AN ABSTRACT OF THE THESIS OF

Alexis K. Mills for the degree of Master of Science in Water Resources Engineering presented on August 24, 2015.

Title: Exploring the Impacts of Climate and Management on Coastal Community Vulnerability through Alternative Future Scenarios

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John Bolte

Coastal communities throughout the U.S. Pacific Northwest face heightened risk due to sea level rise and increasing storminess resulting in coastal flooding and erosion hazards. Incorporating uncertainty with respect to both climate change and policy decisions is essential to project the evolving probability of coastal inundation and erosion, and the associated community vulnerability through time. Coupled models of coastal hazards, ecosystems, development, and socioeconomics allow decision-makers to explore the effects of policy decisions in conjunction with climate forcing, land use change, and economic disturbances and can provide a means of examining the feedbacks between climate change and adaptation under uncertain climatologic and socioeconomic futures. *Envision*, a spatially explicit multi-agent modelling platform that provides a scenario-based, policy centric framework for examining interactions between human and natural systems across a landscape, is used in the two papers below to explore strategies that may reduce vulnerability to coastal hazards within the context of uncertainty and climate change. Probabilistic simulations of total water levels allow for representation of variability of sea level rise, wave climate, and the El Niño Southern Oscillation both as individual climate drivers and under a range of climate change scenarios through the end of the century. Additionally, stakeholder

generated policy scenarios capture variability in human response. The approaches described here provide a foundation through which to explore alternative management scenarios related to coastal hazards and can be transferred to other coastal systems to further assess how hazards may be affected by both climate change and management decisions.

Exploring the Impacts of Climate and Management on Coastal Community Vulnerability through Alternative Future Scenarios

by
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APPROVED:

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Major Professor, representing Water Resources Engineering

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Alexis K. Mills, Author

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CONTRIBUTION OF AUTHORS

Dr. John Bolte is the developer and principal programmer for the *Envision* platform and contributed to model development.

Dr. Peter Ruggiero helped to develop many of the coastal change modeling processes used in this modeling effort and guided stakeholder engagement.

Katy Serafin developed the full simulation total water level model used in this analysis.

Eva Lipiec helped refine policies and policy language through coordination with the group of stakeholders.

Chad Zanocco developed the Hedonic model used to evaluate property value.

John Stevenson, Patrick Corcoran, and Dr. Denise Lach assisted with coordination of stakeholder outreach efforts that assisted in defining model objectives, validating model assumptions, and communicating results.

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Introduction

Within the past three decades, the coastal U.S. Pacific Northwest has seen a heightened risk of hazards as a result of sea-level rise (SLR), and increasing storm frequency and intensity (Ruggiero et al., 2010, Allan and Komar, 2006) . However, the underlying complexity of these phenomena complicates the prediction of future climate conditions at local scales (e.g., NRC, 2012; Sallenger et al., 2012; Yin et al., 2010). With the continuous influx of population to coastal regions, human stresses on coastal resources and ecosystems coincide with climate change, resulting in uncertain and potentially less habitable shorelines worldwide. In addition, community exposure to coastal change hazards varies depending upon how communities respond and adapt to risk as well as to how population growth and development drive the evolution of the coastal system. As such, it is critical that community planners understand coastal processes and impacts of management decisions when developing adaptation strategies in order to address these emerging challenges in ways that are both cost-effective and sustainable into the future.

To evaluate the impact of policy decisions under uncertain future climate conditions, an approach is needed that marries the predictive and dynamic capabilities of simulation models with a scenario methodology that incorporates stakeholder values and adaptation strategies (Withycombe Keeler et al., 2015, Karvetski et al., 2011). Simulations of alternative futures can help to identify the most important interactions across spatial and temporal scales, leading to improved understanding of the structure and behavior of natural and human systems by researchers and stakeholders alike. In the two papers presented below, *Envision* (Bolte et al., 2007), a spatially explicit, policy centric modeling framework, was used to examine interactions between human and natural systems across a landscape. The first paper primarily focuses on the methodology for alternative futures analysis in coastal Tillamook County, Oregon and the second highlights the variability and uncertainty in physical and human drivers across landscape metrics related to coastal hazards.

Exploring the Impacts of Climate and Management on Coastal Community Vulnerability through Alternative Future Scenarios

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Abstract

Elevated risk of coastal flooding and erosion due to climate change throughout the U.S. Pacific Northwest necessitates the evaluation of climatic and socioeconomic change on important landscape metrics. Coupled models of coastal hazards, ecosystems, socioeconomics, and landscape management allow decision-makers to explore the effects of policy decisions in conjunction with climate forcing and can provide a means of examining the feedbacks between climate change and adaptation under uncertain futures both in physical and human dimensions. Presented here is the development and assessment of alternative future scenarios using *Envision*, a spatially explicit modelling platform which allows alternative futures analysis across the natural and human landscape within a scenario-based, policy centric framework. As applied in this project, *Envision* consists of three main components: a climate and coastal hazard submodel, population and development submodels, and policy scenario simulation. Coastal flooding and erosion were probabilistically simulated using total water levels within a total of 99 future climate scenarios. In addition, five policy scenarios were developed iteratively with input from stakeholders in Tillamook County, Oregon to capture variability within the human system. Alternative futures were evaluated in terms of landscape metrics, which were also determined through the stakeholder engagement process. Results suggest that both climate change and management decisions have a significant impact across the landscape, and can potentially impact geographic regions at different magnitudes and timescales. The outlined approach provides a foundation through which to explore alternative scenarios related to coastal hazards and can be transferred to other coastal systems to further assess how hazards may be affected by climate change and management decisions.

1 Introduction

With the continuous influx of populations to coastal regions, human stresses on resources and ecosystems coincide with climate change, resulting in uncertain and potentially less habitable shorelines worldwide (Neumann et al., 2015). The coastal U.S. Pacific Northwest faces an increased risk of hazards as a result of sea-level rise (SLR), and increasing storm frequency and intensity (Ruggiero et al., 2010; Allan and Komar, 2006). However, trends in SLR, storm frequency, and wave climate attributed to global climate change are difficult to accurately predict, particularly at local scales. Sea level rise is highly spatially and temporally variable, and while there is a documented acceleration of mean global SLR, local processes such as tectonic uplift contribute a high degree of uncertainty (e.g., NRC, 2012; Sallenger et al., 2012; Yin et al., 2010) Additionally, downscaled predictions of future wave heights , storm intensity and frequency, and patterns of El Niño Southern Oscillation (ENSO) have variable projections by the end of the century, and can potentially exacerbate coastal flooding and erosion (Cai et al., 2014; Hemer et al., 2013; Wang et al., 2014).

The inherent geographic variability in climate impacts emphasizes the need for place-based approaches to climate vulnerability analysis and adaption planning that also take into account the values of local stakeholders (e.g., Kelly and Adger, 2000; Moser et al., 2012; Turner et al., 2003). Community exposure to coastal change hazards varies depending upon how communities respond and adapt to risk as well as to how population growth and development drive the evolution of the coastal system. As such, it is critical that community planners understand the impacts of management decisions when developing adaptation strategies to address these emerging challenges in ways that are both cost-effective and sustainable into the future. Examples of solutions that can potentially prevent community exposure to coastal hazards include (a) hard and soft engineering solutions (e.g. rip-rap revetments, sea walls, or beach nourishment) ; (b) nonstructural measures that accommodate coastal risks while continuing coastal occupancy and land use (e.g., flood insurance, stricter building and zoning codes, and elevating structures); or (c) relocation away from coastal hazard zones (e.g., planned retreat using construction setbacks, buy-outs, and reactive relocation from the shoreline; Klein et al., 2001). Understanding the consequences of such solutions is essential to developing adaptive capacity, or the ability to sustain quality of life, within communities (Gallopín, 2006; Smit and Wandel, 2006).

To evaluate the impact of policy decisions under uncertain future climate conditions, an approach is needed that marries the predictive and dynamic capabilities of simulation models with a scenario methodology that incorporates stakeholder values and adaptation strategies (Keeler et al., 2015, Karvetski et al., 2011). Policy and climate scenarios have recently been combined within modeling platforms to assess climate change impacts and vulnerabilities across different sectors (e.g. Le et al., 2010; McNamara and Keeler, 2013; Bolte et al., 2007) and have emerged as a powerful tool in integrated assessment and policy analysis within the context of climate change because they account for a range of uncertainty in complex and dynamic systems (Berkhout et al., 2002). These alternative pathways of plausible futures characterize the magnitude and extent of future climate change; associated potential impacts on physical, natural, and human systems; the costs and possible effectiveness of mitigation and adaptation policies; the interactions among and trade-offs between climate change impacts and policies of adaptation and mitigation; and the relationship between climate change and socioeconomic development (Berkhout et al., 2013; Mokrech et al., 2012; Moss et al., 2010; Nicholls et al., 2008; van Vuuren et al., 2011). Simulations of alternative futures can ultimately help identify the most important interactions across spatial and temporal scales, leading to improved understanding of the structure and behavior of these systems by researchers and stakeholders alike.

Presented here is a transferrable methodology for development and evaluation of alternative futures with respect to coastal flooding and erosion in Tillamook County, Oregon within a spatially explicit, multi-agent based framework. First, the background establishes the historic climatologic and socioeconomic baseline in Tillamook County followed by a discussion of the modeling platform, *Envision*, and the development of a suite of probabilistic climate change scenarios that reflect various assumptions regarding SLR, wave height, and major ENSO occurrences and their impact on future total water levels (TWLs). In addition, the methodology details the five policy scenarios that were developed iteratively with a group of stakeholders to capture a range of landscape management options. Finally, the resulting alternative futures are evaluated using a suite of landscape metrics, and the benefits and drawbacks of various adaptation strategies under a range of climate scenarios are explored along with an analysis of the model sensitivity to parameterization of the human system.

2 Coastal Tillamook County, Oregon

Roughly 23 percent of Tillamook County's approximately 25,320 permanent residents live within a half mile of the Pacific Ocean (U.S. Census Bureau, 2014). The 104 kilometer coastline also draws visitors and non-permanent residents alike. Coastal geomorphology varies from sandy, dune backed beaches, which compose the majority of the shoreline, to sandy beaches backed by rip rap, cobble and boulder beaches adjacent to headlands, bluff-backed beaches, and cliffs. Headlands restrict alongshore sediment transport between four littoral cells, which are further divided by estuaries.

The past few decades have seen increased exposure to coastal hazards in Tillamook County that can be attributed to three main climatological drivers; sea level, increases in wave heights (related to winter storms), and frequency of ENSO events. Komar et al. (2011) found rates of relative sea level rise of approximately 1.3 mm per year along the central to northern Oregon Coast between 1980 and 2010. Further, the Pacific Northwest is exposed to extreme extratropical storms, with winter waves regularly reaching heights in excess of 7 meters (Allan and Komar, 2006). Ruggiero et al. (2010) found increasing wave heights along the Oregon Coast, with the annual mean increasing at a rate of 1.5 cm per year, the winter mean increasing at a rate of 2.3 cm per year, and annual maximum increasing at a rate of 9.5 cm per year over the past three decades. In addition, recent El Niño events (i.e. 1997/1998, 2009/2010) have resulted in severe flooding and erosion. At present, over 65% of the Tillamook County coastline is erosional with approximately 40% of the coast eroding at rates exceeding one meter per year (Ruggiero, et al., 2013).

3 Envision Framework

Envision (Bolte et al., 2007) is a multi-agent based modeling platform which couples landscape process models with socioeconomic drivers and management strategies to explore change trajectories through time via a variety of metrics (Figure 3.1). Envision has been used to characterize floodplain trajectories (Hulse et al., 2009), impacts of urban expansion (Guzy et al., 2008) and is currently used for wildfire–land management, long-term ecological management, and a variety of other coupled human–natural systems applications (e.g. Koch et al., 2012; Yospin et al., 2015). This integrative modeling approach allows scientists and managers to explore the complexity of landscape patterns that result when decision-making entities and their policies are included as part of evolving landscapes.

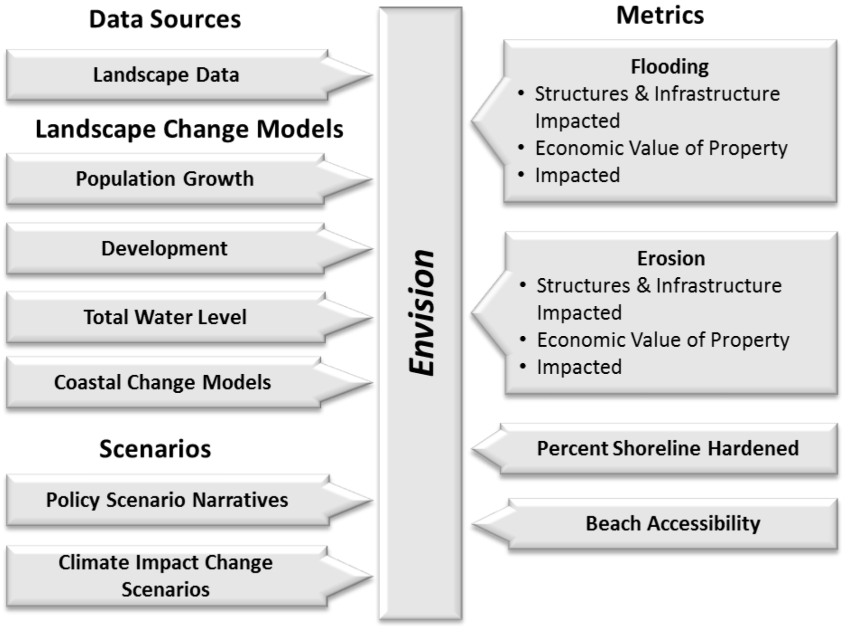

Figure 3.1: Envision inputs, landscape change models, and evaluative models specific to the modeling of coastal hazards in Tillamook County, Oregon.

Alternative futures analysis within Envision involves three primary aspects: 1) dataset development, 2) model development and integration, and 3) policy development. Dataset development occurs in conjunction with stakeholder engagement subsequent to the determination of relevant evaluative metrics. All datasets must be spatially explicit (e.g., census tracks, geomorphologic parameters). Envision enables spatial-temporal simulation of landscape change through the synchronization of multiple submodels. These submodels, or “plug-ins”, periodically change the underlying landscape, reflecting biophysical processes that occur independently of human action. The modular architecture allows for the addition or modification of any number of submodels.

Envision includes a multi-agent based modeling subsystem to represent human decisions on the landscape. A set of agents operate across the landscape by selecting and applying policies in response to landscape signals and other factors influencing their decision-making behavior.

Actors can be based on individuals, collections of individuals, or can be abstractions with no real world counterpart. The application of a policy by an actor results in changes of landscape attributes. Policies, which are typically grouped to form scenarios, contain information about site attributes defining where the policy can be considered and outcomes that the policy is intended to accomplish.

During simulation, *Envision* generates a set of both spatially detailed and spatially aggregated landscape evaluators reflecting scenario outcomes for a variety of metrics, most notably development/land-use patterns, shoreline modifications, population projections, and impacts to the landscape by coastal hazards. These landscape metrics indirectly introduce feedbacks into the system by quantifying the actor or policy's impact on the landscape. The sections below describe (1) how Tillamook County was represented geospatially, (2) the submodels used to simulate coastal hazards, population growth, and development, and (3) the development of climate and policy scenarios.

3.1 **Geospatial Representation of the Landscape**

A landscape in *Envision* consists of a set of spatial containers or polygons called integrated decision units (IDUs) that specify the resolution at which processes and actors can operate on the landscape. For this study, the 2,934 km^2 study area of Tillamook County was divided into approximately 130,000 IDUs. Areas of the IDUs range from less than 50 square meters to greater than 10 square kilometers. The IDUs were formed through the intersection of multiple geometric layers representing baseline data. The baseline geometry for the IDU layer were county defined tax lots with underlying information including ownership, zoning, and presence of a dwelling or building. Each IDU has a unique set of attributes relevant to the landscape and evaluative models. Taxlots near the shoreline were further subdivided using a

100 m alongshore by 10 m cross shore grid to more accurately resolve coastal flooding and erosion hazards (Figure 3.2).

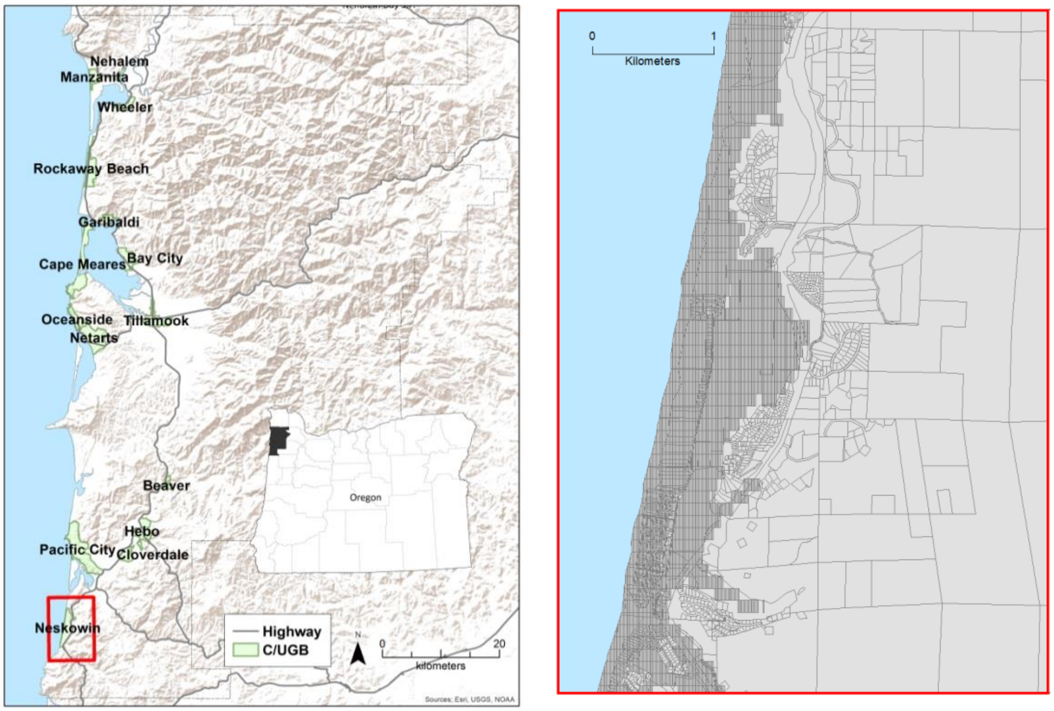

Figure 3.2: Map of Tillamook County study area (left) and an inset showing scale of IDUs near the shoreline in the unincorporated community of Neskowin (right) . All community and urban growth boundaries (C/UGB) are indicated for the study area.

3.2 Coastal Hazards and Climate Simulation

A submodel within *Envision* was developed to capture coastal hazards and climate change impacts across the landscape. Within this submodel, total water levels (TWLs) were used to derive coastal flooding and erosion along the outer coast. The probabilistic simulation of alongshore TWL components and the resulting impacts to the shoreline are discussed in the following sections.

