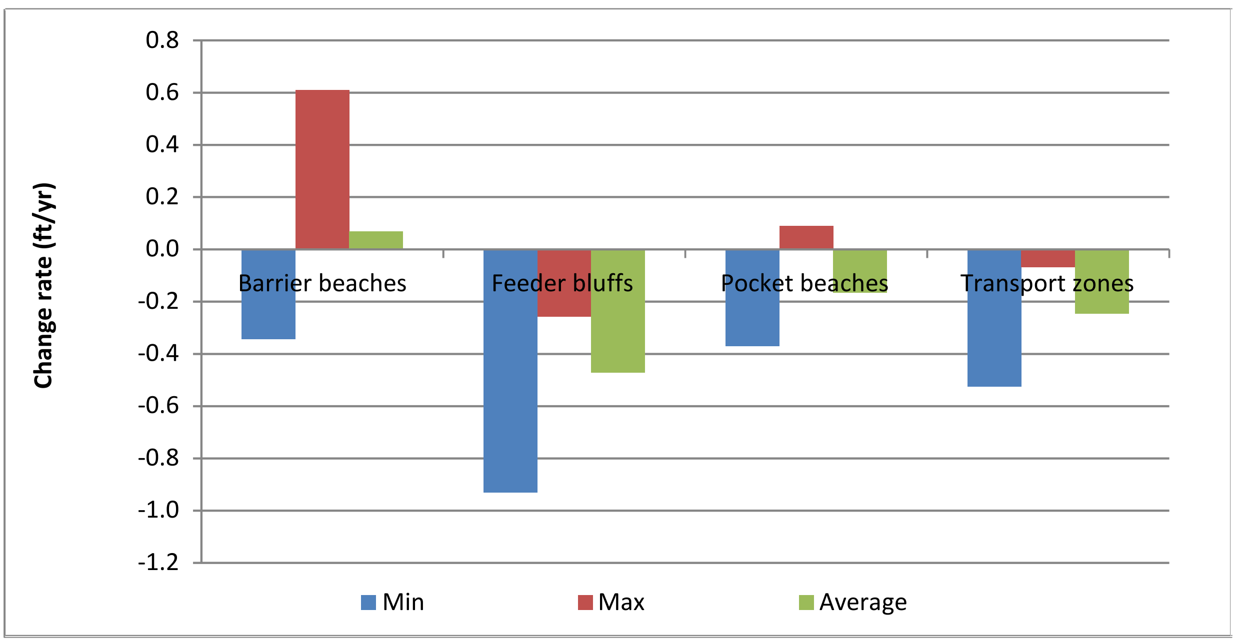


Figure 7. Minimum, maximum and average change rates across shoretypes. Minimum values represent the lowest change rates, which if less than zero represent erosion.

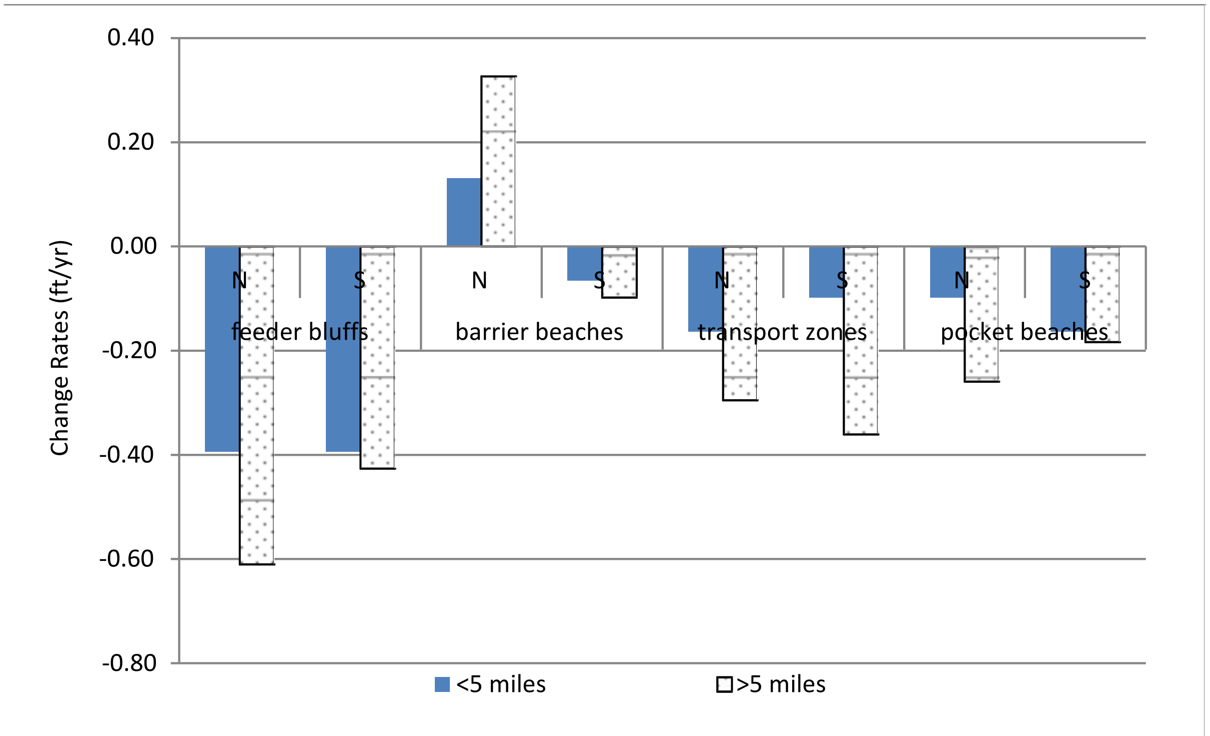


Figure 8. Average change rates within shoretypes of variable fetch and shore orientation. Values less than zero represent erosion or recession.