3.2.1 Probabilistic Simulation of Total Water Levels

TWLs are calculated as a linear superposition of the tide, non-tidal residual, and runup associated with wave height (Figure 3.3; Allan and Komar, 2006; Ruggiero, 2013; Ruggiero et al., 2010).

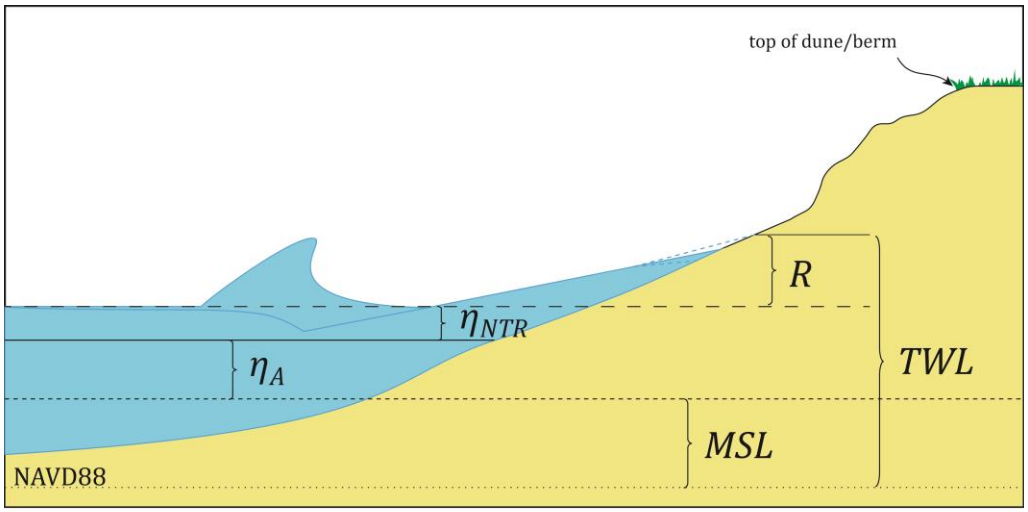

Figure 3.3: Diagram of TWL components (Serafin and Ruggiero, 2014)

$$TWL = MSL + \eta_A + \eta_{NTR} + R \quad (1)$$

where MSL is the mean sea level, η_A is the deterministic astronomical tide, and η_{NTR} is the nontidal residual generated by physical processes including wind setup and barometric surge. *R*, the maximum vertical extent of the wave runup on a beach or structure above the still water level, was calculated using the 2% exceedance rate with methods described in the following two sections.

Using the total water level full simulation model (TWL-FSM) developed by Serafin and Ruggiero (2014), probabilistic time series of wave height, wave period, wave direction, MSL, η_A and η_{NTR} allowed for the incorporation of variability and non-stationarity within climate scenarios discussed in Section 3.4. These TWL parameters were generated for an offshore deep water location not affected by shoaling or refraction processes. As such, it was necessary to propagate the waves toward the nearshore using regional bathymetry. Because the numerical transformation of waves is computationally expensive over a large study region, lookup tables were developed to relate offshore (deep water) triplets of significant wave height (SWH), peak period (T_p), and mean wave direction (MWD) to their nearshore (20 m water depth) equivalents using radial basis functions (Camus et al., 2011). The wave climatology was discretized into representative wave conditions which were transformed to the nearshore (García-Medina et al., 2013) using stationary model runs of SWAN (Booij et al., 1999). This allows for any combination of a deep water triplet's nearshore equivalent to be interpolated from the results of the SWAN model runs. Wave runup parameterization (Stockdon et al., 2006) relies on the deep water equivalent SWH and T_p as inputs, so transformed waves were linearly back shoaled from the 20 m contour to deep water. Waves were then propagated to the shore using 100m (alongshore) resolution geomorphology including backshore beach slope (defined as the slope between the MHW shoreline contour and the dune toe), dune crest, and dune toe which were extracted from a combination of 2009 LiDAR Data from Oregon Department of Geology and Mineral Industries (DOGAMI) and 2011 LiDAR data from U.S. Army Corps of Engineers using techniques developed by Mull and Ruggiero (2014).

3.2.2 Runup Formulation for Dune Backed Beaches

Wave runup can contribute significantly to the damage potential of waves along the Pacific Coast. Vertical runup is composed of both setup and swash and was calculated for sandy dune backed beaches using the 2% exceedance value of swash maxima using an empirical relation for extreme wave runup by Stockdon et al. (2006).

$$R_{2\%} = 1.1\left\{0.35\,\beta_f(H_0L_0)^{\frac{1}{2}} + \frac{(H_0L_0(0.563\beta_f{}^2 + 0.004))^{1/2}}{2}\right\} \quad (2)$$

$$L_0 = \frac{gT_p{}^2}{2\pi} \quad (3)$$

where $\beta_f\, is$ the backshore slope as computed between MHW and dune toe, H_0 is the deepwater SWH, L_0 is the deepwater wave length, T_p is the peak wave period and g is the acceleration due to gravity. This formula is applicable over a variety of beach conditions, ranging from dissipative to reflective, and was thus suitable for all dune-backed beaches in this study area.

3.2.3 Runup Formulation for Barrier, Bluff, and Cobble Berm Backed Beaches

Runup on BPS, bluffs, cliffs, and cobble berms depends upon the height and steepness of the incident wave, the beach and barrier slopes, and design characteristics of the backshore structure including its permeability. The approach described here is based upon the TAW (Technical Advisory Committee for Water Retaining Structures) method, which provides a mechanism for calculating the runup adjusted for various reduction factors that include the surface roughness, the influence of a berm (if present), and effects associated with the angle of wave approach (Van der Meer, 2002).

First, the wave height at the toe of the barrier was calculated, $DWL_{2\%}$ (Dynamic Water Level) which includes the combined effects of the still water level, wave setup, and dynamic portion of runup as follows

$$DWL_{2\%} = MSL + \eta_A + 1.1\left\{0.35\,\beta_f(H_0L_0)^{\frac{1}{2}} + \frac{0.06(H_0L_0)^{1/2}}{2}\right\} - E_J \quad (4)$$

$DWL_{2\%}$ is then used to establish the significant wave height

$$H_{mo} = DWL_{2\%} * 0.78 \tag{5}$$

where E_J is the elevation of the dune toe (the junction between the dune and upper beach), and H_{mo} is the wave height at the structure toe with the commonly used breaker index of 0.78. If the depth limited breaking was larger than the offshore wave height, the offshore wave height (H_0) was used instead.

The barrier slope was determined subsequent to the calculation of wave height and period at the toe of the barrier. Because the runup process is influenced by the change in slope from the breaking point to the maximum extent of vertical wave runup, the characteristic slope was specified for the same region. For this formulation, the local structure slope was computed between the TWL computed using the Stockdon et al. (2006) formulation and the wave setup plus the static water level. If the setup calculated using the Stockdon et al. (2006) formulation combined with the tide was greater than the structure crest, the composite slope was used. For sandy beaches backed by bluffs, cliffs, or cobbles, nearshore bathymetric and topographic profiles (~1 meter cross shore resolution) allowed for the extraction of local slope and were assumed static through time. For sandy beaches backed by backshore protective structures (BPS), the local geomorphology was dynamic (see following sections). New or modified rip rap slopes were assumed to be constructed with a 2:1 slope, consistent with best engineering practices.

Finally, the $R_{2\%}$ was calculated using a series of reduction factors

$$R_{2\%} = \left\{ \begin{array}{c} 1.75 H_{mo} \gamma_b \gamma_r \gamma_\beta \, \xi \; (0 < \xi < 1.8) \\ H_{mo} \gamma_b \gamma_r \gamma_\beta \left\{ 4.3 - \frac{1.6}{\xi^{\frac{1}{2}}} \right\} \; (\xi \geq 1.8) \end{array} \right\} \tag{6}$$

$$\gamma_\beta = \begin{cases} 1.0 - 0.0033|\beta|, (0 \leq |\beta| \leq 80) \\ 1.0 - 0.0033|80|, (|\beta| > 80) \end{cases} \quad (7)$$

where γ_b is the berm reduction factor, γ_r is the roughness reduction factor, and ξ is the breaker parameter ($tan\beta / \left(\frac{H_{mo}}{L_0}\right)^{0.5}$). The wave direction factor, γ_β, is determined using β, the mean direction of wave approach. The roughness reduction factor is dependent upon the characteristics of the backshore feature (Table 3.1). No berm reduction factor was adopted as no such feature is present within the Tillamook County study area.

Table 3.1: Reduction factors used in the calculation of runup

Backshore Feature	Reduction Factor
Near vertical bluff face	1.0
Highly vegetated bluff face	0.6
Backshore protective structure	0.55-0.6

3.2.4 Coastal Flooding

To reduce computational complexity, flooding within *Envision* was calculated for the maximum yearly TWL event using a bathtub-type inundation model which considers only two variables: the inundation level and ground elevation (Schmid et al., 2014). The coastal hazards submodel allows for selection of yearly maxima independent of spatial homogeneity such that different storms throughout the year may produce the maximum TWL event for each alongshore location depending upon local geomorphic and climatic conditions. Because of the simplicity of the bathtub model, TWLs at the inlets were reduced to reflect a combination of non-tidal residual and tide only, thus eliminating any swash, while the full TWL was used for the remainder of the coastline. Flooding occurred only if the dune or structure crest was overtopped by the TWL. To determine pathways of flooding in the backshore, hydraulic connectivity between individual IDUs was determined using a 1 m resolution Digital Elevation Model (DEM).

3.2.5 Coastal Erosion

Three forms of erosion combine to evaluate coastal retreat as follows (after Baron et al., 2014)

$$\text{Coastal Erosion} = (CCR_{SB} + CCR_{Climate}) * \text{T} + CC_{Event} \quad \textbf{(8)}$$

where CCR_{SB} is the long-term (interannual- to decadal-scale) coastal change rate, $CCR_{climate}$ is the coastal change rate associated with climate change-induced factors, T is time in years, and CC_{Event} is the event-based erosion based on the maximum yearly TWL. Within the model, erosion was restricted to dune-backed beaches. Failure of BPS and bluff/cliff erosion was not accounted for. Both chronic (CCR_{SB} and $CCR_{Climate}$) and event based (CC_{Event}) are discussed in further detail below.

3.2.5.1 Chronic Erosion

A linear shoreline change rate was used to capture erosion associated with sediment budget factor and climate drivers not associated with SLR (CCR_{SB} , Ruggiero et al., 2013). The influence of SLR on erosion was characterized using a Bruun Rule (1962) calculation. Given a yearly rise in SLR, the yearly landward shoreline retreat was found as follows

$$CCR_{Climate} = \frac{L}{B + hc} SLR = \frac{SLR}{tan\beta_{sf}} \quad \textbf{(9)}$$

where L is the cross shore distance to the water depth h_c, the depth of closure, B is the elevation of the onshore feature, and $\tan\beta_{sf}$ is the shoreface slope. Shoreface slopes were estimated using the slope between mean high water line (MHW, 2.1 meter contour relative to NAVD88) derived from LiDAR data and the 25 m isobath. On dune-backed beaches, beach slope remained static through time as the dune erodes landward and equilibrium was reached while the dune toe elevation was allowed to rise at the rate of SLR. On beaches backed by BPS, the beach was assumed to narrow at the rate of the total chronic erosion. Beaches were further narrowed in the process of maintaining (i.e. raising to accommodate higher TWLs) and constructing BPS structures at a 2:1 slope.

3.2.5.2 Event-based Erosion

Coastal retreat also takes place during large winter storm events or periods of elevated water levels in the form of wave-induced foredune erosion, in which the magnitude of erosion depends on the elevation of the TWL relative to the toe of the foredune (Ruggiero et al., 2001; Sallenger, 2000; Stockdon et al., 2006). A modification of the foredune erosion model presented by Kriebel and Dean (1993) was implemented within the coastal hazards submodel which assumes that the volume of sediment eroded from the foredune during a storm is deposited in the nearshore as the equilibrium profile shifts as follows

$$CC_{Event} = \frac{T_D}{T_S}\left(\frac{(TWL_{\max yearly} - MHW)\left(x_b - \frac{h_b}{tan\beta_f}\right)}{dhigh - MHW + h_b - (TWL_{\max yearly} - MHW)/2}\right) \quad \textbf{(10)}$$

where T_D is the storm duration, T_S is the erosion response time scale, x_b is the surf zone width from the MHW position determined using an equilibrium profile, h_b is the breaking-wave water depth relative to MHW, $tan\beta_f$ is the beach slope, and $dhigh$ is the crest of the dune. A constant equilibrium shape parameter described beach profile concavity, as shown in Mull and Ruggiero (2014). Calculating CC_{Event} for a particular storm required scaling the erosion response using a ratio of the erosion response time scale (T_S) to the storm duration (T_D). T_S is theoretically dependent upon the ability of sediment to withstand erosive wave forces and was calculated as a function of h_b and $dhigh$. A mean storm event duration (approximately 10 hours) was used for the entire study region.

3.3 Simulation of Population Growth and Development

While the allocation of people and development varied based upon policies articulated within policy scenarios, the mechanisms for that allocation remained constant across all alternative future scenarios. Within *Envision*, two autonomous processes were used to simulate socioeconomic change across the landscape within the study area of Tillamook County. The first was used to allocate population across the landscape and the second to allocate and assign value to new development.

An *Envision* submodel, *Target (Envision* Developer's Manual, 2015), was used to grow and limit population at the IDU level. Specific data required for this analysis included tax lot coverage, zoning data and maximum capacities for each zone type, census data, and information regarding growth rates. *Target* allocates population at some overall study wide growth rate onto the polygonal IDU landscape through the creation and examination of two surfaces: 1) a current population density surface, and 2) a population capacity surface. The population capacity surface represents build-out population density of the IDU based on zoning class. The allocation of growth involves an IDU-by-IDU evaluation of existing population and of the capacity for new population. New population is spatially allocated proportionally to the difference between the existing density and the capacity surface, resulting in the model moving the existing density surface towards the capacity surface. This function was modified by introducing weighted preference factors (e.g. a preference to locate near the coastline) into the allocations. These preference factors modify the differences between the existing density surface and capacity surface based on underlying IDU values, defined via a spatial query associated with the preference.

In lieu of IDU-level population data, initial IDU population density was estimated from the 2010 census at the block-group level. A single projection of population growth from the Oregon Office of Economic Analysis through 2050 was used across all policy scenarios. Subsequent to 2050, a constant population growth rate was used allocating a total of approximately 12,000 new residents into the county by 2100 (Oregon Office of Economic Analysis, 2013). Because no spatially explicit projections of population growth exist for the Tillamook County study area, urban growth areas and community growth areas were assumed to maintain a constant fraction of the county-wide population through 2100 while still allowing geographic preferences between policy scenarios (Figure 3.4),.

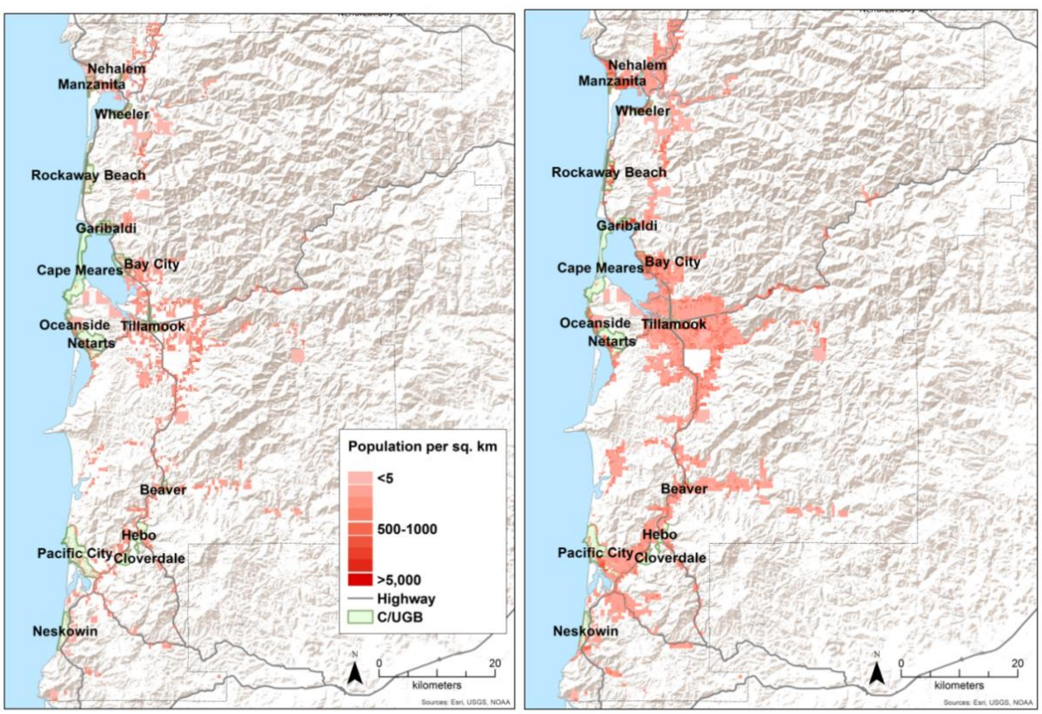

Figure 3.4: Tillamook County population in 2010 (left) and projected population under a *Status Quo* policy scenario (i.e. no change in current policies) in 2100 (right)

New development was allocated to the landscape based on the population growth rate in a separate *Envision* submodel, *Developer (Envision* Developer's Manual, 2015). The number of people per dwelling unit varied by town or city and also by distance from the coast. Many coastal dwellings are owned as non-primary homes; therefore the number of people per dwelling unit is much lower than the number of people per dwelling unit in areas further from the coast. For each pre-defined area, new population growth determines the number of new dwelling units required, and within each IDU, the dwelling unit capacity was based on the population density. At each time step, this capacity was used to generate a sorted list based on the greatest discrepancy between population density and number of existing dwelling units. Dwelling units were allocated until the entire new population for that time step was accommodated. Finally, a Hedonic pricing model (e.g. Bin et al., 2008) was used to determine the value of new development as follows

$$Assessed\ Value\ (\$) = f\begin{pmatrix}\text{lot size, distance to shoreline, presence of BPS, distance to major highway,}\\ \text{number of buildings, geographic location (within growth boundaries)}\end{pmatrix} \quad \textbf{(11)}$$

3.4 Development of Climate Impact Scenarios

Probabilistic TWL simulations combining variations of SLR, wave climate, and the probability of occurrence of major El Niño events from the year 2005 through 2099 accounted for uncertainty in climate projections and served as climate impact scenarios. First, projections from the *National Research Council's Sea Level Rise for the Coasts of California, Oregon, and Washington (2012)*, were used to define three SLR scenarios; low, medium, and high (Figure 3.5). Bounds on the SLR projections were specific to the Oregon and Washington, yet still maintained a high range of variability as they included a combination of regional steric and ocean dynamics, cryosphere and fingerprinting effects, and vertical land motion.

Next, projected changes in significant wave heights (SWHs) were based on wave height distributions developed from the variability of statistically and dynamically downscaled projected global climate model estimates for the Northeast Pacific Ocean (Hemer et al., 2013; Wang et al., 2014) . To account for the range in variability in the downscaled data, the wave climate was allowed to increase or decrease across the various SLR scenarios (Figure 3.5).