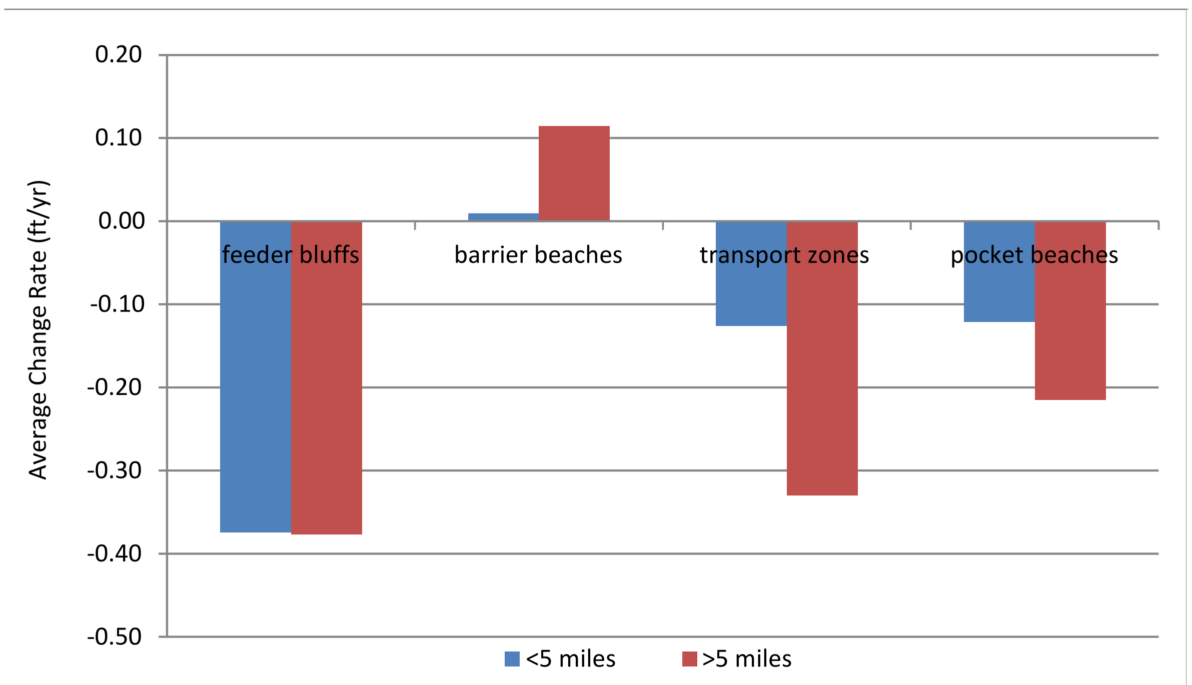


Figure 9. Average change rates of different shoretypes of different fetch categories.

The final erosion rates used for projecting future erosion are categorized by exposure (maximum measured fetch) and displayed in Table 6.

Table 6. Average change rates (ft/yr) of geomorphic shoretypes sorted by exposure category.

Exposure	Feeder bluffs	Barrier beaches	Transport zones	Pocket beaches
<5 miles	-0.394	0.009	-0.126	-0.121
>5 miles	-0.623	0.114	-0.330	-0.215

4.2 Transgression Model Outputs

The erosion rates resulting from shore change analysis (Table 6) and sea level rise rates were used to calculate accelerated erosion rates and measured bluff recession distances for each sea level rise scenario and planning horizon. Sea level rise rates were calculated at 10-year intervals by applying an integration using sea level rise data from the Friday Harbor NOAA tide station and the NRC sea level rise projections. Rates were brought into Equation 1 with current change rates from the shore change analysis to calculate the estimated erosion for each of the different fetch categories, planning horizons, and SLR scenarios. Table 7 displays the decadal iterations of measured erosion of feeder bluffs with both short and long fetch for both the moderate and high SLR scenarios. Table 8 displays the final estimated erosion for each shoreform, fetch category, scenario and planning horizon.

Table 7. Decadal iterations of Equation 1 and resulting estimated feeder bluff erosion (ft) based on increasing SLR rates of various fetch categories and SLR scenarios (NAS 2012).

Estimated Feeder Bluff Erosion (m=mod, h=high, s=short fetch, l=long fetch)				
Year	**Moderate scenario Short-fetch (ft)**	**Moderate scenario Long fetch (ft)**	**High scenario Short fetch (ft)**	**High scenario Long fetch (ft)**
2009	0	0	0	0
2010	-0.4	-0.54	-0.84	-1.14
2020	-5.26	-7.1	-9.89	-13.36
2030	-11.24	-15.18	-20.02	-27.04
2040	-18.17	-24.55	-31.12	-42.04
2050	**-25.93**	**-35.03**	**-43.1**	**-58.23**
2060	-34.46	-46.54	-55.92	-75.54
2070	-43.67	-58.99	-69.52	-93.91
2080	-53.53	-72.31	-83.85	-113.27
2090	-63.99	-86.44	-98.89	-133.58
2100	**-75.03**	**-101.35**	**-114.59**	**-154.79**

Table 8. Final estimated erosion of shoreforms with short and long fetch for different SLR scenarios (moderate, high) and planning horizons (2050, 2100).

Estimated change (ft) for shoreforms with less than 5 miles exposure					
Average change (ft/yr)	Shoretype	2050 Mod	2050 High	2100 Mod	2100 High
-0.39	Feeder bluffs	-25.9	-43.1	-75.0	-114.6
-0.12	Transport zones	-8.6	-14.4	-25.0	-38.2
-0.12	Pocket beaches	-8.4	-14.0	-24.4	-37.2
Estimated change (ft) for shoreforms with greater than 5 miles exposure					
Average change (ft/yr)	Shoretype	2050 Mod	2050 High	2100 Mod	2100 High
-0.62	Feeder bluffs	-35.0	-58.2	-101.4	-154.8
-0.33	Transport zones	-23.0	-38.2	-66.5	-101.5
-0.22	Pocket beaches	-15.0	-25.0	-43.4	-66.3

The final estimated erosion rates for feeder bluffs with less than 5 miles of fetch range from approximately 26 ft, based on a moderate SLR scenario in 2050, to approximately 115 ft in 2100 for the high SLR scenario. Feeder bluffs with greater than 5 miles of fetch are anticipated to incur greater bluff recession on the order of 10 ft by 2050 or 40 ft by 2100 (Table 8). Considerably less erosion is likely to occur along transport zones and pocket beaches, although transport zones with more than five miles of fetch will incur up to 100 ft of bluff recession in the high scenario by 2100. According to these results, pocket beaches with low exposure were by far the least vulnerable to bluff recession.

Erosion vulnerability polygons were generated using the buffer distances reported in Table 8. Buffers extended landward of the bluff crest were created for each shoretype within different fetch categories for each SLR scenario and planning horizon. Buffers were clipped or truncated where they intercepted bedrock geology, which presents a natural constraint to shoreline translation. In areas where the crest of the bank or shoreline was inundated the buffer was applied to the new inundated shoreline. Buffers were converted to polygons from which infrastructure could be selected.

Mapping results of erosion and inundation areas are best viewed at close scale due to the resolution of the data set. Figures 10 to 13 display snap shots of results to display the variety of ways the data can be displayed to enhance understanding of the relative vulnerability to SLR implications in San Juan County. Results can be displayed by scenario or planning horizon or specifically by the source of vulnerability.