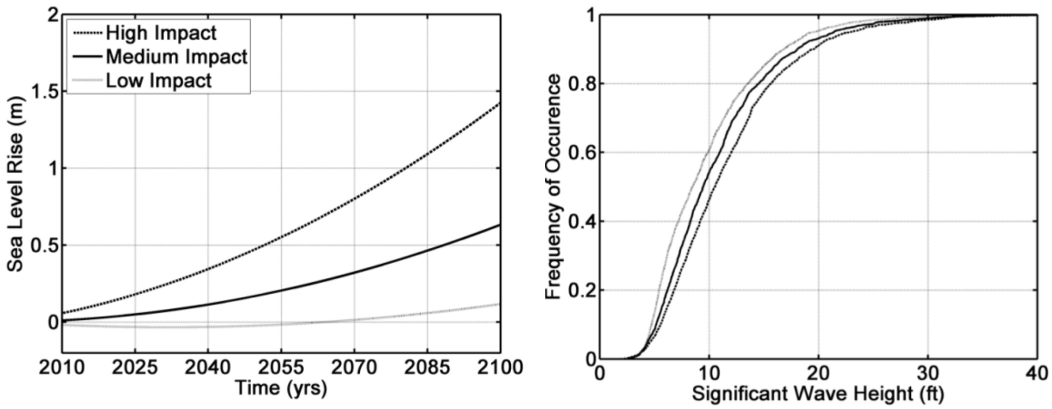

Figure 3.5: Three SLR (high, medium, and low) scenarios from NRC (left) and the shift in wave climate from early to late century (right). The solid line in the distribution figure (right figure) represents a "present-day" SWH distribution. The dotted line to the right of the solid line represents an increase to the present-day SWH distribution, while the dotted line to the left of the solid line represents a decrease in the present-day SWH distribution by 2100.

Finally, water levels and wave heights are also affected by major El Niño events, which have been associated with severe flooding and erosion events in the Pacific Northwest. Due to the uncertainty surrounding the changing occurrence of storms, the frequency of major ENSO events was allowed to vary continuously between half of present day frequency (~once per two decades) and double present day frequency. These combinations of three SLR scenarios, wave climate variability, and ENSO frequency projections were used to capture the inherent variability of the physical drivers. Thirty-three probabilistic TWL simulations for each high, medium, and low impact climate scenario, resulted in a total of 99 different climatic conditions.

3.5 Iterative Co-development of Policy Scenarios

The alternative futuring process allowed for feedback and learning opportunities at several levels. The first came through the utilization of the modeling framework, *Envision,* as described above. A second opportunity arose when the model design or results were used to interact with stakeholders. This interaction allows the researchers to gain information with respect to decision-making across the landscape. To accomplish the latter, a group of local stakeholders, including representatives from state legislature, community advisory committees, city managers and mayors, county commissioners, and property owners among others were consulted to identify possible policy scenario narratives to be represented within *Envision*. This participatory modeling approach fostered an environment of ownership and understanding amongst both researchers and the stakeholder community, and ensured that the scenarios modeled were representative of a broad range of management options.

3.5.1 Formation and Modeling of Individual Policies and Policy Scenarios

Policies were developed based on discussions with stakeholders and reflect several categories, including shoreline modifications and development restrictions. Each policy was modeled with as specific set of triggers, or assumptions. Some of these triggers were based upon historic evidence while others that lacked concrete examples in the Pacific Northwest were generated and validated through collaboration with the stakeholders or a literature review. For example, in determining when buildings must be relocated within or removed entirely from parcels in response to hazards, current policy language states that the building must require repairs equal to half of the value of the property (i.e. a significant repairs requirement). Because the current version of the coastal hazards submodel computes flooding as a binary state and cannot capture depths and velocities, the aforementioned threshold was impossible to capture. In this particular case, repetitive impact to buildings by coastal hazards provided a proxy for significant damage because the size of the study area precluded the use of more computationally expensive physics-based flooding and erosion models. Model sensitivity to individual triggers and policy outcomes is explored in Section 4.5.

Sets of individual policies made up a total of four initial policy scenario narratives in order for stakeholders to weigh tradeoffs and evaluate differences between scenarios (Table 3.2). Each policy scenario narrative dictated how humans managed the landscape, both in terms of how and where population growth and development were allocated, and how people and resources were protected from coastal hazards. A fifth policy scenario, *Hybrid*, was generated through a ranking process in which stakeholders voted for preferred policies and scenarios based on results from the four initial policy scenarios. Each of the five policy scenarios was crossed with a total of 99 climate impact scenarios, resulting in 495 alternatives futures through which landscape metrics were evaluated to assess potential effectiveness of management options.

Table 3.2: Five policy scenario narratives iteratively co-developed with local stakeholders

Policy Scenario Narrative	Policy
Status Quo: **Continuation of present day policies.**	• Determine urban/community growth boundaries (U/CGB) in accordance with present-day policy. • Maintain current BPS and allow more BPS to be built on eligible lots.
Hold the Line: **Policies are implemented that involve resisting environmental change in order to preserve existing infrastructure and human activities**	• Determine U/CGB in accordance with present-day policy. • Maintain current BPS and allow more BPS to be built on eligible lots. • Add beach nourishment for locations where beach access in front of BPS has been lost. • Construct new buildings or developments only on lots eligible for BPS construction • Construct new buildings above the Federal Emergency Management Agency's (FEMA) Base Flood Elevation (BFE) plus an additional 3ft and in the safest site of each respective lot.
ReAlign: **Policies are implemented that involve shifting development to suit the changing environment.**	• Determine U/CGB in accordance with the present-day policy but with prevention of new development within coastal hazard zones. • Prohibit construction of BPS on additional properties, regardless of Goal 18 eligibility, but maintain previously constructed BPS. • Construct new buildings above the FEMA BFE plus an additional 3ft and in the safest site of each respective lot. • Remove buildings impacted repetitively by coastal hazard from within the hazard zone and establish conservation easements. • Inventory lots located outside of the coastal hazard zones and re-zone to permit future higher density development within the U/CGB.
Laissez-Faire: **Current policies (state and county) are relaxed such that development trumps the protection of coastal resources, public rights, recreational use, beach access, and scenic views.**	•Permit increased proportion of development outside the U/CGB. •Eliminate BPS construction requirements.
Hybrid: **Policies are implemented in accordance with the preferences established by the Tillamook County stakeholders that involve shifting development to suit the changing environment.**	• Determine U/CGB in accordance with the present-day policy but with development restrictions within coastal hazard zones. • Prohibit construction of BPS on additional properties, regardless of Goal 18 eligibility, but maintain previously constructed BPS. • Construct new buildings above the FEMA BFE plus an additional 3ft and in the safest site of each respective lot. • Remove buildings impacted repetitively by coastal hazard from within the shoreline and establish conservation easements. • Inventory lots located outside of the coastal hazard zones and re-zone to permit future higher density development within the U/CGB. •Require movement of buildings frequently impacted by coastal hazards to a location above the FEMA BFE plus an additional 3ft and in the safest site of each respective lot. If the building was again impacted by coastal hazards, remove it from within the hazard zone and establish conservation easements.

4 Evaluating Alternative Futures with Respect to Landscape Metrics

Stakeholders and researchers established a set of metrics to allow the exploration of alternative futures within *Envision*. In general, the most important metrics were related to 1) growth and development, 2) exposure to coastal hazards and mitigation techniques, 3) public good. The following sections will explore example metrics in each of these categories as well as how individual communities were impacted by coastal hazards.

4.1 Metrics related to growth and development

Because many of the adaptation and land use management policies employed alter development patterns on the landscape, growth and development were compared across the five different scenarios.

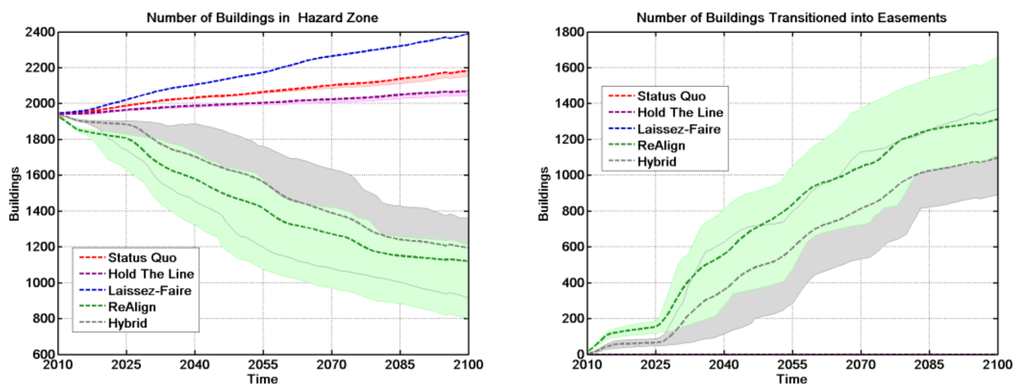

Figure 4.1: County-wide number of buildings located within the coastal hazard zone (left) and number of buildings relocated out of the coastal hazard zone through an easement process (right). Easements only occur under the ReAlign and Hybrid policy scenarios. Dashed lines indicate the mean of the medium impact climate scenarios. Shading indicates the range of the mean of the low and high impact climate scenarios.

Figure 4.1 illustrates relative trends involving development within the coastal hazard zone. None of the five policy scenarios allocated more than 500 additional buildings within the coastal hazard zone, with the *Laissez-Faire* policy scenario allocating the greatest number due to the relaxation of growth boundaries and increased likelihood of development closer to the shoreline. Because the projected county-wide growth rate was moderate (0.39%-0.78% per year), no growth boundaries were filled to capacity. In the *Hold the Line* policy scenario, new growth in the hazard zone was limited primarily by a policy which permits construction only on the safest site within a parcel and secondarily by a policy which permits development only on beachfront properties eligible to construct BPS. The bounds of climate variability (shaded areas within Figure 4.1) were largest for the policy scenarios (*ReAlign* and *Hybrid*) which remove buildings and population from the coastal hazard zone through an easement process. Up to 1,800 buildings were relocated to safer areas outside the hazard zone in the *ReAlign* policy scenario under the mean of all high impact probabilistic climate (TWL) scenarios (Figure 4.1, right). Approximately 500 fewer buildings are converted to easements in the mean low impact climate scenario. In the *Hybrid* policy scenario, in which buildings are first relocated to the safest site of the parcel and then removed from the hazard zone if hazard exposure persists, fewer properties were transitioned into easements than within the *ReAlign* policy scenario. These development patterns altered exposure to coastal hazards, as examined in the next section.

4.2 Metrics related to hazard exposure

Metrics related to hazard exposure provided insight regarding (1) when homeowners will need backshore protection structures (BPS) to protect their property, (2) how property will be impacted by coastal flooding and erosion hazards, and (3) how costs of protecting property change over time.

Figure 4.2: BPS constructed through time in a medium impact climate scenario under the *Status Quo* policy scenario in Rockaway Beach, Oregon. Rockaway Beach is located in the southern portion of the northernmost littoral cell.

Within the five policy scenarios, BPS and nourishment were the only two structural mechanisms (hard and soft) considered for the protection of backshore development. To protect property from erosion, most beachfront property owners would need to armor their properties prior to 2040 according to simulation results (Figure 4.2, map of Rockaway Beach).

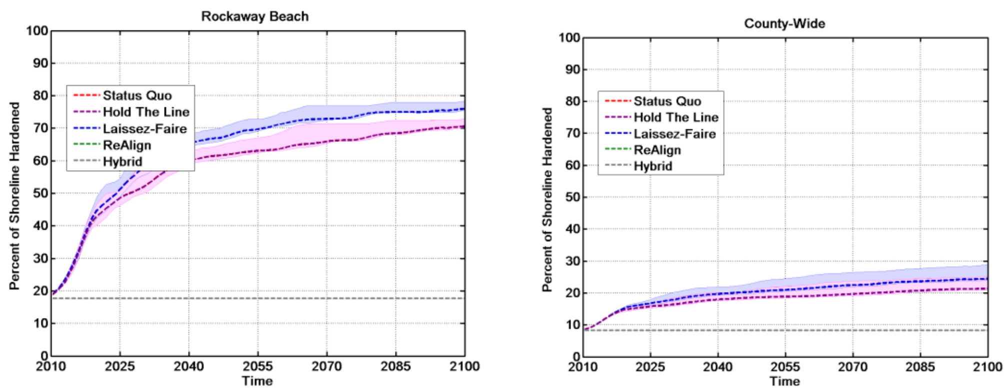

Figure 4.3: Percent of shoreline hardened through time in the Rockaway Beach littoral subcell (left) and in all of Tillamook County (right). Restrictions to BPS construction in *Hold the Line* and *Status Quo* are similar, so the extent of shoreline hardened in both of these policy scenarios is equal. Similarly, *ReAlign* and *Hybrid* policy scenarios allow no further armoring of the beach and thus overlap in the figure above. Dashed lines indicate the mean of the medium impact climate scenarios. Shading indicates the mean of the low and high impact climate scenarios.

More BPS were constructed in the *Laissez-Faire* policy scenario than in the other policy scenarios as restrictions related to BPS construction permitting were eliminated (Figure 4.3). In the *ReAlign* and *Hybrid* policy scenarios, further armoring of the shoreline was prevented, thus the percent of shoreline hardened was constant through time. In Rockaway Beach, a maximum of ~80% of the shoreline was hardened as the community was predominately developed by the end of the century (Figure 4.3, left). County-wide however, no policy scenario armored more than 30% of the entire shoreline as population along most of the coast was still relatively sparse by 2100 (Figure 4.3, right). Variability due to climate scenarios altered the extent of armored coastline by no more than 10%.

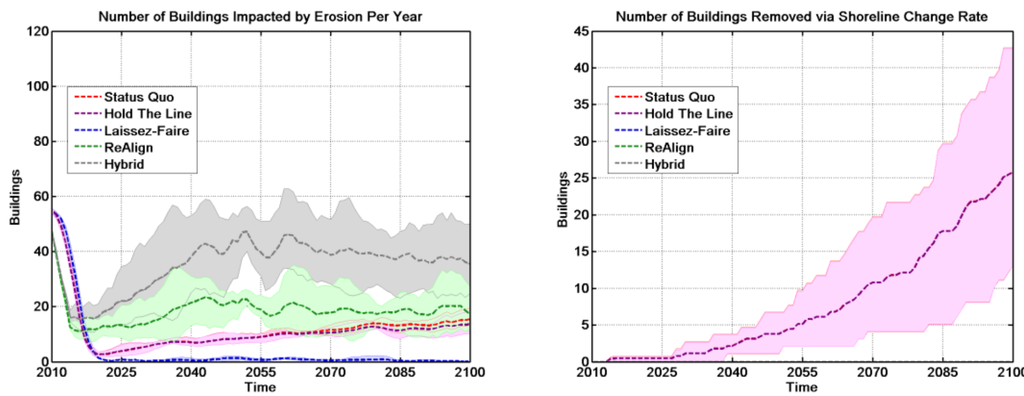

Figure 4.4: Average number of buildings impacted by event based erosion (left) and the cumulative number of buildings removed by long term shoreline change (right). Dashed lines indicate the mean of the medium impact climate scenarios. Shading indicates the mean of the low and high impact climate scenarios. Scenarios that appear in the legend but not in the figure remain at zero due to policy differences.

As a result of shoreline armoring, the number of properties exposed to event-based erosion through time was reduced in three of the five policy scenarios (Figure 4.4, left). The *Laissez-Faire* policy scenario resulted in the fewest number of buildings impacted by erosion (event-based or long term) as property owners constructed BPS regardless of current eligibility status. Variability in the number of buildings impacted by event based erosion was minimal between climate impact scenarios. The lack of BPS construction in the *ReAlign* and *Hybrid* policy scenarios resulted in greater impacts to buildings by erosion and greater variability with respect to climate scenarios. In addition to the buildings exposed to event based erosion, buildings were removed by the long term shoreline change rate (both sea level rise and sediment budget factors) once the toe of the dune moved landward of the building(Figure 4.4, right). Under policy scenarios in which BPS construction was permitted but limited based on current Oregon laws, up to 45 buildings were lost due to long-term shoreline change. Under the *ReAlign* and *Hybrid* policy scenarios, buildings were removed via easements and thus were not lost due to chronic erosion.

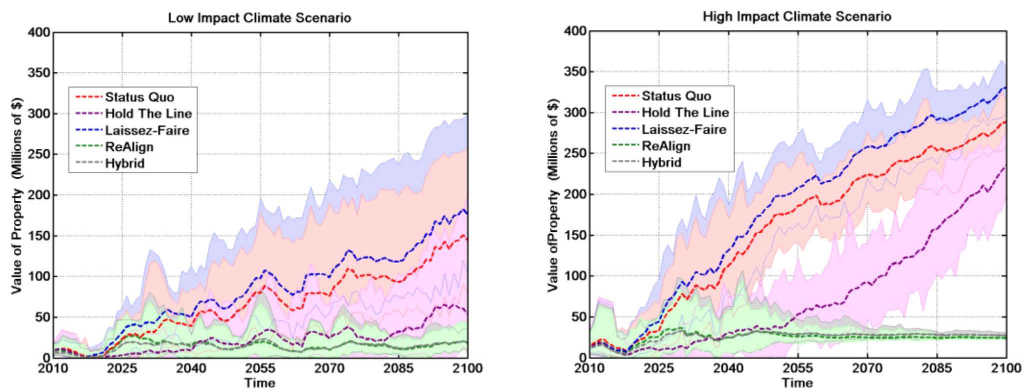

Figure 4.5: County-wide average assessed value of property impacted by flooding under a low impact climate scenario (left) and high impact climate scenario (right). The dashed line indicates the mean of the climate impact scenario. Shaded bounds indicated the minimum and maximum values.

The value of property impacted by flooding was assessed under both a low and high impact climate scenarios (Figure 4.5). Near the end of the century, there was greater variability in the low climate impact scenario than in the high impact scenario, although in general more property was impacted by flooding in the high impact climate scenario, and is more than doubled under the *Laissez-Faire* policy scenario. The decrease in variability within the high SLR scenario was due to the exceedance of a flooding threshold by approximately mid-century, after which the combined effects of SLR and geomorphologic change resulted in the frequent-to-persistent inundation of property within the coastal hazard zone. The increase of property impacted by flooding during the first half of the century was in response to the construction and maintenance of BPS. Because BPS prevented any landward migration of the dune, the long term erosion rate due to both sediment budget factors and to SLR causes the beach to narrow, thus increasing TWLs. While homeowners were able to build up BPS in response to rising TWLs, they were limited by the elevation of the property and the requirement to maintain the view shed. In addition, raising the elevation of the structure crest forces the extension of the structure horizontally, further narrowing the beach. Thus, the presence of BPS increased beach slope, often increasing vulnerability to coastal flooding. In this analysis, BPS were predominately unsuccessful at reducing flooding hazards within Tillamook County. The highest value of property impacted by flooding occurred under the *Laissez-Faire* policy scenario, both because BPS construction was permitted without restriction and because the rate of new development near the shoreline was elevated. In the *ReAlign* and *Hybrid* policy scenarios, fewer flooding impacts occurred by 2100 compared to the other policy scenarios due to both the relocation of people and development away from coastal hazard zones and the limitation of further BPS construction. Variability within these two policy scenarios (*ReAlign* and *Hybrid)* with respect to climate was also the smallest towards the end of the century because most of the population and buildings within the hazard zones are relocated through the formation of easements. The information above indicates that policies that move people and buildings away from coastal hazards are most successful in protecting property from flooding impacts whereas policies that permit the construction of BPS protect property from erosion impacts.