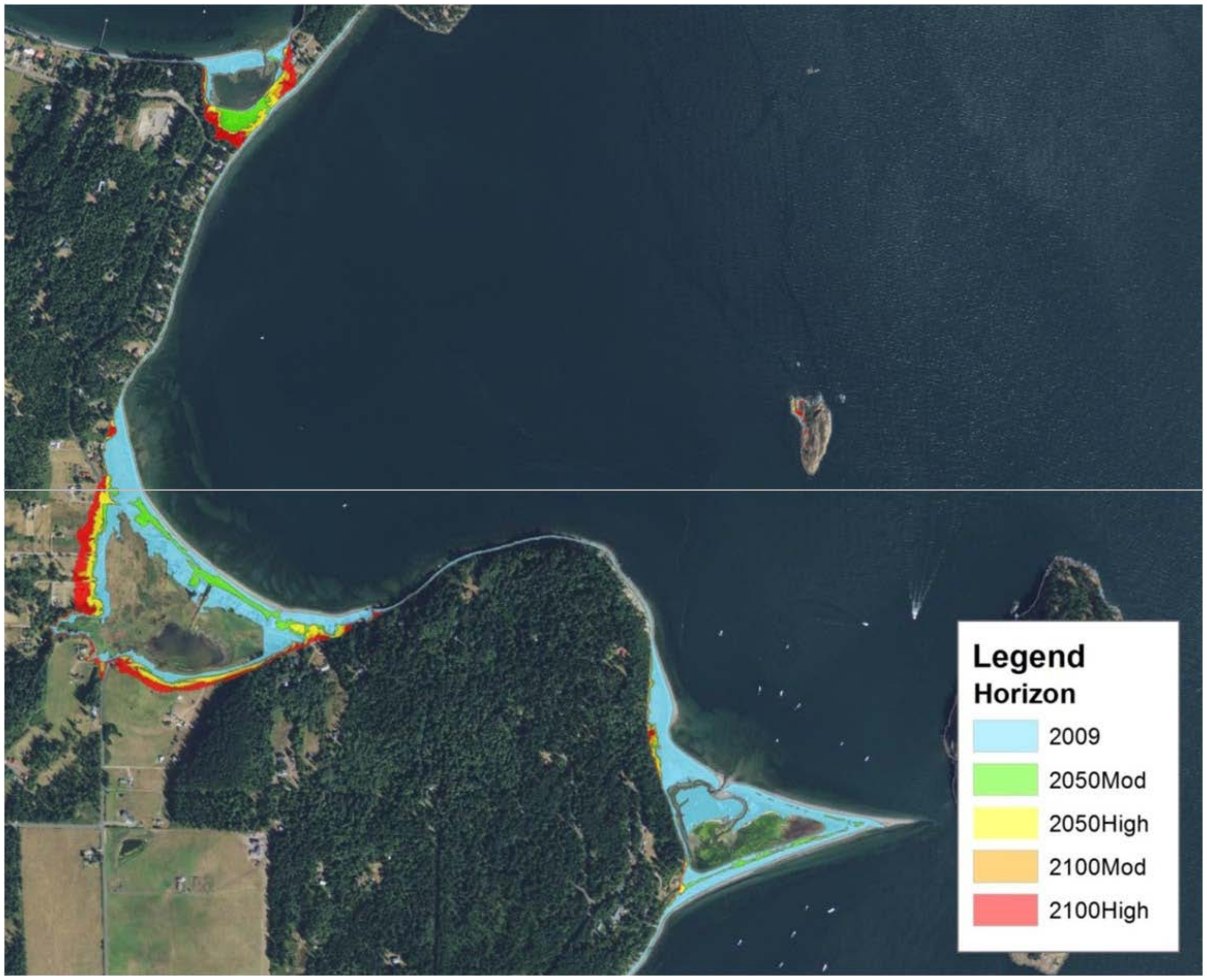
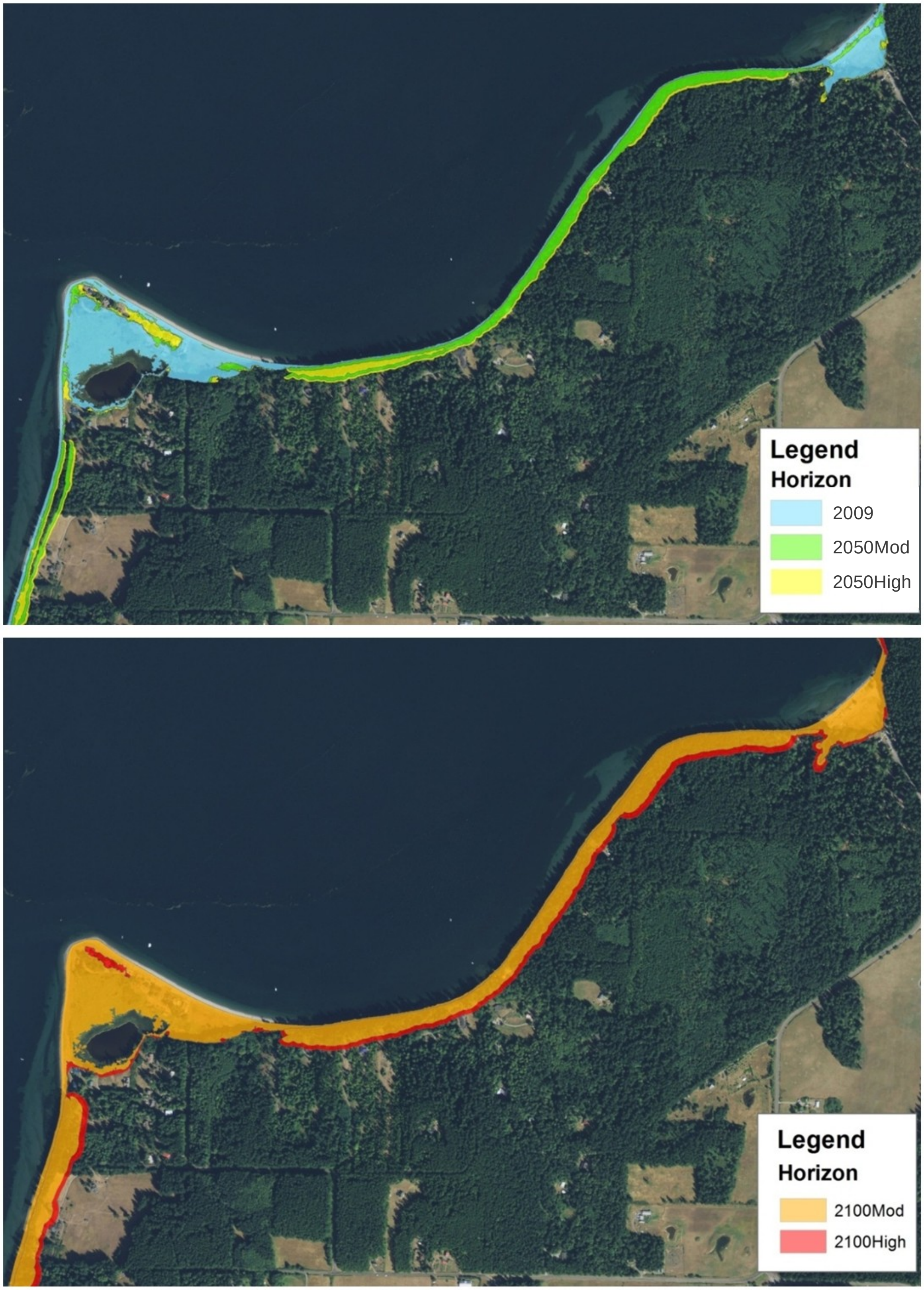


Figure 10. Inundation mapping of northeast Lopez Island.



Figures 11& 12. Areas vulnerable to erosion and inundation on northwest Lopez Island in 2050,2100.