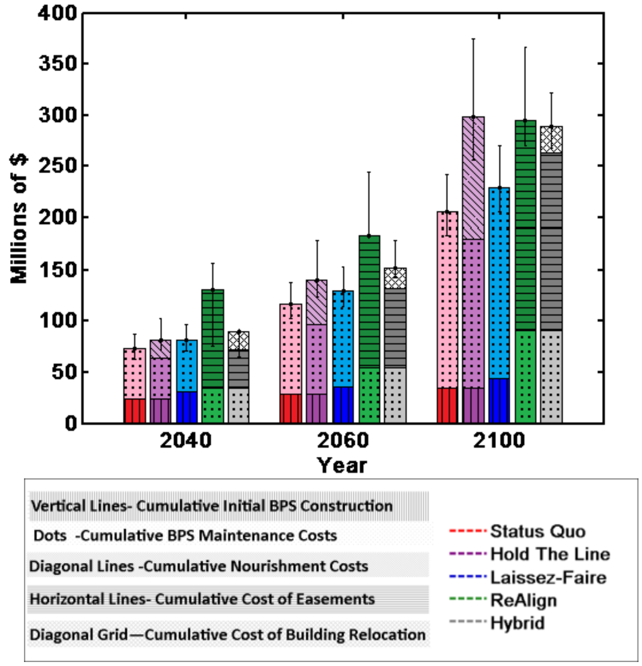

Figure 4.6 Cumulative costs associated with protecting coastal property across Tillamook County. Bars indicate the mean of the medium impact climate scenarios. Error bars indicate the mean total value under the low and high impact climate scenarios. Costs were based on ESA, 2012.

Comparing costs of policy scenarios over time allows for the evaluation of tradeoffs (Figure 4.6). BPS construction and maintenance costs in the *Status Quo* and *Hold the Line* policy scenarios were similar early in the century, but diverged towards the end of the century as nourishment offset some of the costs of raising BPS to account for higher TWLs. The greatest expenditures for both BPS construction and maintenance occurred under the *Laissez-Faire* policy scenario, costing ~$250 million between 2010 and 2100 (~$2.5 million per year). The *Hold the Line* and *ReAlign* policy scenarios were most expensive (~$300 million) as a result of nourishment and the creation of easements (under the assumption that the assessed value of the property was equal to the cost of easement creation), respectively.

4.3 Metrics Related to Public Good

Metrics related to public good include (1) the extent of shoreline that was accessible to recreation and (2) the length of road that was impacted by coastal hazards. Within the context of this project, beach accessibility was defined as the ability to walk the beach alongshore (evaluated at every 100 meters). Based on stakeholder input, particular sections of beach were considered inaccessible when the maximum daily TWL reached the toe of the dune or structure more than 10% of the year.

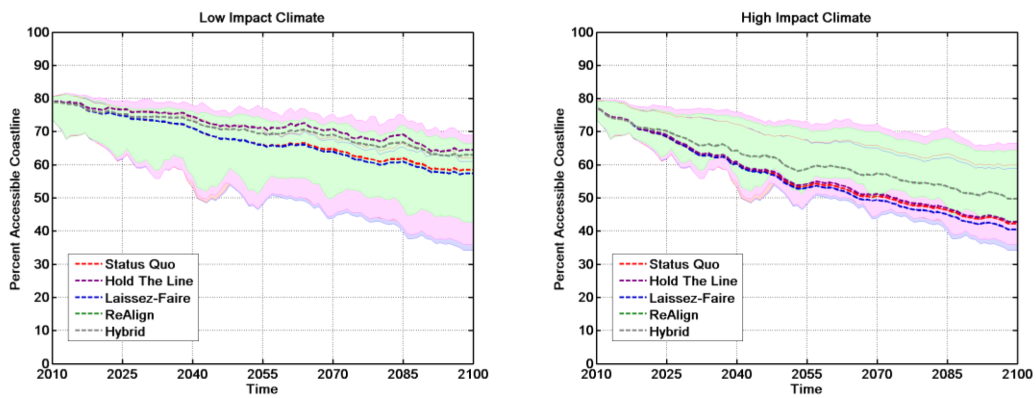

Figure 4.7: County-wide percent of the coastline accessible. Accessibility is defined as the ability to traverse the (dry) beach in the alongshore direction. The dashed line indicates the mean of the climate impact scenario. Shaded bounds indicated the minimum and maximum values.

By the end of the century, the combination of climate impacts and hardening of the shoreline significantly reduced beach accessibility (Figure 4.7). Accessibility was greatest under the *ReAlign*, *Hybrid*, and *Hold the Line* policy scenarios, and the most limited access occurred under the *Status Quo* and *Laissez-Faire* scenarios. Beach nourishment in the *Hold the Line* scenario did not maintain beach accessibility under all climate impact scenarios and was ineffective under the medium and high impact climate scenarios as the extension of BPS onto the beach in response to higher TWLs prevented the maintenance of accessibility. Under the *ReAlign* and *Hybrid* policy scenarios, the prevention of new BPS construction and relocation of impacted buildings preserves accessibility while under the *Status Quo* and *Laissez-Faire* policy scenarios BPS reduced accessibility by mid-century.

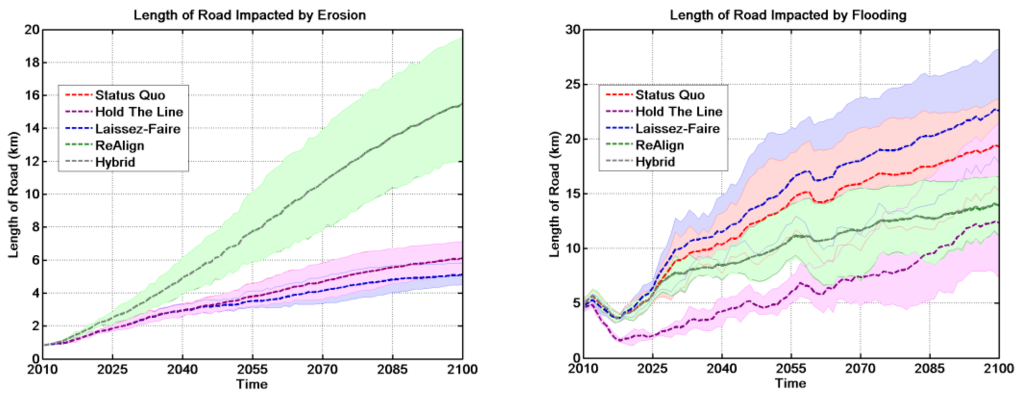

Figure 4.8: County-wide length of road (km) impacted by erosion (left) and flooding (right). Dashed lines indicate the mean of the medium impact climate scenarios. Shading indicates the mean of the low and high impact climate scenarios.

Because (1) no satisfactory methods for extending infrastructure networks in the future scenarios currently exist and (2) the projected population growth rate in Tillamook County is relatively low, current infrastructure was considered sufficient to accommodate the projected growth within this analysis. The length of road impacted by erosion was greatest in the *ReAlign* and *Hybrid* policy scenarios as a result of lack of new BPS construction (Figure 4.8, left). In contrast, the length of road impacted by flooding was greatest in the *Laissez-Faire* policy scenario as a result of increased total water levels due to beach narrowing caused by the presence of BPS (Figure 4.8, right). Overall, options that relocate people away from the shoreline or preserve current geomorphologic conditions through nourishment provide higher accessibility to beaches and roads through time.

4.4 Comparing Results by Community

Comparing metrics across individual communities can indicate whether policies are more or less effective within geographical regions. In some instances, policies that positively impact one region may negatively impact another. Similarly, differences between policy and climate scenarios may be more pronounced in some areas than in others.

Compared below are two communities within the Neskowin littoral cell located at the southern end of the study area (Figure 3.1), Neskowin and Pacific City, under a medium impact climate scenario. The Neskowin littoral cell has experienced shoreline progradation in the northern section (near Pacific City) and significant erosion in the southern part (near the village of Neskowin). Results indicated that the number of buildings potentially exposed to coastal change through time was not spatially consistent due both to management decisions climate change, and the location of the community within the littoral cell.

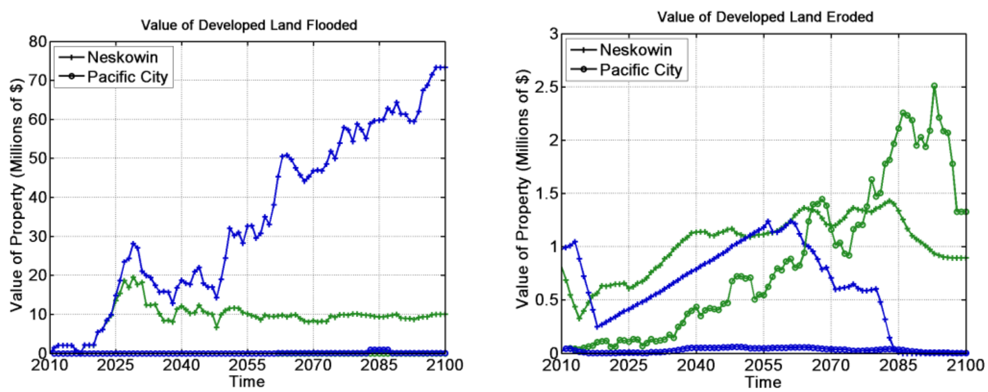

Figure 4.9: Value of property impacted by flooding (left), and value of property impacted by erosion (right) in the *Laissez-Faire* (blue) and *ReAlign* (green) policy scenarios under the mean medium impact climate scenario. Lines that do not appear on the graph remain near or equal to zero through the simulation period. Note that the vertical axes are not the same scale.

In the both the *Laissez-Faire* and *ReAlign* policy scenarios, Neskowin experienced tens of millions of dollars of impacts by flooding (Figure 4.9, left). In contrast, Pacific City saw only minimal impacts to property by flooding near the end of the century in the medium impact climate scenario. While Neskowin faced impacts by erosion early in the century, Pacific City surpassed these impacts in the final quarter of the century under the *ReAlign* policy scenario (Figure 4.9, right). However, in both communities, the value of property impacted by erosion was at least one order of magnitude less than the value of property impacted by flooding. This was due to (1) to the fact that most of the Neskowin community is already armored to prevent further erosion and (2) fewer buildings in Pacific City are within the hazard zone, and (3) the erosion rates in Pacific City are smaller both due to sediment budget factors and local morphology.

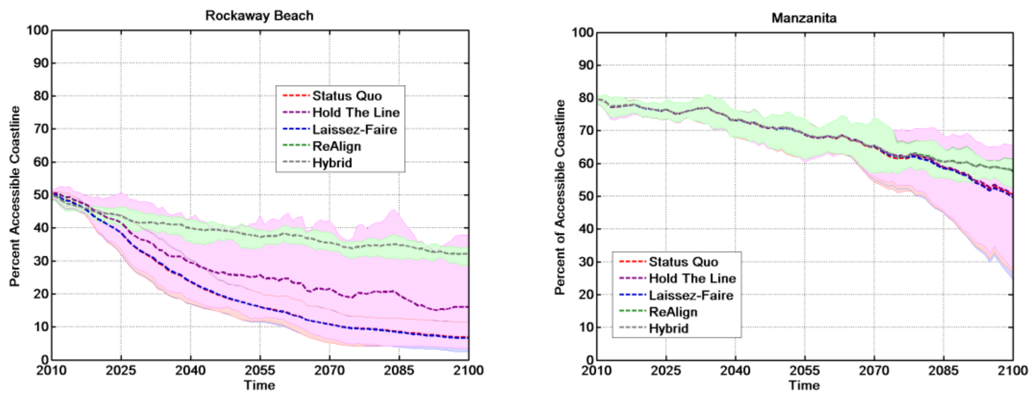

Figure 4.10: Percent accessible coastline in Rockaway Beach (left) and Manzanita (right).

At the northern end of the study area, within the Rockaway Beach littoral cell, the communities of Rockaway Beach and Manzanita (Figure 3.1) face comparable dissimilarities in impact timing and magnitude with respect to beach accessibility. Currently, the beach in Manzanita is more accessible than in Rockaway Beach; a trend that persists into the future under all climate scenarios (Figure 4.10).

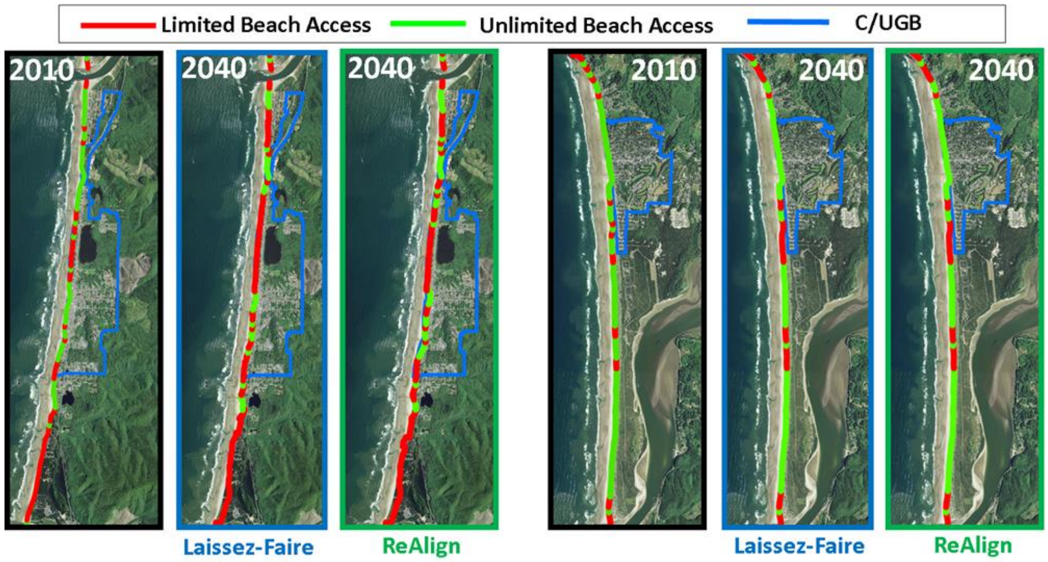

Figure 4.11: Beach accessibility in 2010 (black) and 2040 in the Laissez-Faire (blue) and ReAlign policy scenarios (green) in a medium impact climate scenario. The left three panels show Rockaway Beach. The right three panels show Manzanita.

The greatest difference between policy scenarios with respect to beach accessibility was under the *Laissez-Faire* and *ReAlign* policy scenarios, which permitted unlimited BPS construction and restricted all BPS construction, respectively (Figure 4.11). However, this difference was only visible within Rockaway after approximately 2035. This spatial heterogeneity was due to higher levels of erosion in the southern end of the littoral cell as well as a greater number of buildings with the coastal hazard zone in Rockaway Beach which necessitated armoring.

Overall, communities with higher levels of development near the shoreline were more sensitive to climate impacts. In addition, communities near the southern end of littoral cells saw higher exposure to coastal hazards due to morphological conditions (steeper beach slopes), higher long term erosion rates and the impacts of ENSO events, which temporarily alter incident wave directions. Questions specific to each of the three storylines described above are summarized below to illustrate major tradeoffs and findings (Table 4.1).

Table 4.1: Summary of results summarized by storyline.

Storyline	Question	Summary
Development	How do development patterns change over time?	• By 2100, the total population of Tillamook County increased by approximately 12,000 people across all policy and climate scenarios. However, the underlying population density patterns differ by policy scenario. • Under all policy scenarios, much of Tillamook County was still sparsely populated by 2100.
	How does the implementation of land use adaptation policies alter development?	• Land use adaptation policies shift population and buildings outside of hazard zones. • In the medium and high impact climate scenarios, a greater population and number of buildings were relocated outside of the hazard zone than in a low climate impact scenario.
Property Risk	How will property be impacted by coastal flooding and erosion hazards?	• Policies that move people and buildings away from coastal hazards were most successful in protecting property from flooding impacts whereas policies that permit the construction of protected property from erosion impacts. • Policy scenarios affected coastal hazards within individual communities at different temporal scales and in varying magnitudes.
	When will homeowners need BPS to protect their property?	• To protect property from erosion, the majority of beachfront property owners needed to armor their properties prior to 2040.
	How do the costs of protecting property change over time?	• Cost associated with protecting the assessed value of coastal property increased overtime in all of the policy scenarios.
Public Good	What extent of the beach is accessible?	• By mid-century, the combination of climate impacts and hardening of the shoreline significantly reduced beach accessibility. • Beach accessibility decreased under all policy scenarios by 2100, but less so in the *Hold the Line*, *ReAlign*, and *Hybrid* policy scenarios.
	What are the relative costs of keeping the beach accessible?	• The cost of converting beachfront property into easements was more than the cost of nourishing beaches across the county under all climate impact scenarios.
	How will roads be impacted by coastal hazards?	• Policies that added BPS significantly reduce the length of road impacted by erosion, but increase the length of road exposed to flooding.

4.5 Model sensitivity to parameters related to human decision making

To determine the usefulness of the model under uncertain policy parameterization, landscape metrics indicated above were used to evaluate model sensitivity to policy triggers discussed in Section 3.5.1. For each parameter used in the model, a minimum and maximum value was simulated in addition to the baseline under a medium impact climate scenario. Baseline values were determined predominately based upon conversations with stakeholders or using historic/current values. All population parameters were based on the current distribution of people across the Tillamook County landscape. Parameter minima and maxima were intended to capture the possible range of the parameter in order to address the uncertainty within many of the parameters in lieu of a full Monte-Carlo analysis. Presented in Table 4.2 are the underlying trigger and response variable ranges under the *Status Quo* and *Hybrid* policy scenarios.

Table 4.2: Range of policy parameters tested in the *Status Quo* and *Hybrid* policy scenarios.