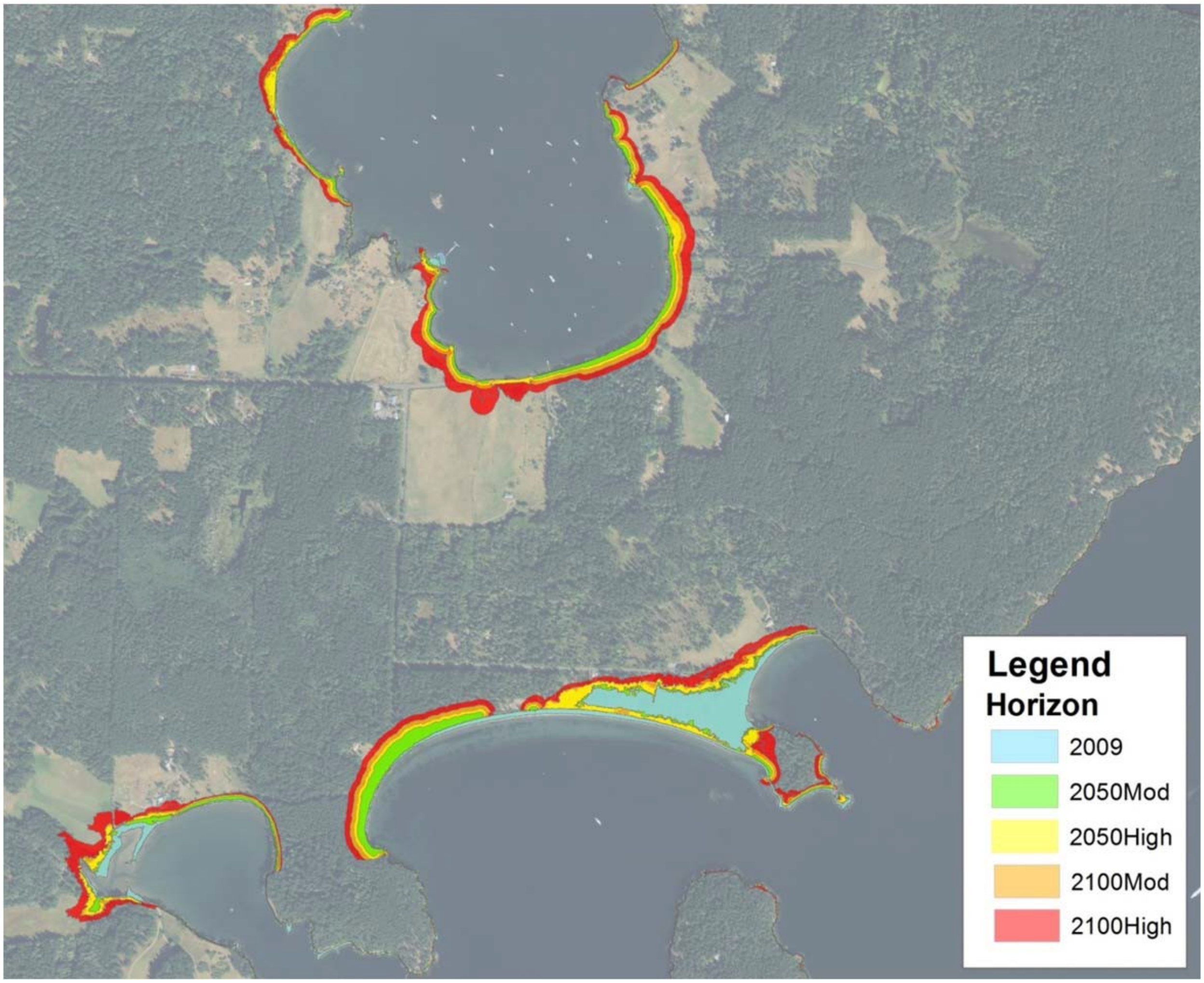


Figure 13. Areas vulnerable to erosion and inundation on eastern Shaw Island across all scenarios and planning horizons.

4.3 Vulnerable Infrastructure

Roads and structures that were encompassed within inundation and erosion polygons were selected to identify areas of heightened vulnerability in San Juan County. In addition, roads and structures that are currently located below the highest observed water levels (MHHW plus 3.4 ft) were identified. In total 2.3 miles of San Juan County road are below the highest observed water levels and are likely inundated during storm events that coincide with high water. More road length appears to be threatened by inundation than erosion. More than eleven miles of road are likely to be threatened by erosion or inundation by 2050, according to the high SLR scenario. By 2100, based on the high SLR scenario, almost 20 miles of road will be vulnerable to erosion on inundation.

Vulnerable roads are distributed throughout the county however several specific pockets with more vulnerable road length exist. Several short stretches of vulnerable roads occur on San Juan Island around the middle of Griffin Bay, near Davidson Head and Mosquito Pass. False Bay Road is vulnerable in several locations as well as Cattle Point Road. The northeast and western shores of Shaw Island have several roads that are vulnerable to sea level rise including: Indian Cove, Blind Bay, Neck Point, and Squaw Bay. Similarly several roads on Orcas Island are vulnerable; however they are widely distributed throughout the island excluding two clusters of vulnerable roads near West Sound, Crescent Bay, and along the north shore of the Island north of East Sound. Lopez has the greatest length roads vulnerable to SLR. Clusters of vulnerable road are found surrounding Fisherman Bay, and the shores between Mackaye, Barlow, and Agate Bays (Figure 14).

Table 9. Length (in miles) of road vulnerable to inundation or erosion associated with SLR scenarios (moderate, high) and planning horizons (2050, 2100) in San Juan County. HOWL = highest observed water level.

Threat type	HOWL	2050 Mod	2050 High	2100 Mod	2100 High
Erosion	NA	2.6	3.9	5.2	6.1
Inundation	2.3	3.8	7.4	8.2	13.4
Total	**2.3**	**6.4**	**11.4**	**13.4**	**19.5**

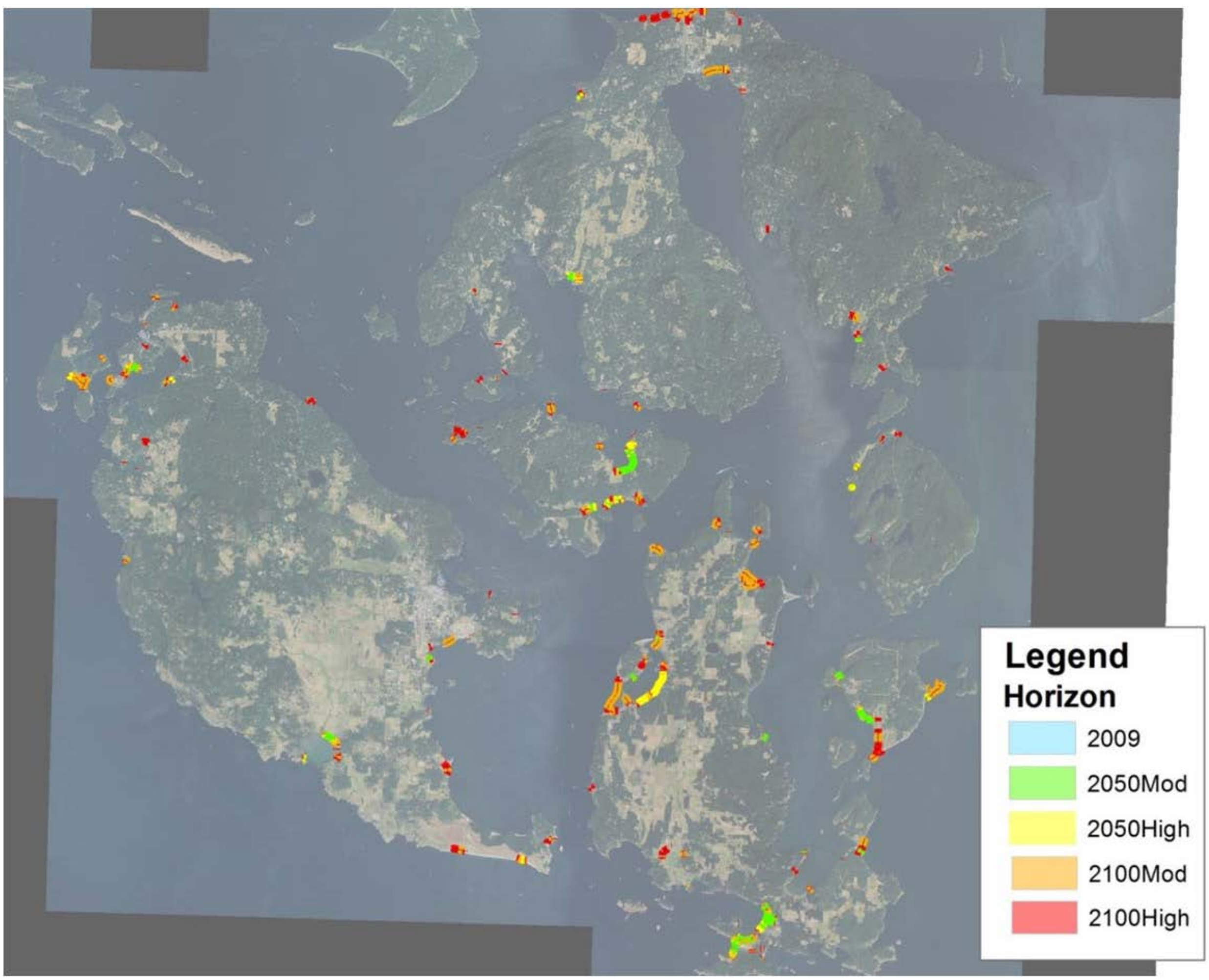


Figure 14. Roads vulnerable to erosion or inundation associated with SLR in San Juan County.

Similar to roads, structures that were encompassed within the erosion and inundation polygons associated with different SLR scenarios and planning horizons were selected to better understand the spatial variability of SLR vulnerability across San Juan County. A 20-ft buffer was placed around the structure points, as a home within 20 ft of the bluff crest is likely threatened by erosion. Similarly for inundation threats, structures that are within 20-ft of the shoreline are likely to be threatened (particularly since this model does not include waves and HOWL does not integrate wave run-up).

Structures that are currently located below the highest observed water levels were identified, as these structures could potentially be inundated during storm events that coincide with high water. Currently, 69 structures are located below the highest observed water levels (MHHW + 3.4 ft). These structures should be evaluated to determine if home owners are aware of the threat and have historically incurred storm damage.

Table 10. Number of structures vulnerable to inundation or erosion associated with SLR scenarios (moderate, high) and planning horizons (2050, 2100) in San Juan County. HOWL = highest observed water level.

Threat type	HOWL	2050 Mod	2050 High	2100 Mod	2100 High	Total
Erosion	9	247	127	233	235	842
Inundation	69	239	106	48	249	711
Both	9	57	19	12	7	104
Total	**69**	**486**	**233**	**281**	**484**	**1553**

Over one-hundred structures are vulnerable to both inundation and erosion throughout San Juan County. Many of these structures are vulnerable to both threats as early as 2050 based on the moderate SLR scenario. Nine structures are currently threatened by both erosion and inundation (at or below the highest observed water level and within 20 ft of the bluff crest).

Tables 11 and 12 report the number of homes vulnerable to inundation and erosion (respectively) across each of the islands in San Juan County. Results show that slightly more homes are vulnerable to erosion than inundation in the County across most scenarios and planning horizons, excluding the high projection for 2100, in which slightly more structures will be threatened by inundation than erosion. Generally more structures are threatened on the more developed islands with greater populations and more structures. Lopez Island has far more structures threatened by erosion over inundation due to the prevalence of eroding bluffs on the Island (Tables 11 and 12). Orcas and San Juan Islands had similar counts of threatened structures.

Table 11. Number of structures vulnerable to inundation associated with SLR scenarios (moderate, high) and planning horizons (2050, 2100) in San Juan County by island. HOWL = highest observed water level. A lack of LIDAR data precluded assessment of Stuart, Johns, Sucia or Waldron Islands.

Island	2009 HOWL	2050 Mod	2050 High	2100 Mod	2100 High	Total
San Juan	2	51	22	11	101	187
Orcas	14	75	36	17	52	194
Lopez	41	50	30	10	39	170
Shaw	4	17	6	4	23	54
Blakely	0	8	2	2	11	23
Brown	0	2	1	0	3	6
Decatur	7	29	7	4	9	56
Pearl	1	4	2	0	9	16
Center	0	2	0	0	2	4
Obstruction	0	1	0	0	0	1
Total	**69**	**239**	**106**	**48**	**249**	**711**

Table 12. Number of structures vulnerable to erosion associated with SLR scenarios (moderate, high) and planning horizons (2050, 2100) in San Juan County by island. A lack of LIDAR data precluded assessment of Stuart, Johns, Sucia or Waldron Islands.

Island	2050 Mod	2050 High	2100 Mod	2100 High	Total
San Juan	42	27	48	54	171
Orcas	54	27	34	40	155
Lopez	101	57	103	88	349
Shaw	7	2	7	6	22
Blakely	22	6	13	16	57
Brown	5	1	3	2	11
Decatur	16	7	25	29	77
Total	**247**	**127**	**233**	**235**	**842**

The large majority (67%) of structures identified as vulnerable to SLR implications were buildings classified as residential, however “other” building types were also fairly common (Figure 15). Structures categorized as “other” commonly represented recreational buildings such as boat houses, hangars, net sheds and rental cabins. Figure 15 displays the building types vulnerable to erosion or inundation based on results of this assessment.