Policy	Parameter	Parameter Range		
		Min	**Baseline**	**Max**
***Status Quo* Policy Scenario**				
Determine urban/community growth boundaries (U/CGB) in accordance with present-day policy.	Population Growth Rate	0.75 * Projection	(OOEA, 2013) Projection	1.5 * Projection
	Portion of Growth Added Within UGB	25%	47%	75%
	Portion of Growth Added Within 0.5 Miles of the Shoreline	5%	22%	50%
Maintain current BPS and allow more BPS to be built on eligible lots.	Averaging time (N)-BPS	1 yr.	5 yrs.	10 yrs.
	N- year average percent impact days per year (IDPY)	15%	40%	65%
	Erosion Frequency	1 yr./ 5 yrs.	3 yr. /5 yrs.	8 yr. / 10 yrs.
	Distance from SW edge of IDU to 2-yr avg. Event Based Erosion Extent	10 m	20 m	30 m
	BPS Permits Issued	3/yr.	6/yr.	10/yr.
	Height of BPS	10 yr. avg. max TWL	5 yr. avg. max TWL	Max 5 yr. max TWL
	Cost of BPS	$500/m/m	$1350/m/m	$2000/m/m
	Cost of BPS Maintenance (Yearly % of original cost)	0.50%	2%	10%
	Maintenance Frequency	2 yrs.	5 yrs.	10 yrs.
***Hybrid* Policy Scenario**				
Determine U/CGB in accordance with the present-day policy but with development restrictions within coastal hazard zones.	Hazard Zones (as created by the Department of Geology and Mineral Industries)	High Hazard Zone	Moderate Hazard Zone	Low Hazard Zone
Inventory lots located outside of the coastal hazard zones and re-zone to permit future higher density development within the U/CGB.	Zone Conversion	Low Density to High Density	Low Density to Med Density	Rural to Med Density
Require movement of buildings frequently impacted by coastal hazards to a location above the FEMA BFE plus an additional 3ft and in the safest site of each respective lot. If the building is again impacted by coastal hazards, remove it from within the hazard zone and establish conservation easements.	Frequency of Flooding	1 out of 5 yrs.	3 out of 5 yrs.	8 out of 10 yrs.
	Frequency of Erosion	1 out of 5 yrs.	3 out of 5 yrs.	8 out of 10 yrs.
Construct new buildings above the FEMA BFE plus an additional 3ft and in the safest site of each respective lot.	Cost to raise new building	$60/ sq. ft./ 10 ft. raise	$130/sq. ft./ 10 ft. raise	$200/sq. ft./ 10 ft. raise
Prohibit construction of BPS on additional properties, regardless of eligibility, but maintain previously constructed BPS.	Height of BPS (Maintenance only)	10 yr. avg. max TWL	5 yr. avg. max TWL	Max 5 yr. max TWL
	Cost of BPS Maintenance	0.50%	2.0%	10%
	Maintenance Frequency	2 yrs.	5 yrs.	10 yrs.

The model was considered to be sensitive to a policy or socioeconomic parameter if the value of a metric (i.e. buildings impacted by flooding) differed from the baseline policy scenario value by more than ~10% under a medium impact climate scenario.

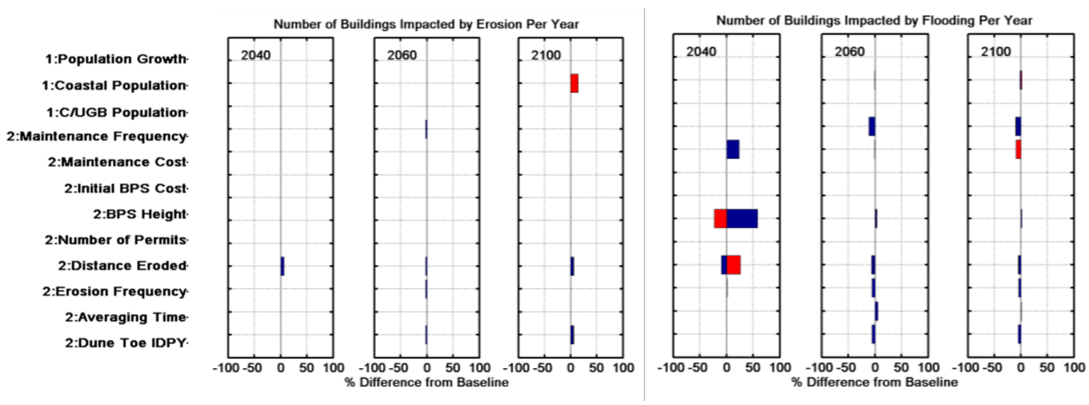

Figure 4.12: Example of sensitivity analysis for the Status Quo policy scenario. Decadally averaged number of buildings impacted by flooding (left) and erosion (right) per year in 2040, 2060, and 2100. Blue indicates the minimum parameter value and red indicates the maximum parameter value. The model was considered sensitive to the policy parameter if the metric was altered by more than 10%.

Of particular interest was how each of the policy parameters impacted exposure to erosion and flooding hazards under the *Status Quo* policy scenario (Figure 4.12). The only parameter to which the number of buildings impacted by erosion was sensitive to was development preference near the coastline (Figure 4.12, left). A larger growth rate near the coast increased the population at risk of erosion hazards. The lack of sensitivity in metrics related to erosion indicates that the triggers for policies related to BPS were fairly robust. Buildings impacted by flooding indicated higher sensitivity to policy parameters (Figure 4.12, right) For instance, both the frequency of maintenance and construction height of BPS impacted the exposure to flooding hazards at varying magnitudes throughout the century. Height of BPS construction was most important early in the century, when TWLs were lower on average due to the combined effects of SLR, wave climate, and geomorphology. During this period, the heights of new BPS or elevated BPS were more sensitive to whether the design was specified based on either the average yearly maximum TWL or the greatest of the recent yearly maximum TWLs. Furthermore, the sensitivity of the model to policy parameters was asymmetric. Raising one parameter may have no effect whereas lowering that same parameter may significantly impact a metric. This was true with the policy parameters related to allocation of growth.

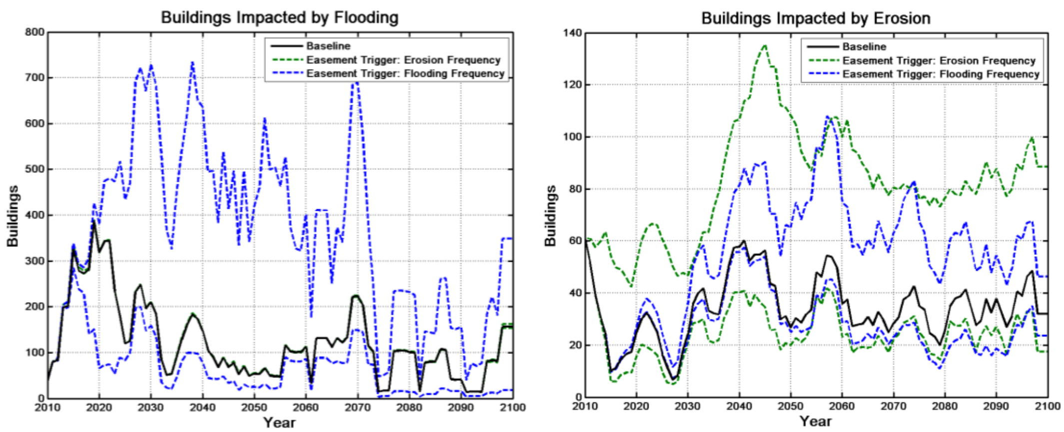

Figure 4.13: Sensitivity of the number of buildings impacted by flooding (left) and number of buildings impacted by erosion (right) to the frequency of flooding and erosion impacts under the *Hybrid* policy scenario and medium impact climate scenario. The dashed lines surrounding the baseline metric value indicate the range of the metric using the minimum and maximum estimate. In the figure on the left, the green line is hardly visible as the variability caused by that trigger is minimal.

Time series of buildings impacted by hazards were also used to evaluate sensitivity over time under the *Hybrid* policy scenario (Figure 4.13). Flooding metrics were only sensitive to the frequency of flooding required to first relocate the building to the safest location within the taxlot or parcel, and following further impacts by flooding in the new location, to relocate that building outside of the coastal hazard zone through an easement (Figure 4.13, left). Because the metrics shown in Figure 4.13 were so sensitive to the frequency of hazard exposure, the ability to model the force and depth of inundation events would be an improvement upon the current flooding model. Both flooding and erosion metrics were found to be sensitive to the frequency of flooding impacts required prior to relocation of buildings/conversion into easements. However, this sensitivity was again asymmetric, with greater sensitivity to raising the threshold for relocation and movement of population and buildings outside of the hazard zone.

In total, 16 policies were modeled using 25 different policy parameters, 11 of which were considered significant using the aforementioned threshold. In general, there were four categories of sensitive parameters (Table 4.3). In this application, the model is fairly insensitive to policies focused on restricting new development because the projected county growth rate in the county was slow.

Table 4.3: Four categories of sensitive model parameters

Policy Category	Parameter Category (Sensitive Parameters)
BPS	Extent of maximum event based erosion, height, frequency of maintenance, and cost
Nourishment	Amount, frequency, and cost
Easement/Relocation of Property to Safest Site	Frequency of exposure to flooding and erosion
Population Allocation	Proclivity to locate near coastline

The model sensitivity analysis indicates that improvement in coastal hazards modeling techniques could potentially refine and improve results. Because landscape metrics were sensitive to values used to parameterize policies, model results are estimates of landscape trajectories rather than projections of future values. However, consistent parameterization between policy scenarios allows for comparative analysis of management strategies under a range of climate scenarios.

4.6 Assumptions, Limitations and Constraints of this Analysis

A number of limitations and constraints were imposed during the data development and modeling phases of this project. These limitations are summarized below:

1. Only datasets that were available for the entire Tillamook County study area were employed in the analysis.
2. The same policy sets were applied in each community, no sub-regional differences in policies were considered.
3. Population growth was assumed to be the same in all policy scenarios, and was based on only county-wide estimates of population growth for each county provided by the Oregon Office of Economic Analysis.
4. No demographic shifts or corresponding shifts in choice behavior were considered throughout the analysis period.
5. There was no accounting for BPS failure (i.e. no erosion could take place once a BPS was constructed).
6. The model capturing yearly maximum inundation extent was binary (the polygon was either flooded or not) and did not account for forces upon structures.
7. Scarcity of resources (e.g. sediment required for beach nourishment) was not accounted for.
8. This project did not include the effects of estuarine flooding on the landscape.
9. While this work predominately explored traditional structural solutions to erosion hazards, future analysis will include scenarios with ecological engineering strategies such as planting of beach grasses along the dune for sediment entrapment.

5 Conclusions

Tillamook County, Oregon, like many coastal communities, is increasingly faced with the impacts of climate change, including sea level rise, shifts in wave heights, and changes in the frequency of El Niño events. This paper presents a methodology for comparing the effectiveness of policy decisions under a range of climate impact scenarios using the *Envision* modeling platform. Combined within *Envision* were three distinct submodels used to represent change processes in the underlying landscape, including a submodel which permits the probabilistic simulation of total water levels to capture flooding and erosion hazards. In addition, five policy scenarios were co-developed with local stakeholders to represent a range of plausible management strategies. Simulated future landscapes resulting from physical and human drivers were compared both on a county-wide scale and within individual communities using a set of metrics related to development, property risk, and public good. The alternative future scenarios explored here were intended as bounds within which researchers, stakeholders, and policy makers can build shared problem understandings, foster agreement around certain desirable and undesirable future outcomes, explore trade-offs, and analyze policy options under different future climates. For example, tradeoffs must be considered when utilizing rip-rap revetments to reduce the risk of erosion hazards. This analysis indicates that while these structures lessen the impacts of erosion, they may simultaneously reduce beach accessibility through the modification of beach morphology and coincident increase of total water levels and can substantially increase flooding hazards if the crest elevation of the structures is limited so as not to negatively impact the viewshed..

This work helps coastal resource managers consider climate adaptation and mitigation options by incorporating a greater understanding of the risks of sea level rise and other climate impacts under a range of management options. Methods outlined here to characterize the magnitude, uncertainty, and spatial variability of coastal flooding and erosin, as well as potential changes in property exposure to these hazards, provide insight on changes in vulnerability over time. While no alternative future presented in this analysis is presumed to forecast the future landscape in Tillamook County, the range of futures allows comparative analysis of management solutions in order to evaluate their effectiveness with respect to changing coastal climate and to facilitate a dialog surrounding adaptation and resilience in this hazard-prone region. Furthermore, this procedure can assist in the balancing of community development with long-term sustainability and resilience in a manner that is feasible, flexible, and transferable among many growing coastal communities.

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Simulating variability and uncertainty related to coastal hazards in Tillamook County, Oregon with respect to human decisions and climate change

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Abstract

Coastal communities throughout the U.S. Pacific Northwest face heightened risk due to sea level rise and changing storminess patterns resulting in coastal flooding and erosion hazards. Incorporating uncertainty with respect to both climate change and policy decisions is essential to project the evolving probability of coastal inundation and erosion, and the associated community vulnerability through time. *Envision*, a spatially explicit modelling platform that provides a scenario-based framework for examining interactions between human and natural systems across a landscape, was used to explore strategies that may reduce vulnerability to coastal hazards within the context of uncertainty and climate change. Probabilistic simulations of extreme total water levels were used to assess variability of sea level rise, wave climate, and the El Niño Southern Oscillation both as individual climate drivers and under a range of climate change scenarios through the end of the century. Additionally, human drivers, modeled as individual management decisions and within policy scenarios captured variability in human response. The relative contribution of variability and uncertainty from both climate change and policy decisions was quantified using three landscape metrics related to flooding, erosion, and beach accessibility. In general, human decisions introduced greater variability and uncertainty to the impacts to the landscape by coastal hazards than climate change uncertainty. Quantifying uncertainty within the *Envision* framework improves the usefulness of the model and can help determine the relative impact of policy and management decisions on the adaptive capacity of Pacific Northwest communities under a range of future climate scenarios.

1 Introduction

The inherent variability of dynamic coastal systems, combined with the pressure of coastal development, creates a high degree of uncertainty surrounding future coastal (IPCC, 2013; Neumann et al., 2015; Oliver-Smith, 2009). The formulation of policies in response to climate change poses challenges as it forces decision-making under unknown future conditions (Webster et al., 2003; Wilby and Dessai, 2010) . Policy-makers need ways to assess the possible consequences of a range of decisions to accommodate and protect increasing population along the coastline (Patt et al., 2005). Understanding how to cope explicitly with uncertainty in rates and magnitudes of climate change and human response as well as how propagated uncertainty may limit the ability to quantify outcomes at a range of geographic scales is important in the development of adaptive capacity within communities.

Analyses that couple physical landscape processes related to climate change with human behavior have been used extensively in both mitigation and adaptation studies (e.g. Murray et al., 2013; Le et al., 2010; McNamara and Keeler, 2013). Integrated scenario analysis can provide an important mechanism in the assessment of climate change and climate change policy, allowing analysts and stakeholders to explore complex and uncertain futures and address feedbacks between natural and human systems (e.g. Berkhout et al., 2013; Evans et al., 2013; Mokrech et al., 2012; Nicholls et al., 2008; van Vuuren et al., 2011). An important analytical challenge in combining climate scenarios and human adaptation scenarios is that they each deal with different forms of uncertainty. While climate scenarios are predominately used to address uncertainty in physical systems, socio-economic scenarios are concerned with uncertainties in economic, social, political, and cultural systems (Berkhout et al., 2013).

Within the past three decades, the coastal U.S. Pacific Northwest has seen a heightened risk of hazards as a result of sea-level rise (SLR), and increasing storm frequency and intensity (Ruggiero et al., 2010, Allan and Komar, 2006) . The underlying complexity of these phenomena complicates the prediction of future climate conditions at local scales (e.g., NRC, 2012; Sallenger et al., 2012; Yin et al., 2010). Predictions of SLR by the end of the century vary from approximately 0.1 to 1.5 meters along the Oregon coast and are dependent upon impacts of land deformation, atmospheric, and cryospheric variables (NRC, 2012). Furthermore, downscaled predictions of wave heights and the relative frequency and intensity of El Niño Southern Oscillation (ENSO) events are variable (Cai et al., 2014; Hemer et al., 2013; Wang et al., 2014). Thus, capturing coastal hazards in response to fundamental uncertainty within each of these three climate drivers (SLR, wave heights, and ENSO frequency) and how that uncertainty may be exacerbated by their concurrence is critical in designing response and adaptation strategies.

In addition to quantifying variability with respect to climate, informed climate adaptation also requires estimates of the uncertainty in consequences for a range of possible human actions (Patt et al., 2005; Webster et al., 2003). Responses to coastal hazards vary depending upon local social, political, and physical climate (Adger et al., 2009; Karvetski et al., 2011; Kelly and Adger, 2000; Moser et al., 2012). In Tillamook County, Oregon, where approximately one quarter of all permanent residents live within a half mile of the Pacific Ocean, several communities already experience issues related to limited beach accessibility, flooding, and erosion (Ruggiero et al., 2013). To protect new and existing development, communities in coastal areas similar to Tillamook County protect infrastructure through either structural engineering solutions (e.g. rip-rap revetments, sea walls) or through land use changes (e.g.

options related to zoning, urban and infrastructure development, and regulations; Klein et al., 2001) .

This paper evaluates uncertainty within the context of coastal hazards through alternative futures analysis combining climate change and human decision-making within Tillamook County. *Envision* (Bolte et al., 2007), a spatially explicit, policy-centric modeling framework, was used to examine interactions between human and natural systems across this coastal system. First, uncertainty was addressed in the form of individual climate drivers (i.e. wave height, sea level rise) and management drivers (i.e. development restrictions, construction of backshore protection structures (BPS)). Second, uncertainty was examined within the context of alternative future scenarios capturing both climate and management alternatives. Probabilistic simulations of total water levels along the shoreline captured the variability of sea level rise, wave climate, and ENSO events under a range of climate change scenarios through the end of the twenty first century, and a set of policy scenarios related to management decisions and socioeconomic trends were developed and used to explore variations in the human system. Through a range of landscape metrics related to coastal hazards exposure and public good, the methodology outlined here answers two questions: 1) which drivers (human or physical) deviate the most from baseline conditions? and 2) how does driver uncertainty vary through time in response to these drivers with respect to landscape metrics?

2 Methods

Presented below is the framework through which climate change, socioeconomic change, policy choices, and coastal hazards were simulated as well as the methods for deriving climate and decision making variability and uncertainty within that framework.

2.1 Alternative futuring through coupled human and natural systems modeling

Envision (Bolte et al., 2007) is a spatially explicit, multi-agent based modeling platform which couples biogeophysical models with socioeconomic drivers and management strategies to explore landscape change trajectories. This integrative modeling approach allows scientists and managers to explore outcomes and tradeoffs that result when decision-making entities and their policies are included as part of evolving landscapes. Envision enables spatial-temporal simulation of landscape change through the synchronization of multiple sub-models which are described below in the context of modeling coastal hazards in Tillamook County.

2.1.1 Simulating hazards using total water levels (TWL)

Within *Envision*, event-based coastal flooding and erosion were simulated based upon the maximum yearly storm event within a single submodel. Coastal flooding and erosion hazards are related to depth, wave height, frequency, and duration of inundation as well as the elevation of relevant backshore features (e.g., dune crest). Total water levels (TWLs) have frequently been used to derive coastal hazards along the outer coast (e.g. Stockdon et al., 2007, Allan and Komar, 2002;, Ruggiero, 2013). TWLs are calculated as a linear superposition of the tide, non-tidal residual, and runup associated with wave height (Ruggiero et al., 2001, Allan and Komar, 2006; Ruggiero, 2013) as follows:

$$TWL = MSL + \eta_A + \eta_{NTR} + R_{2\%} \quad (1)$$

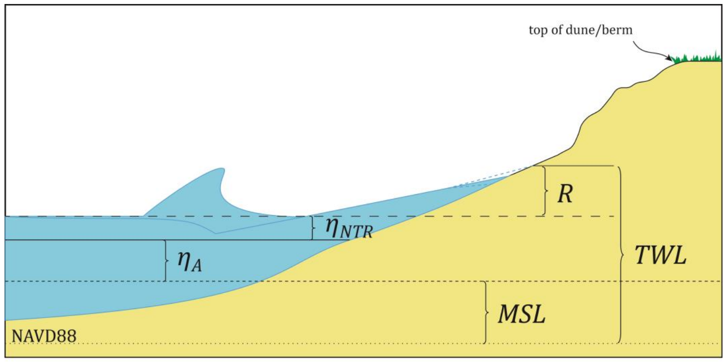

Figure 2.1: Diagram of TWL components (Serafin and Ruggiero, 2014)

where MSL is the mean sea level, η_A is the deterministic astronomical tide, η_{NTR} is the nontidal residual generated by physical processes including wind setup and barometric surge, and R is the maximum vertical extent of wave runup on a beach or structure above the still water level (Sorensen, 1997). The Total Water Level Full Simulation Model (TWL-FSM, Serafin and Ruggiero, 2014)), was used to generate probabilistic time series of daily maximum wave height, wave period, wave direction, MSL, η_A and η_{NTR}, capturing variability and non-stationarity in these parameters between 2010 and 2100. The vertical component of wave runup was calculated using the two percent exceedance rate, $R_{2\%}$. An empirical relationship by Stockdon et al. (2006) was used to compute runup on sandy, dune backed beaches, whereas runup on backshore protective structures (BPS), bluffs, cliffs, and cobble berms was calculated based upon the TAW (Technical Advisory Committee for Water Retaining Structures) method, which provides a mechanism for adjusting the runup value based on parameters of the backshore feature (e.g. roughness and porosity; NHC, 2005; Pullen et al., 2007;Van der Meer, 2002).

Flooding and erosion hazards were assessed at 100 m alongshore resolution for the maximum yearly TWL event. Where the maximum yearly TWL exceeds the height of a backshore feature (i.e. dune, BPS), the extent of inundation was computed using a simple bathtub model (e.g. Schmid et al., 2014) . In addition to flooding, three mechanisms of coastal change were combined to evaluate cross-shore coastal retreat (after Baron et al., 2014):

$$\text{Coastal Erosion} = (CCR_{SB} + CCR_{Climate}) * \mathrm{T} + CC_{Event} \quad (2)$$

where CCR_{SB} is the long-term (interannual to decadal scale) coastal change rate (Ruggiero et al., 2013), $CCR_{climate}$ is the coastal change rate associated with climate change-induced factors, T is time in years, and CC_{Event} is the event-based erosion based on the maximum yearly TWL. To capture event-based erosion, a modification of the foredune erosion model presented by Kriebel and Dean (1993) was implemented (Mull and Ruggiero, 2014) which assumes that the volume of sediment eroded from the foredune during a storm is deposited in the nearshore as the equilibrium profile shifts. This event based erosion estimate is given as:

$$CC_{Event} = \frac{T_D}{T_S}\left(\frac{(TWL_{\max yearly} - MHW)\left(x_b - \frac{h_b}{tan\beta_f}\right)}{dhigh - MHW + h_b - (TWL_{\max yearly} - MHW)/2}\right) \quad (3)$$

where T_D is the storm duration, $T_S$is the erosion response time scale, x_b is the surf zone width from the MHW position determined using an equilibrium profile, h_b is the breaking-wave water depth relative to MHW, $tan\beta_f$ is the beach slope, and $dhigh$ is the crest of the dune..

Within the coastal hazards submodel, erosion was restricted to dune-backed beaches and neither the potential failure of backshore protection structures (BPS) nor bluff/cliff erosion was accounted for. On beaches backed by protective structures, the beach was assumed to narrow at the rate of the total local chronic erosion, resulting in dynamic beach slopes through the simulation period. Modeled beaches were further narrowed in the process of maintaining (i.e. raising to accommodate higher TWLs) and constructing BPS structures at a

2:1 slope. On dune-backed beaches, beach slope was static as the dune erodes landward and equilibrium is reached.

2.1.2 Simulating growth and development processes

In addition to modeling physical landscape processes, human population growth and associated development processes were simulated using two submodels. The first submodel, *Target (Envision* Developers Manual, 2015), was used to grow and allocate population based upon a growth rate and a build out capacity. The build out capacity was generated prior to model simulation using zoning class and existing population distribution patterns. New population was spatially allocated proportionally to the difference between the existing density and the capacity surface, biased with preference factors reflecting circa 2010 population patterns (i.e. a preference to locate near the coastline or within a growth boundary). New development was allocated to the landscape based on population growth and the number of people per building in a separate *Envision* submodel, *Developer (Envision* Developers Manual, 2015).

2.2 Evaluation of climate change and human decision making uncertainty

Variability and uncertainty with respect to both climate change and human decision making were expressed through policy and climate drivers. The derivation of those drivers and their use within the context of scenarios is described below.

2.2.1 Capturing climate uncertainty through probabilistic simulation of TWLs

The impact of climate change was analyzed through the perturbation of six individual climate drivers. In each simulation of an individual climate driver, current landscape conditions were maintained with no application of policies and the allocation of population onto the landscape was unrestricted by growth boundaries. Landscape metric uncertainty and variability was measured through thirty probabilistic simulations of the period of 2010-2099 with variations of SLR, wave climate, and the probability of occurrence of major El Niño events (Table 2.1).

Table 2.1: Range of SLR, wave height, and ENSO frequency implemented in the analysis of individual climate drivers

Climate Driver	Baseline Value	Low Estimate	High Estimate
Sea Level Rise	N/A	0.1 m	1.4 m
Wave Height	Historic	-0.4 cm	+0.4 cm
ENSO Frequency	Historic	0.5	2

Projections accounting for regional steric and ocean dynamics, cryosphere and fingerprinting effects and vertical land motion from the *National Research Council's Sea Level Rise for the Coasts of California, Oregon, and Washington (2012)* were used to bound SLR projections. Significant wave heights (SWHs) , were based on wave height distributions developed from the variability of statistically and dynamically downscaled projected global climate model estimates for the Northeast Pacific Ocean (Hemer et al., 2013; Wang et al., 2014) . Finally, the frequency of El Niño events was varied between half of present and double present frequency. Thirty time series of historic, or baseline, climatic conditions were also simulated as a reference case.

2.2.2 Capturing human decision making uncertainty through policy options

Using *Envision'*s policy representation framework, human decision making was represented across the landscape through an array of policies reflecting land management alternatives. The suite of six policies was developed in collaboration with a group of local stakeholders that characterize reasonable actions that might be taken to build community adaptive capacity to climate change (Table 2.2).

Table 2.2: Policies implemented in the analysis of individual management drivers.

Policy	Abbreviation	Description
1	BPS	Maintain current BPS and allow more BPS to be built on eligible lots.
2	Nourishment	Add beach nourishment for locations where beach access in front of BPS has been lost.
3	Easements	Remove buildings impacted repetitively by coastal hazard from within the hazard zone and establish conservation easements.
4	Relocate	Require movement of buildings frequently impacted by coastal hazards to a location above the FEMA BFE plus an additional 3ft and in the safest site of each respective lot.
5	Safest-Site	Construct new buildings above the Federal Emergency Management Agency's (FEMA) Base Flood Elevation (BFE) plus an additional 3ft and in the safest site of each 6respective lot.
6	Hazard Zone	Determine Urban/Community Growth Boundaries (U/CGB) in accordance with the present-day policy but with prevention of new development within coastal hazard zones.

Each policy was implemented individually under the thirty baseline climate simulations so that only changes resulting from that particular management decision were reflected in the results.

2.2.3 Capturing uncertainty within the context of scenarios

In addition to simulating individual drivers across the landscape, climate and policy scenarios were used to evaluate and examine uncertainty and variability derived from physical and human drivers. Scenarios allow for observation of feedbacks that may or may not be visible when simulating only individual drivers. Bounds on significant wave height and El Niño frequency were equal to those used during the simulation of individual drivers (i.e. frequency of ENSO varied between half and double the historic frequency, see Table 3.1). However, within scenarios, these two parameters were allowed to vary continuously. Combinations of three SLR scenarios, wave climate variability (Figure 2.2a), and ENSO frequency projections were used to capture the inherent variability of the physical drivers through a total of 33 probabilistic TWL simulations for each high, medium, and low impact climate scenario (Figure 2.2b).

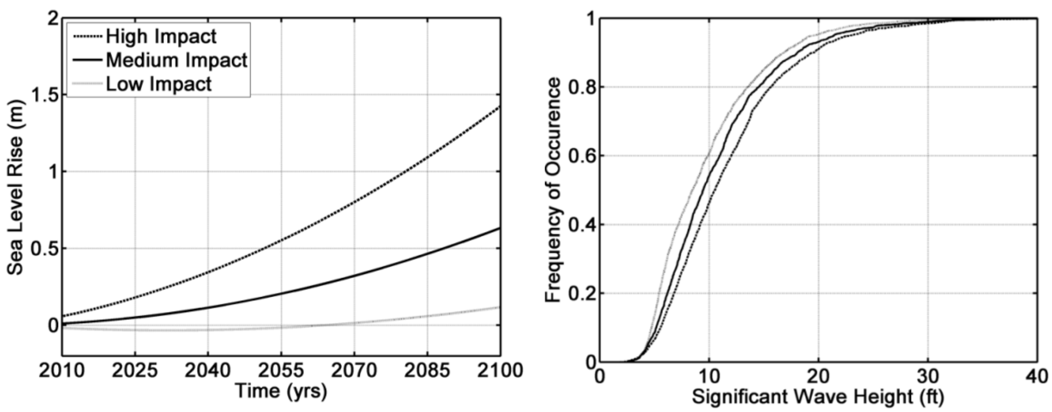

Figure 2.2: Three SLR (high, medium, and low) scenarios from NRC (left) and the shift in wave climate from early to late century (right). The solid line in the distribution figures represents a "present-day" SWH distribution. The dotted line to the right of the solid line represents an increase to the present-day SWH distribution, while the dotted line to the left of the solid line represents a decrease in the present-day SWH distribution by 2100.

In addition to climate scenarios, sets of individual policies were used to create four distinct policy scenario narratives (Table 2.3). In most cases, general policies were developed with variations specific to each policy scenario narrative. Each policy scenario was simulated across all 33 climate scenarios.

Table 2.3: Four policy scenario narratives iteratively co-developed with local stakeholders. Each policy scenario contains a unique grouping of individual policies similar to those listed in the previous section.

Policy Scenario	Narrative
Status Quo	Continuation of present day policies.

Hold the Line	Policies or decisions were implemented that involve *resisting* environmental change in order to preserve existing infrastructure and human activities
ReAlign	Policies or decisions were implemented that involve *shifting development* to suit the changing environment.
Laissez-Faire	Current policies (state and county) were *relaxed* such that existing buildings, infrastructure and new development all trump the protection of coastal resources, public rights, recreational use, beach access, scenic views.

3 Landscape metric variation in response to climate and policy uncertainty

Variation from baseline conditions and between scenarios as well uncertainty resulting from each of the climate and human drivers was measured with respect to landscape metrics related to coastal hazards and public good. In addition to directly comparing the metric value under baseline and driver conditions, the percent difference from the baseline value was calculated for decadal average between 2030-2040, 2060-2070 and 2090-2100.

3.1 How do physical and human drivers alter the landscape through time?

The variability with respect to landscape metrics was quantified for each of the six policies under a baseline scenario with no changes to ENSO frequency, wave climate, sea level, or management of the landscape. For the purposes of this paper, variability with respect to individual climate and human drivers is defined as the difference in the landscape metric resulting from the perturbation of the human or climate driver. First, the metric through time is shown under both the mean baseline and perturbed climate driver.

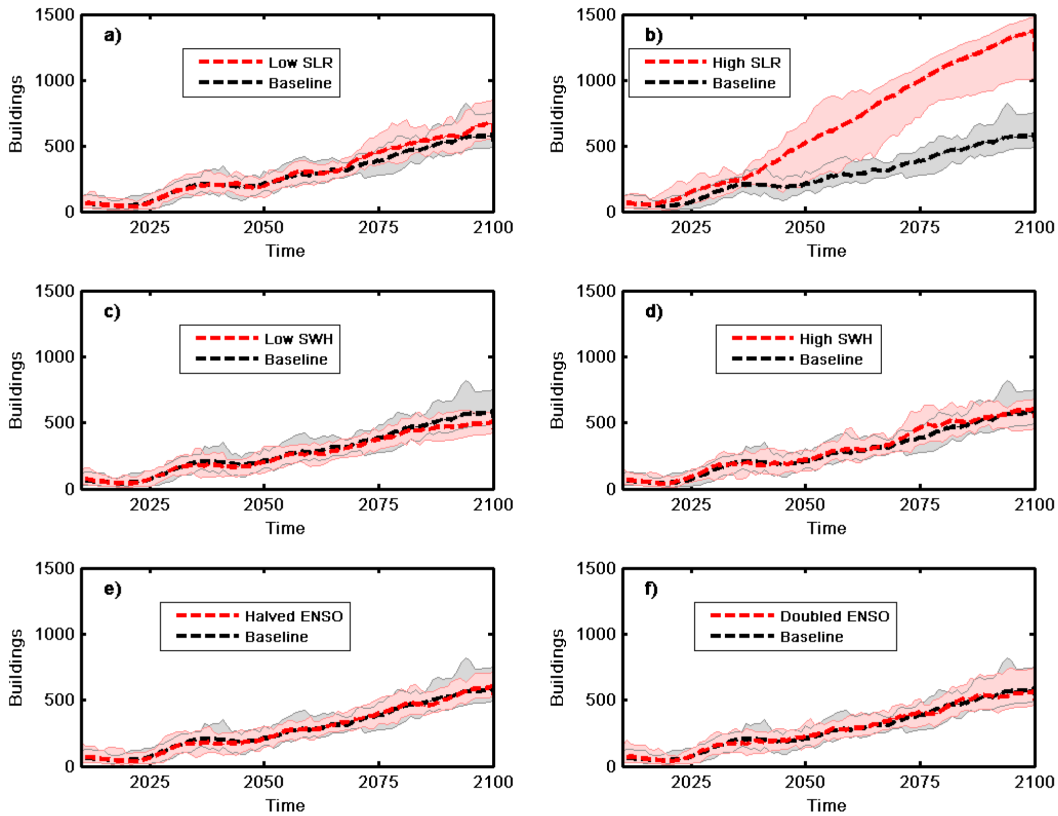

Figure 3.1: Number of buildings impacted by flooding through time under each of the six climate drivers compared to the baseline. Dashed lines indicate the decadal mean of all simulations. Bounds represent the minimum and maximum decadal means.

High SLR was the most influential of the physical drivers in terms of impacts to buildings by flooding (Figure 3.1b). While the frequency of ENSO events did not shift metric values from the baseline (Figure 3.1e, f), significant wave height did influence flooding (Figure 3.1c, d), particularly in the latter half of the century. Under even a baseline scenario there was an increase in the average number of buildings impacted through time.

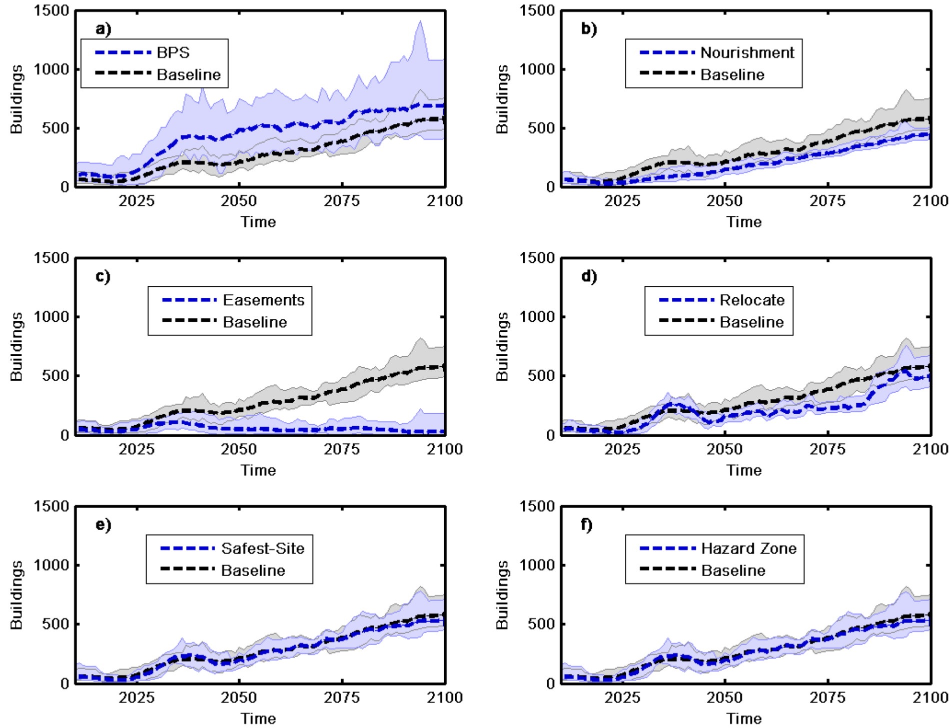

Figure 3.2: Number of buildings impacted by flooding through time under each of the six human drivers compared to the baseline. Dashed lines indicate the decadal mean of all simulations. Bounds represent the minimum and maximum decadal means.

The number of buildings impacted by flooding indicated more variation from the baseline with respect to policy drivers (Figure 3.2). In particular, this metric was sensitive to the construction of BPS, the nourishment of beaches fronting BPS, the formation of easements, and the relocation of buildings to safer areas within a parcel (Figure 3.2a-d). While BPS protected property from erosion, those protected properties ultimately experienced greater levels of flooding due to the modification of local morphology. Because BPS prevents landward migration of the dune, the long term erosion rate due to sediment budget factors caused the beach to narrow, thus increasing TWLs. BPS were maintained through time to prevent overtopping; however, the height of BPS was limited to preserve current view sheds. Additionally, raising the elevation of the structure crest forced the extension of the structure horizontally, further narrowing the beach, which resulted in increased vulnerability to coastal flooding. The addition of sediment onto the beach through the process of beach nourishment reduced flooding impacts through the widening of the beach and subsequent reduction in TWLs (Figure 3.2b). Simulated easements effectively move buildings outside of the hazard zone, whereas relocating buildings within the existing parcel was only partially effective (Figure 3.2c, d). Model results indicated that restrictions on new development (i.e. hazard zone implementation and the requirement to construct new homes only in the safest site of a parcel) reduce impacts minimally by the end of the century due to the low projected growth rate within the county (Figure 3.2e, f). Higher levels of deviation from the baseline would be expected if greater population, and thus more development, was projected for the region in the future.