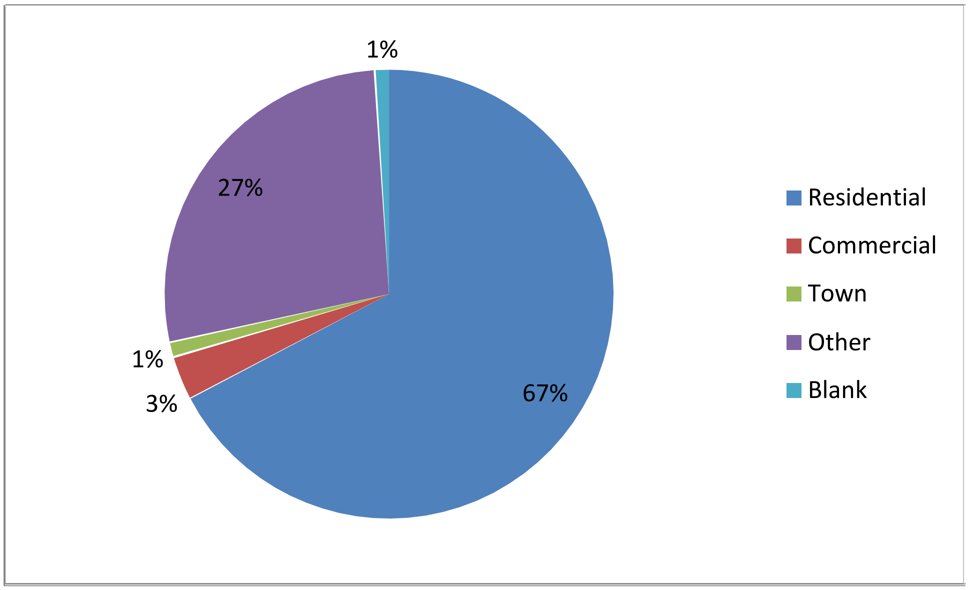


Figure 15. Building types vulnerable to erosion or inundation.

4.4 Policy Recommendations

The tools developed as part of this project were designed to enhance local understanding of the impacts of SLR and effectively identify the most immediate threats and greatest areas of vulnerability across the County. Once informed of the vulnerability, policy makers can address the underlying causes and begin to ameliorate additional vulnerability (Pethick and Crooks 2001). Some of the most effective uses of these outputs are to inform coastal management, local engineering works, and related planning efforts. These tools can also form the basis for more in-depth sea level rise resilience and adaptation planning such as those developed by Johnson (2000) and Russell and Griggs (2012). Because of the long-term nature of climate change and sea level rise, the opportunity exists to adapt to climate change impacts while maintaining environmental, social, and economic health.

There are various approaches to identify adaptation strategies, actions, and priorities, which should reflect local planning objectives and align with regional management efforts, particularly those associated with natural hazards and critical areas. Variable costs are associated with different management approaches and cost-benefit analyses can help inform decisions. For example the cost of protecting critical infrastructure will likely be much greater than changing shoreline management policies to create larger setback distances that would restrict future development in threatened areas. Project sequencing should also be considered as some areas will be threatened in the more immediate future, while others may not be vulnerable to until the latter half of this century.

The selection of feasible response strategies will likely be dependent on the overall objectives of local and regional managers and implementation costs. For example priorities could be identified based on the most immediate threats or threats to critical infrastructure, such as public utilities, hospitals and critical road networks.

Results from this assessment can be used to clearly locate priority areas where multiple threats are likely to occur, particularly in a shorter time-frame. For example, areas vulnerable to both inundation and erosion by 2050 represent the most immediate threats identified in this study. It also appears that considerably more road length and number of structures are vulnerable to inundation between now and 2050 than by erosion or between 2050-2100 (Tables 11 and 12). In contrast, among the structures threatened by erosion (bluff recession), most are vulnerable between 2050 and 2100. Therefore developing management strategies for inundation hazards appears to be a greater priority in San Juan County. The greatest number of vulnerable structures to both erosion and inundation are found on Lopez Island, followed by Orcas and San Juan Island (Tables 11 and 12). Planners should consider relocating or adapting critical infrastructure in these areas and explore funding programs to help facilitate the selected actions (adaptation, protection, retreat). Long-term strategies should also be developed for areas that are identified as vulnerable in 2100.

Development should be restricted in areas identified as vulnerable to SLR impacts and long-term management plans should reflect the lack of sustainability. In a recently published guidance document designed to help local governments in BC prepare for climate change (West Coast Environmental Law 2012, http://www.retooling.ca/_Library/docs/WCEL_climate_change_FINAL.pdf) , governments are advised to review the context of potentially legal liability and a changing climate with regard to:

- The vulnerability of existing infrastructure
- New infrastructure
- Permitting and inspections
- Approval of development in areas subject to increased risk of natural hazards such as flooding, landslides (and other climate change impacts).

For example in British Columbia, some SLR adaptation guidance suggests applying current setback regulations to the 2100 location of the bluff crest (pers. com. J. Shah 2013). Long-term sustainable coastal development should integrate future vulnerabilities associated with changing conditions due to SLR and CC. Sustainable development in coastal systems also requires the preservation of intact coastal processes for resilience.

Outreach and education to communities in which SLR vulnerability is high should also be conducted. Public input during the development of strategies and priorities can help to garner support and share the message with other community members. Education on how vulnerable areas were identified can help community members understand the origin of the mapping products and how the data can be used. Pilot outreach efforts could target the islands with the greatest vulnerability, such as Lopez Island. Pilot outreach and education efforts should focus on fostering community dialogue, enhancing understanding of sea level rise planning principles, and solicit input on the content and recommended potential solutions.

Results of this analysis can be paired with additional data for better management of natural coastal resources. For example, drift cells with large reductions in sediment supply (due to armored feeder bluffs), are likely to be less resilient (Pethick and Crooks 2000) and additional coastal recession and habitat loss may occur as a result. Recent work conducted by CGS and Friends of the San Juans in which the relative risk and/or resilience of priority nearshore habitats were assessed should be linked with the results of this analysis (MacLennan et al. 2012). Together these data could better inform management priorities from a habitat perspective. Priority habitats which are located waterward of areas vulnerable to erosion are at greater risk of being armored, which is known to degrade and eliminate habitats and the processes that sustain them. Outreach to property owners with structures that are threatened in the more immediate future (2050 moderate or high scenarios) located landward of priority habitat areas could be conducted to explore long-term management options. Protecting structures with shore armor that will likely be threatened by bluff recession should be cautioned against, as this management response will likely exacerbate down-drift and adjacent erosion, degrade important habitats, and may not be effective at preventing bluff recession over time.

The most effective uses of these tools are for improved long-term coastal management. Intermediate and long-term vulnerability to sea level rise implications in San Juan County have been identified from which management and planning strategies can be developed. A detailed SLR adaptation plan aimed at increasing local resilience, reducing vulnerability, and preserving resources would be a valuable follow up to this work.

4.5 Data Interpretation and Intended Utility

The purpose of this study was to provide an estimate of ***potential*** future hazards and **NOT** to predict actual erosion or flooding. Actual erosion from SLR may lag potential erosion, especially for bluffs composed of dense glacial deposits and/or due to potentially increased supply of littoral material. The ways in which the analysis could be improved are discussed further below, as well as important characteristics to be mindful of when interpreting this data.