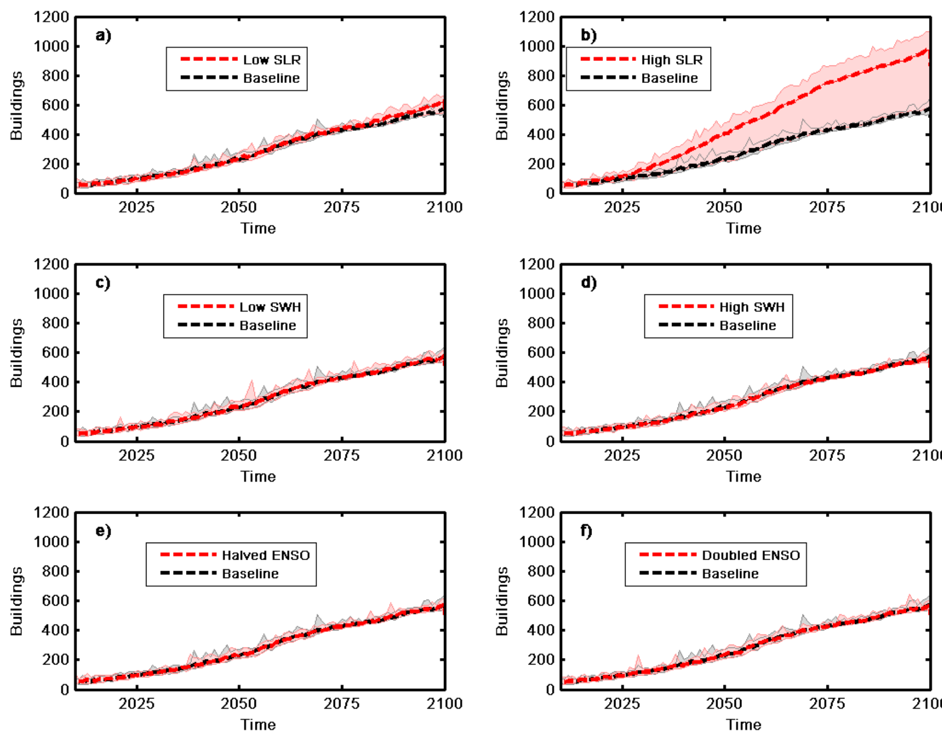

Figure 3.3: Number of buildings impacted by erosion through time under each of the six climate drivers compared to the baseline. Dashed lines indicate the decadal mean of all simulations. Bounds represent the minimum and maximum decadal means.

The number of buildings impacted by erosion only deviated from the baseline under the two heightened SLR simulations (Figure 3.3). The rising trend under all simulations was a result of buildings impacted by (1) the background shoreline change rate related to sediment budget factors, which is applicable under all climate drivers, (2) the shoreline retreat due to SLR, and/or (3) increased erosion during storm events. During the past three decades, over 65% of the Tillamook County coast has been erosional with approximately 40% of the coast eroding at rates exceeding one meter per year (Ruggiero, et al., 2012). Thus, near the end of the century, the model indicates almost 600 structures would be impacted by the greatest yearly storm event under the baseline climate scenario. The introduction of a sediment budget factor into the model based upon historical trends reduces the variability with respect to climate in the number of buildings impacted by erosion. This long term signal may obstruct potential sensitivity to both ENSO frequency and shifts in SWH.

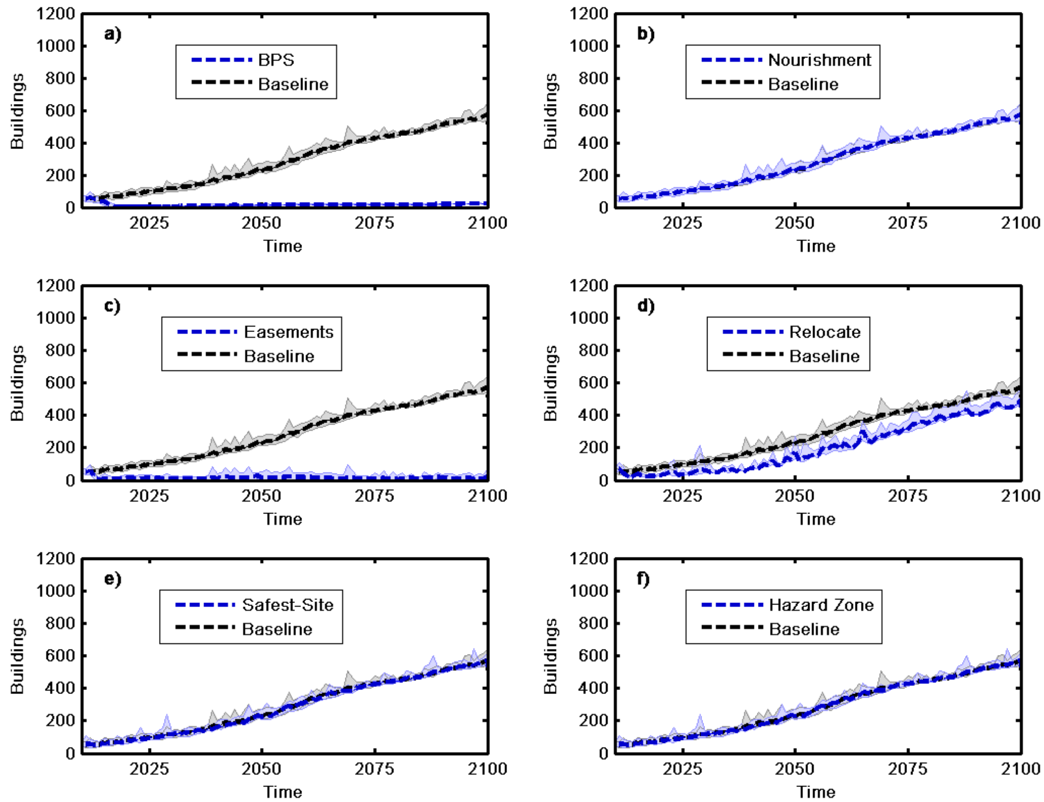

Figure 3.4 Number of buildings impacted by erosion through time under each of the six human drivers compared to the baseline. Dashed lines indicate the decadal mean of all simulations. Bounds represent the minimum and maximum decadal means.

Three modeled policy drivers had an impact on the number of buildings impacted by erosion; the construction of BPS, the formation of easements in response to hazard exposure, and the relocation of buildings to the safest site within a parcel (Figure 3.4). Both the creation of easements and the construction of new BPS essentially eliminated exposure to hazards (Figure 3.4a,c) whereas the relocation of buildings only reduced the exposure by approximately 200 buildings by the end of the century (Figure 3.4d).

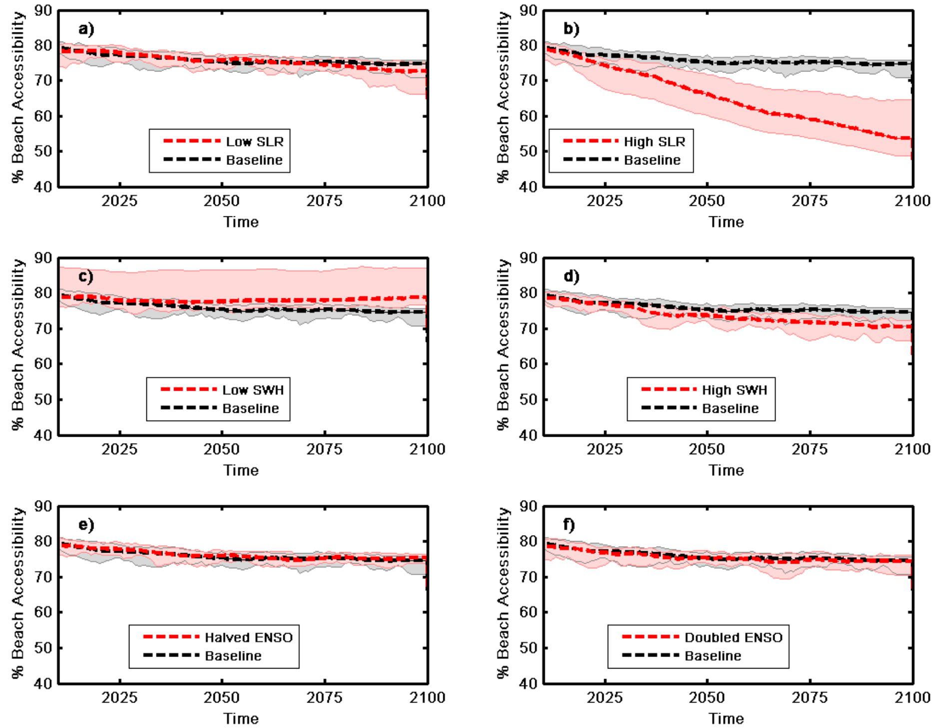

Figure 3.5: Beach accessibility through time under each of the climate drivers. Dashed lines indicate the decadal mean of all simulations. Bounds represent the minimum and maximum decadal means.

The third metric, beach accessibility, defined here as the ability to walk the beach at least 90% of the time during the maximum daily TWL, was also impacted by both SLR and wave climate (Figure 3.5). High SLR alone decreased beach accessibility from approximately 80% to less than 60% (Figure 3.5b). Should Tillamook county experience lower significant wave heights into the future, results indicate that accessibility may be increased by up to 10% compared to the baseline (Figure 3.5c). Raising wave heights by the same margin had less of an impact, decreasing accessibility by less than 5% (Figure 3.5d). As with the two metrics related to coastal hazard exposure, variability in ENSO frequency produced only minimal variations from the baseline (Figure 3.5e, f).

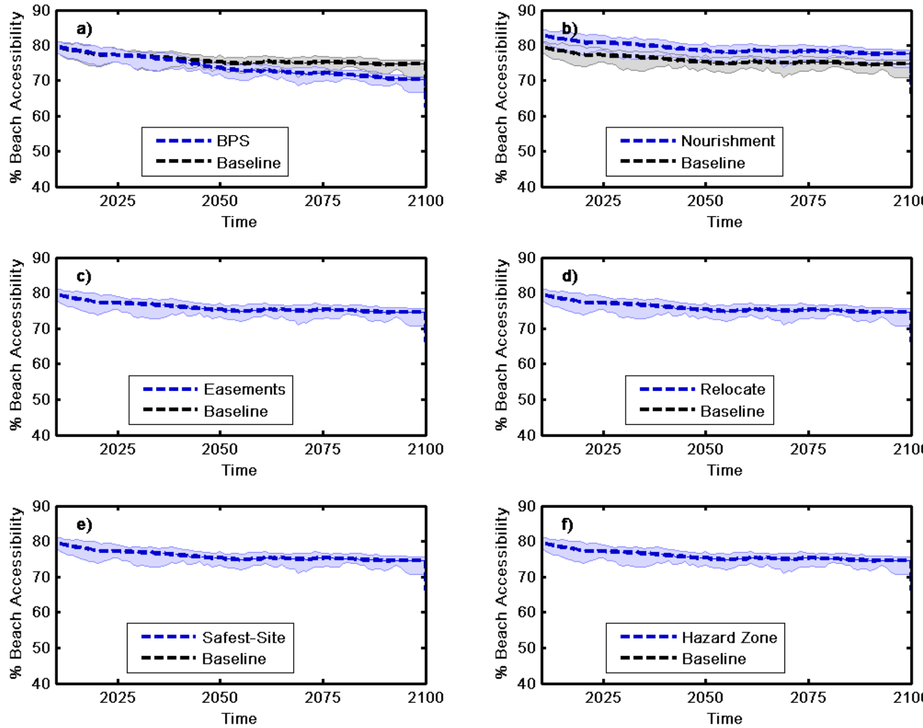

Figure 3.6: Beach accessibility through time under each of the policy drivers. Dashed lines indicate the decadal mean of all simulations. Bounds represent the minimum and maximum decadal means.

The model suggests that policy drivers impact beach accessibility less than climate drivers (Figure 3.6). The most significant variation from baseline occurred during BPS construction, which reduces accessibility by less than 10% (Figure 3.6a). Including a nourishment policy kept accessibility essentially constant through the century (Figure 3.6b). Other modeled policies had no effect on beach accessibility.

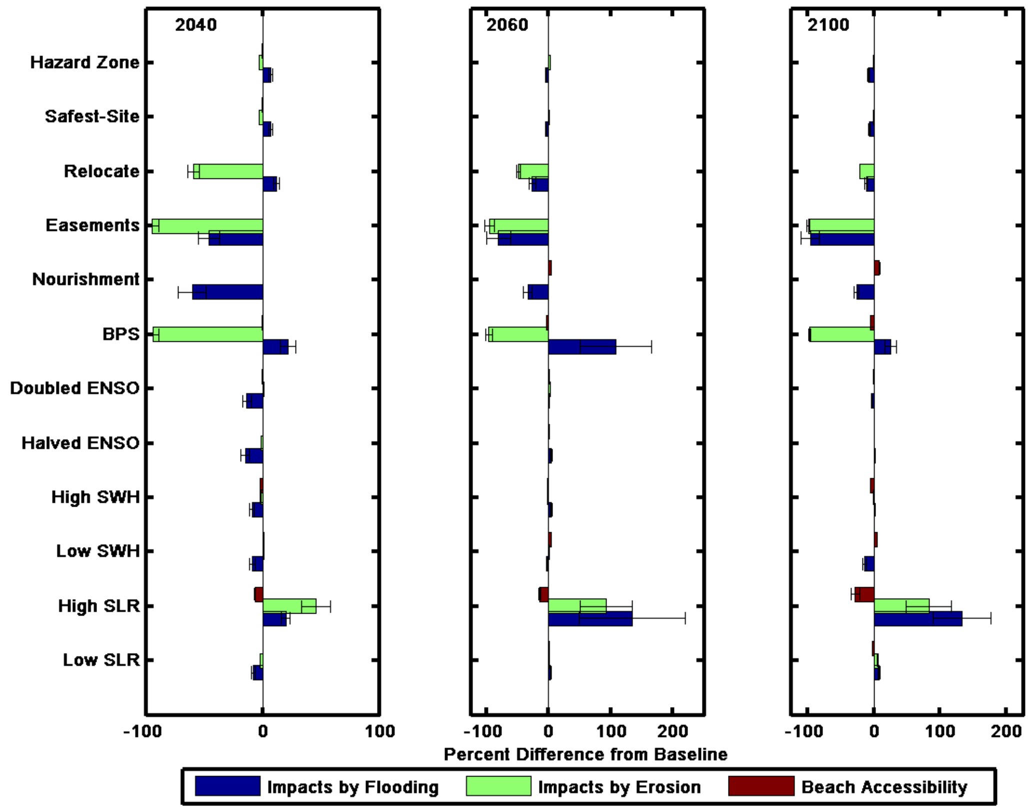

Figure 3.7: The percent difference in each of the (3) metric values between each of the climate and policy drivers and the baseline scenario. Values are presented for three time periods, 2030-2040, 2060-2070, and 2090-2100. Error bars indicate the standard deviation in the percent difference from the baseline.

Modeled deviations from the baseline were asymmetric and did not linearly correspond to the perturbation in the driver variable. Early in the century, human adaptation strategies in the form of easement creation, BPS construction, and beach nourishment overwhelmed climate drivers in two of the three metrics in terms of variation from the baseline (Figure 3.7). While construction of BPS resulted in a reduction of the number of buildings impacted by erosion, the rip-rap revetments were detrimental to the landscape through the reduction of beach accessibility and increased exposure flooding. In contrast, nourishing the beach fronting BPS reduced runup, thus increasing beach access and reducing overtopping of the structure crest. Easements reduced coastal hazards exposure by almost 100% and thus had the greatest benefit of any policy. Policies that modify future new development patterns had less of an impact on the landscape due to the small study-wide population growth rate.

Wave height and SLR were the physical drivers with the greatest impact on the three metrics indicated in these results. The county-wide variation in beach accessibility was minimal when compared to the number of properties impacted by coastal hazards and was only influenced significantly by high SLR. By mid-century, the greatest variation from a baseline climate was under a high SLR climate driver, which by 2100 increased the impact of flooding and erosion, and decreased beach accessibility by approximately 150%, 75%, and -30%, respectively.

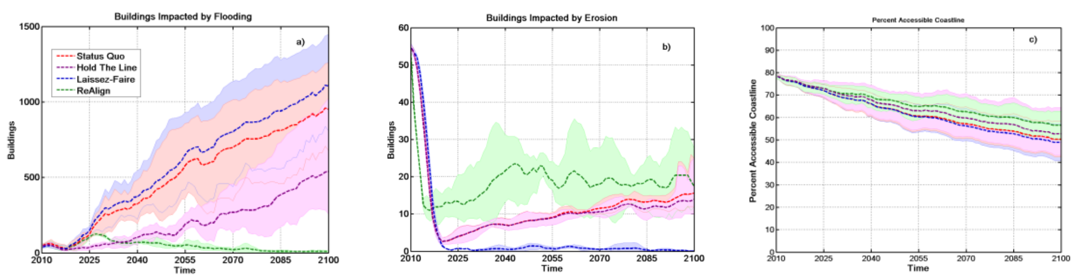

Figure 3.8: Three metrics (buildings impacted by flooding, left; buildings impacted by erosion, middle; beach accessibility, right) compared across five policy scenarios under a range of climate scenarios. Dashed lines indicate the mean of the medium impact climate scenarios. Shading indicates the mean of the low and high impact climate scenarios.

The three metrics described above were also compared under combined climate and policy scenarios (Figure 3.8). Here, variability associated with climate was computed as the range of the mean high and low climate impact climate scenarios within any of the four policy scenarios and the range associated with policy is the difference between the means of the policy scenarios. Greater variability was observed within scenarios than as individual drivers as each policy scenario contains multiple policies and was simulated under 90 climate scenarios with varying shifts of ENSO frequency and SWH (grouped by low, medium, and high SLR). The increase of buildings impacted by flooding during the first half of the century was in response to both climate drivers and policy drivers, predominately in the form of SLR and the construction of BPS (Figure 3.8a). A feedback not observed through individual drivers was the increased levels of BPS construction in response to high SLR. The greatest impacts to buildings by flooding occurred under the *Laissez-Faire* policy scenario, both because BPS construction was permitted without restriction and because the preference for new development near the shoreline was elevated. Flooding impacts under the *ReAlign* policy scenario were reduced by the end of the century due to both the relocation of people and development away from coastal hazard zones and the limitation of further BPS construction.

The relative magnitude of variation between both policy scenarios and climate scenarios was significantly less for buildings exposed to erosion hazards (Figure 3.8b). Erosional trends were much different from the baseline trend observed in the previous section due to both the construction of BPS (in the *Status Quo*, *Laissez-Faire*, and *Hold the Line* policy scenarios) and the formation of easements under the *ReAlign* policy scenario. These two management options reduced the magnitude of erosion impacts by almost two orders of magnitude, even in a high SLR scenario. Thus, in all scenarios, erosion had far less of an impact on the landscape than flooding. Near the end of the century, the impacts of climate and sediment budget factors began to overtake properties not eligible (under current state law) for BPS construction in the *Status Quo* and *Hold the Line* policy scenarios. The *Laissez-Faire* policy scenario had the fewest number of buildings impacted by erosion as property owners construct BPS regardless of current eligibility status. The lack of BPS construction in the *ReAlign* policy scenario resulted in greater impacts to buildings by erosion and greater variability with respect to climate scenarios.

By 2100, the combination of climate impacts and hardening of the shoreline significantly reduced beach accessibility across all scenarios (Figure 3.8c). Greater accessibility was maintained under the *ReAlign* and *Hold the Line* policy scenarios, and reduced under the *Status Quo* and *Laissez-Faire* scenarios. Beach nourishment in the *Hold the Line* scenario did not maintain beach accessibility under all climate impact scenarios and was ineffective under the medium and high impact climate scenarios as the BPS were extended onto the beach in response to higher TWLs.

Table 3.1: Maximum ranges of three metric values associated with climate and human drivers. As individual drivers, the range is measured by the maximum absolute difference from the baseline value in any year during the 90 year time series. Within scenarios, the range associated with climate is computed as the maximum range of the high and low climate impact means within any of the four policy scenarios and the range associated with policy is the greatest difference between the mean of the maximum metric value of all policy scenarios and minimum metric value of all policy scenarios.

	Variability	**Buildings Impacted by Flooding**	**Buildings Impacted by Erosion**	**Beach Accessibility**
As Individual Drivers	Max. Range Associated with Climate	840 Buildings	411 Buildings	33%
	Max. Range Associated with Human Decisions	610 Buildings	555 Buildings	23%
Within Scenarios	Max. Range Associated with Climate	1,780 Buildings	174 Buildings	35%
	Max. Range Associated with Human Decisions	1,922 Buildings	178 Buildings	24%

The relative influence of climate and policy varied when considered as individual drivers and within the context of scenarios (Table 3.1). Generally, the consequences of both climate drivers and human decisions were exacerbated through time under all metrics both within the context of scenarios and as individual drivers. Both policy and climate had significant impacts on the three metrics shown here. The number of buildings impacted by flooding indicated greater variability when compared between policy scenarios. The number of buildings impacted by erosion was more variable with respect to human decisions both within scenarios and when individual drivers were evaluated. In contrast, climate has the largest influence on beach accessibility within the context of policy scenarios and as individual drivers.

Comparing individual drivers to a baseline allows for exploration of metric sensitivity to specific perturbations, whereas comparing metric results across scenarios allows for a more robust comparison of potential feedbacks. For example, the impact of BPS across the landscape was much greater in a high SLR scenario, not only because a higher percentage of the shoreline was armored in response to more frequent collision of the water into the toe of the dune and event-based erosion, but also because increased armoring changed the coastal morphology, thus exacerbating flooding later in the century.

3.2 How do physical and human drivers change landscape metric uncertainty over time?

Along with measuring the variation between scenarios and from a baseline value, quantifying the uncertainty through time under each driver and scenario is important in providing robust assessments of adaptation strategies and management options under a range of climate scenarios. While there are many forms of uncertainty within the modelling process described here, uncertainty as expressed in this paper is equal to the spread in landscape metrics resulting from probabilistic simulations of daily TWLs. The relative coefficient of variance, or the ratio of the standard deviation to the mean, provides a measurement of uncertainty within the 30 simulations under each climate and policy driver.

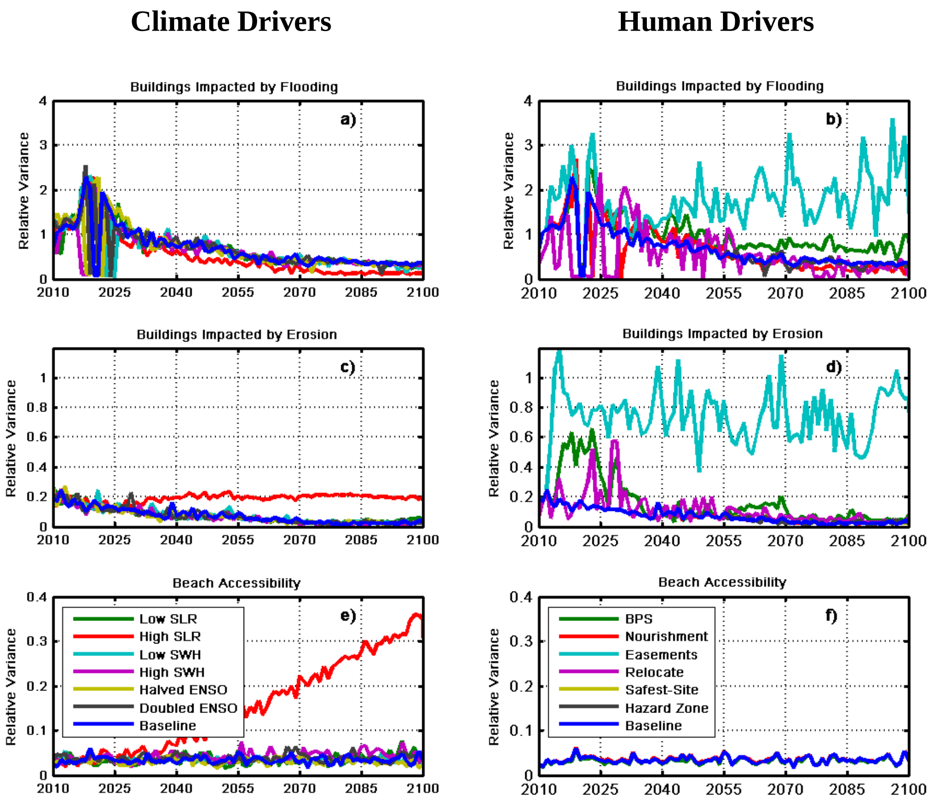

Figure 3.9: Relative coefficient of variance for each of the climate (left) and policy (right) drivers through time.

First, variance is measured for each individual driver and compared to the baseline (Figure 3.9). The highest levels of variance were found in impacts to property by flooding hazards (Figure 3.9a, b). Under all climate drivers, uncertainty with respect to inundation decreased through time, particularly under high SLR. The overall decrease was likely due the presence of BPS and increase in yearly maximum TWLs through time. Within the model, once BPS has been constructed to its maximum level and the beach has been narrowed such that there was frequent overtopping, the same locations were likely to be impacted by flooding on a regular basis. At some point, a threshold was reached under which the same properties experience flooding consistently during the maximum TWL event of the year. Surpassing this threshold was accelerated and exacerbated under the high SLR scenario. There was more uncertainty across the policy drivers than climate drivers with respect to flooding impacts. Easements produced a higher relative coefficient of variance throughout the century because buildings that were regularly flooded were removed from the hazard zone, thus the remaining buildings were impacted with greater temporal irregularity. The relocation of buildings in response to impacts maintained no consistent pattern throughout the century with respect to coastal hazards. Finally, the construction of new BPS indicated higher uncertainty in the mid to late century in metrics related to flooding.

Similarly to flooding hazards, variance within impacts due to erosion decreased over time with the exception of the high SLR climate driver (Figure 3.9c, d). Again, there was higher uncertainty under the policy drivers, particularly within the creation of easements, relocation of buildings, and construction of new BPS, but this uncertainty converged to the baseline levels after the first quarter century for the latter two drivers.

Uncertainty in beach accessibility under all drivers except for high SLR remained fairly constant through time and was smaller than uncertainty for the first two metrics (Figure 3.9e, f). This indicates that under all but a high SLR scenario, the portion of beach within Tillamook County that remains accessible at least 90% of the year is fairly constant, whereas under a high SLR scenario, the accessibility of a segment of coastline from year to year is less predictable.

The majority of the individual physical and human drivers increased the coefficient of variance within the three metrics examined (Figure 3.10, below). Overall, policy drivers indicated a much greater change in uncertainty in impacts to buildings by coastal hazards throughout the century. However, no policy driver shifted uncertainty with respect to beach accessibility by greater than 10%. The construction of BPS and formation of easements generally increased uncertainty with respect to flooding and erosion hazards. Beach nourishment trends reversed near the end of the century, and variance with respect to buildings impacted by flooding was reduced. The relocation of buildings early in the century increased variance with respect to erosion but decreased variance with respect to flooding. Implementing hazard zones with respect to new development and enforcing safest site requirement in coastal areas resulted in no change in uncertainty until midcentury, at which time the two policies decrease uncertainty for metrics related to erosion and increase uncertainty for metrics related to flooding hazards.

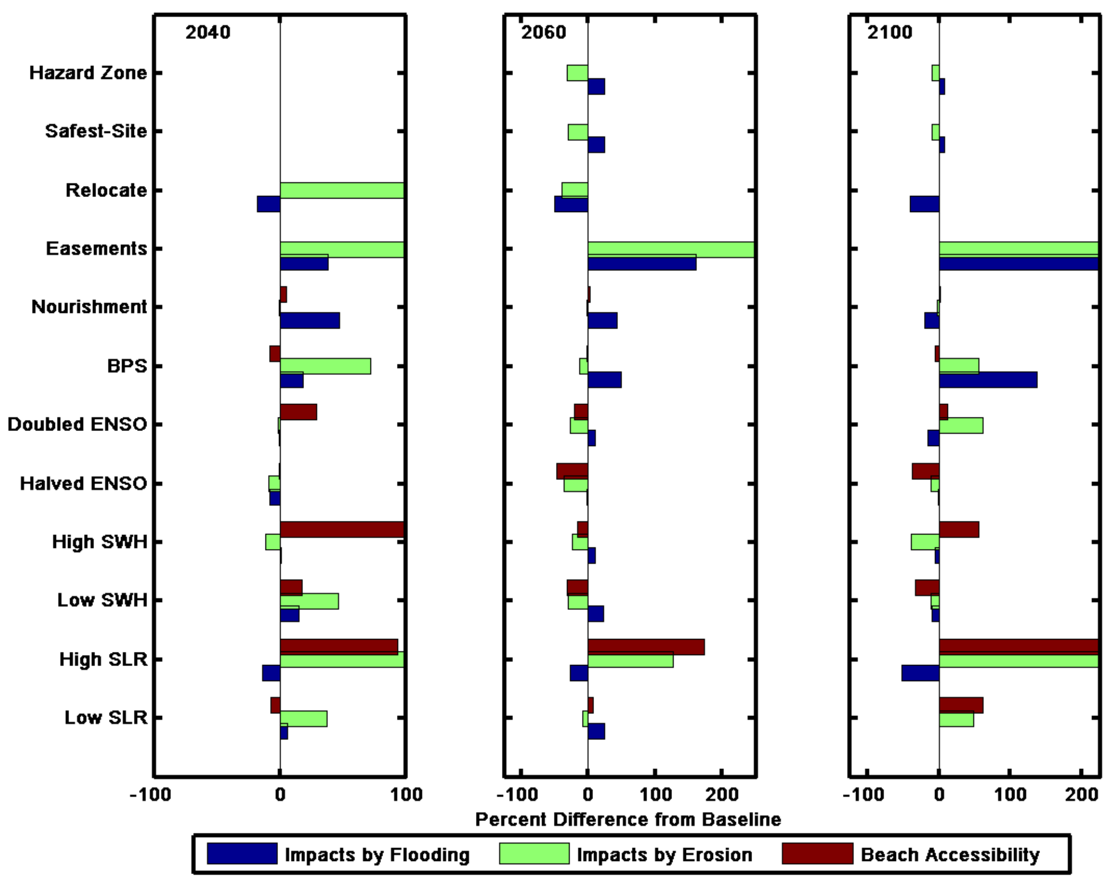

Figure 3.10: The percent difference in the coefficient of variance for each of the (3) metric values between each of the climate and policy drivers and the baseline scenario. Values are presented for three time periods, 2030-2040, 2060-2070, and 2090-2100.

Of the six climate drivers, only high SLR resulted in a persistent pattern of heightened uncertainty with respect to buildings impacted by erosion and beach accessibility (Figure 3.10). As aforementioned, within the model, there was a decrease in variance due to the sustained inundation of coastal properties. Early in the century, the uncertainty in beach accessibility caused by a positive shift in SWH was greater than any other driver, physical or human. This trend was not maintained through the end of the century and was in fact reversed mid-century. Unsurprisingly, decreasing the frequency of ENSO events reduced variance with respect to beach accessibility, while doubling the frequency had mixed effects throughout the century. By the end of the century, increases to climate drivers increased uncertainty in beach accessibility, whereas decreases to these drivers (SWH, ENSO frequency) decreased variance.

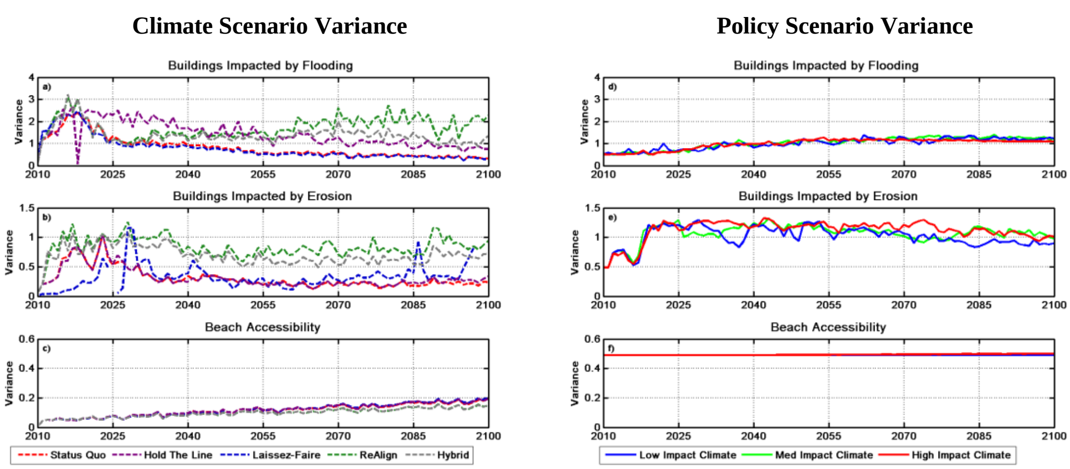

Figure 3.11: Coefficient of variance with respect to climate under each policy scenario (left) and with respect to policy scenarios under a medium impact climate scenario (right)

Uncertainty, quantified using the coefficient of variance, was also examined with respect to policy and climate scenarios (Figure 3.11). Uncertainty attributed to climate was calculated within each policy scenario across all 90 climate simulations (Figure 3.11a-c). Uncertainty attributed to human decisions was calculated under each climate impact scenario (high, medium, and low) across all policy scenarios (Figure 3.11d-f). In three out of the four policy scenarios, uncertainty due to climate decreased over time for the metric of flooding impacts to buildings (Figure 3.11a). The exception occurred under the *ReAlign* scenario, which reflected the increased uncertainty driven by the formation of easements.

Similarly to the previous metric, the number of buildings impacted by erosion was most uncertain with regards to climate under the *ReAlign* scenario (Figure 3.11b). Climate uncertainty under the *Laissez-Faire* policy scenario lacked a distinct trend as the number of buildings impacted is so minimal, causing sensitivity in the coefficient of variance to small differences within the climate simulations. Uncertainty in beach accessibility increased due to climate impacts under all policy scenarios, the most so in policy scenarios in which BPS was constructed (Figure 3.11c)..

Under each climate scenario, relative trends and magnitudes of uncertainty between policy scenarios were essentially equal (Figure 3.11d-f). The coefficient of variance between policy scenarios increased over time with respect to flooding erosion hazards (Figure 3.11d, e). There was no measured change in variance between policy scenarios under any climate scenario in reference to beach accessibility(Figure 3.11f).

Comparing the variance within the context of scenarios indicated that the uncertainty in landscape metrics with respect to climate is dependent upon human decisions, whereas decision making uncertainty was generally consistent across a range of climate drivers.

Table 3.2: Magnitude and trend in relative variance (uncertainty) through time.

		Buildings Impacted by Flooding		**Buildings Impacted by Erosion**		**Beach Accessibility**	
		Max. Rel. Variance	General Trend	Max. Rel. Variance	Trend	Max. Rel. Variance	Trend
Individual Drivers	Climate Uncertainty	2.6	Decrease	0.2	Decrease	0.4	Increase
	Policy Uncertainty	3.7	Decrease	1.1	Decrease	<0.1	Static
Within Scenarios	Climate Uncertainty	3.1	Decrease	1.3	Static	0.2	Increase
	Policy Uncertainty	1.2	Increase	1.3	Increase	0.5	Static

The maximum variance and general trends with respect to policy and climate uncertainty both within scenarios and as individual drivers is illustrated in Table 3.2. Trends within scenarios and in individual drivers were inconsistent across metrics. The metric with the highest uncertainty was exposure to flooding. This uncertainty was greatest under individual management options and typically decreased through time. For erosion hazards, uncertainty was greater within scenarios. Uncertainty in erosion exposure due to individual human and physical drivers decreased through time, whereas uncertainty between policy scenarios increased. The minimal uncertainty of impacts to erosion can be attributed to the shoreline change rate related to sediment budget factors. Future analysis will include exploration of the sensitivity of the model to such factors and whether changes to the historic rate might alter the results presented here. Beach accessibility was less uncertain under almost all scenarios and drivers.

4 Conclusions

Globally, coastal communities are increasingly faced with the impacts of climate change. The combination of sea level rise, changes to wave heights, and possible variations to the frequency and magnitude of El Niño events has the potential to increase the effects of flooding and erosion on coastal populations. The strategies used to mitigate these impacts have the potential to either improve or exacerbate exposure to hazards. Understanding the impact that each decision has on the landscape in combination with how that driver influences the uncertainty of future projections can more robustly inform decisions. Using the spatially explicit, policy-centric modeling platform, *Envision*, the relative impact of six physical drivers (related to climate) and six human drivers (related to management options) was quantified with respect to baseline conditions. Impacts and variance were also quantified under a set of climate scenarios grouped by SLR, and scenarios of grouped policies in order to allow a more thorough exploration of feedbacks between climate and policy.

Variability and uncertainty were measured across three landscape metrics, 1) buildings impacted by flooding, 2) buildings impacted by erosion, and 3) beach accessibility, in order to capture impacts to both the built and natural environments. Variability for the metric of beach accessibility was greatest due to climate within scenarios; for erosion, variability was greatest with respect to individual management options; and for flooding, variability was greatest between policy scenarios. In general, variability with respect to both climate and policy increased over time. Trends in uncertainty decreased, remained static, or increased through time depending upon the metric and driver. Uncertainty was greatest for the metric of flooding hazards and least for beach accessibility. Uncertainty in all landscape metrics with respect to climate was dependent upon human decisions, whereas uncertainty associated with decision making is generally consistent across a range of climate drivers.

Quantifying variability and uncertainty within the *Envision* framework helped improve the usefulness of the model and to determine the relative impact of policy and management decisions on the adaptive capacity of Pacific Northwest communities under a range of future climate scenarios. Understanding the impacts of decisions and climate both as individual drivers and coupled within scenarios can potentially allow for the determination best practices with respect to adaptation policies, within the constraints of the modeled representation of coastal community drivers and processes.

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