This assessment was structured to provide a conservative estimate of areas vulnerable to sea level rise implications. When interpreting results it is important to be mindful of the assumptions and uncertainties built into the mapping and analysis. Quantifiable sources of uncertainty were analyzed and are described in detail in the forthcoming section of this report. Several additional sources of uncertainty that were not quantified as part of the error analysis, should be treated as fundamental assumptions and limitations (see bulleted list below) that should be minded during interpretation of results; while others can be used to improve this type of mapping and analysis in future studies.

<u>Assumptions and Limitations:</u>

- The SCAPE model equation is appropriate for consolidated glacial deposits found in San Juan County and is likely to underestimate the accelerated rate of bluff recession where bluff lithology is less consolidated.
- Projected rates of sea level rise are not significantly different from those reported in the NRC 2012 document.
- Other climate change impacts that could increase bluff erosion rates such as increased precipitation.
- The geologic mapping used in this assessment was low resolution (1:100,000) and did not account for bluff stratigraphy, which commonly affects bluff recession rates.

SLR projections were conservatively applied so as to map the likely upper limits of inundation. Inundation areas were mapped using the NRC SLR projections on the mean higher, high water shoreline plus the additional elevation of the highest observed water level to conservatively estimate the current upper limits of inundation during storm events. The highest observed water level represents both historic conditions (which are anticipated to change) as well as only standing water elevation, which does not account for wave run-up. Wave modeling was not included in this assessment due to a lack of wave data in San Juan County. Data that were available were not appropriate to extrapolate countywide, and limited resources precluded the development of a new wave model for the county. Therefore, inundation associated with wave run-up and wave-induced bluff erosion was not well accounted for in the assessment results. Wave induced erosion is likely a driving force (but not the only source) in the background erosion rates used to delineate areas the vulnerable to erosion.

There are a number of ways in which this mapping effort could be improved. One of the most important refinements would be measuring background erosion rates at additional sites in a variety of shoretypes throughout the county, as this was one of the most limiting data sources. Additional years of analysis would also provide insight into the consistency in shoreline trends. It would also be informative to further stratify shoretypes based on backshore geology (bluff lithology and stratigraphy). Mapping of areas vulnerable to inundation could be improved with a comprehensive LiDAR coverage for San Juan County flown at low tides would also enable more comprehensive analysis. Additionally, reducing the uncertainty in how accretion shoreforms will to respond to sea level rise (in the region) needs attention. As well as further informing the baseline morphology of these shoreforms and what are the central drivers behind the huge variability in change rates as documented in this study.

4.6 Error Analysis

The error analysis conducted for this study included several efforts to reduce uncertainty and limit potential sources of error in addition to quantifying a range of cumulative error. The detailed methods applied in both of these approaches will be described further below. Although several sources of uncertainty are addressed in this effort, additional uncertainties exist both of which will be discussed in this section.

Error Associated with Inundation Mapping

An important data source in the analysis of the impacts of sea level rise in San Juan County was the LiDAR elevation surface collected in 2009 by Watershed Sciences (2009). The report accompanying the LiDAR described the error analysis in the horizontal and vertical. The vertical error was stated as a standard deviation 0.12 ft, meaning that 95% of LiDAR points on a flat surface would have a value within 0.24 ft of their actual elevation.

As part of this error analysis the LiDAR elevation data reported accuracy was independently verified with elevation data derived from other methods. The LiDAR elevation data were compared to seven sites that were previously surveyed by CGS, each with multiple elevation measures of hard surfaces (e.g. paved roads). The sites were located on level terrain to minimize the impact of any horizontal error, vegetation must be minimal, and the reported horizontal and vertical accuracy was high degree. Three sites adjacent to high-quality monuments in flat terrain at ground level were selected. Where multiple survey dates were available from a site, the data from dates closest to summer 2009 were selected to coincide with the dates of LiDAR data collection.

The average difference between the LiDAR and ground survey elevations was found to be 0.01 ft, with a standard deviation of 0.22 ft. This value does include several sources of additional error however. The MLLW datum elevations were based on direct observation of the water level at low tide. Also, the survey methods involved elevation error as high as approximately 0.1 ft. The accuracy reported by the LiDAR data provider was a mean difference of 0.002 ft with a standard deviation of 0.120 ft.

Given the above values, the reported accuracy of the San Juan County LiDAR elevation data flown in 2009 is an accurate assessment of the actual accuracy of the data. However, no verification of the horizontal accuracy was performed during this study.

Error Associated with Bluff/bank Recession Mapping

Peer reviewed research was reviewed to identify techniques to reduce sources of uncertainty and calculate cumulative error in this type of analysis (Moore 2000, Ruggerio and List 2009, Fletcher et al. 2003, Ruggerio et al. 2003, Morton et al. 2004). Measures to reduce unnecessary error and uncertainty of analysis included:

- Use of the largest scale vertical aerial photos (1:12,000)
- Using the most reliable shoreline proxy (bluff crest or bluff toe)
- Used a single digitizer at a consistent scale to reduce error associated with interpretation
- Use of DSAS to reduce error associated with change measures
- Alongshore averaging of change rates were applied within each shoretype to nullify localized trends within a given shoretype
- Careful selection of sampled shoretypes to avoid potential sources of interference to a basic background shoreline change rate such as: bedrock promontories, rock outcrops directly off-shore, dramatic sediment supply loss in the drift cell, and shore armor within the subject shoreform

Several sources of uncertainty have the potential to impact the accuracy of historical shoreline positions and the final estimates of shoreline change rates. Generally, they can be categorized as either positional uncertainty or measured uncertainty. Positional uncertainty: relates to all features, relates to the exactitude of defining the true shoreline position in a given year. Using the most landward visible shoreline proxy enabled us to maintain a relatively lower level of positional uncertainty. Measurement error relates to the operator-based manipulation of the map and photo products (Fletcher et al. 2003) such as the orthorectification process, RMS values, pixel size, and digitizing shoreline features. Measurement error was far more prevalent in this analysis. Cumulative error measures integrated error derived from background (historic) change rate calculations as well as the uncertainty derived from the variability and extrapolation of those change rates.

Potential error was assessed using a formula developed for calculating the maximum level of error derived from this type of analysis (Morton et al. 2004). The equation, which integrates error values from various sources, was adapted slightly to account for the most relevant sources of error in this analysis. Calculations of both the lower and upper limits of the maximum potential error were conducted to facilitate the mapping error buffers. The following sources of error were included in the equation: historic imagery, current imagery, LIDAR, and two different forms of digitizing error. Detailed descriptions of each source of error are shown in Table 12.

[illegible] (Equation 2)

Table 12. Variables, data sources, and descriptions of each type of error included in the error analysis.

Variable	Data Source	Description
E_p	Historic imagery	The range of distortion resulting from the historic imagery. This value is less for digital imagery and is more closely associated with the resolution (pixel size) of the image.
E_c	Current imagery	The San Juan County 2008 orthorectified aerial images and LiDAR (see below) were used to digitize the current condition of the selected shoreline proxy. The 2008 imagery is both highly accurate and high resolution. Additional details can be found at mjharden.com. Error value = 2x the pixel size (pixel size of 0.5 ft, 1 ft maximum error).
E_l	LIDAR	LiDAR was used to guide the delineation of the bluff crest. The 2009 LIDAR data's positional accuracy was estimated by measuring 2x the pixel size (pixel size of 3 ft, 6ft maximum error).
E_{d1}	Digitizing error (1)	This study used only georeferenced aerial photos and LiDAR to determine the location of digitized shoreline proxy (features), so an error value associated with pixel size as the determinant of placement and location of digitized lines is appropriate. Error values associated with pixel size of current imagery is already accounted for so a weighted average of historic air photos pixel size was averaged to obtain the digitizer error value.
E_{d2}	Digitizing error (2)	To avoid introducing additional digitizing error only one analyst digitized the shoreline feature (most commonly bluff or bank crest). Digitizing error was measured by the original analyst by digitizing a bluff crest twice with considerable time between the two interpretation efforts, and then measuring the range of error between the two features locations. The time lapse between digitizing was designed to reduce to the ability of the digitizer to "remember" what they had digitized in the past. The difference in the position of the bluff crest ranged from 1.2 to 11.7 ft.
E_r	Rectification error	The error has been quantified in ArcGIS during the rectification process, as the root mean square (RMS) measures the misfit between points on the image being rectified to the orthorectified base map used. The reported RMS was used in error analysis by Fletcher et al. (2003). For the purposes of this study, the average RMS values for each rectified aerial photograph used to digitize shoreline proxy features were used to represent the rectification error value

The results of the error analysis are presented in Table 13. Historic image distortion, digitizing error, and rectification error were the greatest sources of error.

The average (background) change rates of each shoreform type was extrapolated across shoreforms in San Juan County. To account for the potential error associated with the extrapolation and the range of change rates for each shoretype, the standard deviation (Table 14) was added to the cumulative change rate error. The cumulative error margin (standard deviation + total change rate error) are the final error measures that were used to create the error polygons to aid in the interpretation of results (Table 15).

The minimum and maximum cumulative error were calculated and mapped as polygons to provide a spatial reference for how the error would actually occur on the ground to aid in the interpretation of mapping results. Snapshots of the error buffers are shown in Figures 16 and 17 and full size maps are included in the back of the project map folio.

Table 13. Variables, data sources, range of measured error and cumulative error measures.

Variable	Data Source	Sources of Uncertainty	Low	High
E_p	Historic imagery	historic image distortion	3.3	6.6
E_c	Current imagery	2008 orthorectified image	1	6
E_l	LiDAR	2x pixel size	6	6
E_{d1}	Digitizing error (1)	weighted average pixel size	4.4	4.4
E_{d2}	Digitizing error (2)	measured from heads up digitizing	0.5	11.7
E_r	Rectification error	average RMS for all images	4.3	4.3
Cumulative uncertainty			**7.4**	**18.9**
Annualized uncertainty (49 years)			**0.15**	**0.39**

Table 14. Standard deviation of shore change rates across different shoretypes and exposure categories in San Juan County (1960-2009).

Exposure	Feeder bluffs	Transport zones	Pocket beaches
<5 miles	0.160	0.083	0.112
>5 miles	0.212	0.081	0.106

Table 15. Cumulative error margin for each shoretype and exposure category in San Juan County.

Exposure	Feeder bluffs	Transport zones	Pocket beaches
2050 Low - Cumulative Error Margin			
< 5 miles	12.7	9.6	10.8
> 5 miles	14.9	9.5	10.5
2050 High - Cumulative Error Margin			
< 5 miles	22.4	19.2	20.4
> 5 miles	24.5	19.1	20.2
2100 Low - Cumulative Error Margin			
< 5 miles	28.3	21.2	23.9
> 5 miles	33.0	21.1	23.3
2100 High - Cumulative Error Margin			
< 5 miles	49.7	42.6	45.3
> 5 miles	54.4	42.5	44.7

This error analysis is limited to those sources of uncertainty that could clearly be analyzed. Several additional sources of uncertainty were not quantified as part of this error analysis, some of which can be treated as fundamental assumptions and limitations that should be minded during interpretation of results; while others can be used to improve this type of mapping and analysis in future studies.

Figure 16. Example of buffered error margins to erosion vulnerability for the **moderate SLR scenario in 2050** for Fisherman's Bay, Lopez Island, as found in project GIS geodatabase to facilitate communicating uncertainty in outreach efforts.

Figure 17. Example of buffered error margins to erosion vulnerability for the high SLR scenario in 2100 for Fisherman's Bay, Lopez Island, as found in project GIS geodatabase to facilitate communicating uncertainty in outreach efforts.

5.0 Conclusions

One of the important challenges for sea level rise researchers is to frame assessment results within a context understandable and useful to local decision-makers. If this goal is accomplished, it is more likely that short-term measures that enhance the adaptive capacity of coastal areas to respond to SLR can be implemented at the local level (Neumann et al. 2000).

The results of this assessment provide a foundation for which additional refinement and assessments should be conducted. Russell and Griggs (2013) recently published a guidance document for how to develop a thorough SLR vulnerability assessment and adaptation plan. Adaptation planning at the local level can limit the damage caused by climate change and can reduce the long-term costs of responding to the climate-related impacts that are expected to grow in number and intensity over the coming decades.

Assessing the adaptive capacity of vulnerable areas, identifying particularly vulnerable infrastructure for relocation, such as low-lying sewage treatment plants, hazardous waste facilities, coastal power plants, large hotels and other major infrastructure are critical elements that should be addressed in an adaptation plan (Russell and Griggs 2013). Adaptive actions could then be prioritized by developing a risk assessment that evaluates the probabilities, magnitudes and consequences of events driving the change. A risk assessment should include the following elements (Russell and Griggs 2013):

- actual flood threats or hazards of concern (bluff erosion, beach loss, flooding),
- economic importance and value of public facilities,
- value and importance of private development sectors, both commercial and residential,
- importance of municipal emergency services,
- magnitude of impacts of future hazardous events,
- timing and frequency of hazardous events, and
- certainty of projected impacts to the degree that they can be expected.

Based on the cumulative results of these additional analyses a specific plan of action or adaptation plan could then be developed. Typically, the most important and threatened planning areas are addressed first, such as facilities and developments that are sited at the lowest elevations or closest to the crest of an eroding bluff. Greater detail on each of the elements that should ideally be included in an adaptation plan is described in Russell and Griggs (2013).

The intended utility of this study was to take the first few steps towards understanding the vulnerability and response of different shoreform types and areas of San Juan County to SLR and climate change. Previous assessments of this nature in the Salish Sea have addressed only areas vulnerable to coastal flooding and have not attempted to address or identify areas potentially vulnerable to coastal erosion. By assessing historic (background) change rates across geomorphic shoretypes, and applying an acceleration based on the rate of sea level rise, bluff/bank recession projections were applied for each scenario and planning horizon. The range of projections can be used to prioritize structures and infrastructure with more or less immediate threat. This approach provides coastal managers with a tool that can be applied at multiple scales within San Juan County to inform the development of new policies that specifically address SLR and climate change as well as existing policies and regulations such as setback requirements.

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