

Model of coastal bluff retreat accounting for complex geology of the Salish Sea

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Title: Model of coastal bluff retreat accounting for complex geology of the Salish Sea

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Outlet: Scientific Data

Main Messages/Points

- We develop a model of coastal bluff retreat that accounts for the effects of wetting by tides, storm surge and sea level position, wave energy, and the cohesion of bluff sediment.
- The model explains 60% of the variability in measured historical bluff retreat rates across the Pacific Northwest.
- The model projects acceleration of bluff retreat rates due to increasing total water levels and cumulative wave power from CMIP6 climate scenarios.

Abstract

Sea-level rise is expected to increase the frequency and severity of wave and storm impacts, accelerating shoreline and bluff erosion and retreat. Additionally, increased rainfall intensity is expected to increase cliff-top erosion rates. Shoreline and coastal bluff retreat pose substantial risks to property, infrastructure, and human life, yet few predictive models exist to inform planning, and even fewer seek to account for geologic controls on erosion processes. Bluff erosion is an important source of sediment supply to beaches that provide habitat for commercially and culturally important fish, birds, and shellfish, particularly in the U.S. Pacific Northwest where diverse habitats of mixed sediment composition exist. Recent studies have assembled information on historical bluff retreat and modeled sea level rise and associated effects on wave climate and coastal flooding, which are important elements for assessing future bluff retreat. This paper summarizes the development and implementation of a physically based coastal bluff retreat model across Puget Sound that is derived from several datasets on incident wave conditions, site-specific geologic characteristics, and historical bluff retreat rates. Because the influences of hydrodynamic drivers are explicitly included in the model, we also apply this model to forecast the

influence of changing wave and water level variability under sea-level projections to assess future bluff retreat by 2100. The outputs of projected bluff positions and uncertainty enable vulnerability assessments to increasing coastal erosion hazards to help guide future adaptation efforts.

1 Introduction

Erosion of weakly lithified coastal bluffs is anticipated to increase with sea level rise, leading to substantial damages to property, infrastructure, and ecosystems depended on by people. For example, Vitousek et al. (2023) concluded that 24–75% of California beaches may be lost as a result of 1–3 m of sea level rise by 2100, which would threaten the state’s beach tourism economy. The principal factors that drive coastal bluff retreat are soil saturation and erosion by wave scour. Intense and/or prolonged rainfall, persistent groundwater flow along stratigraphic contacts, and elevated coastal water levels can saturate bluff sediment, increase porewater pressures above thresholds leading to failure, and increase wave scour to undercut, oversteepen, and remove accumulated colluvium at the base of bluffs (Carter and Guy Jr, 1988; Young et al. 2021). Other factors that contribute to coastal bluff failure and retreat include wind and temperature (Roland et al., 2021), seismicity associated with large earthquakes (Griggs and Plant, 1998), micro-seismicity associated with concussion forces of ocean swell on the face of bluffs (Adams et al., 2005), land use modifications to vegetation cover, urban runoff, stormwater routing, and irrigation that cause localized bluff failures (MacLennan et al., 2018). Although these factors affect bluff failure, the long-term landward migration of coastal bluffs requires sufficient wave scour. Wave scour redistributes colluvium deposited at the base from top-down erosion and resets the system for undercutting. Otherwise, the accumulated colluvium would buffer subsequent wave effects (Kline et al., 2014) and decrease landward displacement of the bluff crest erosion (Figure 1).

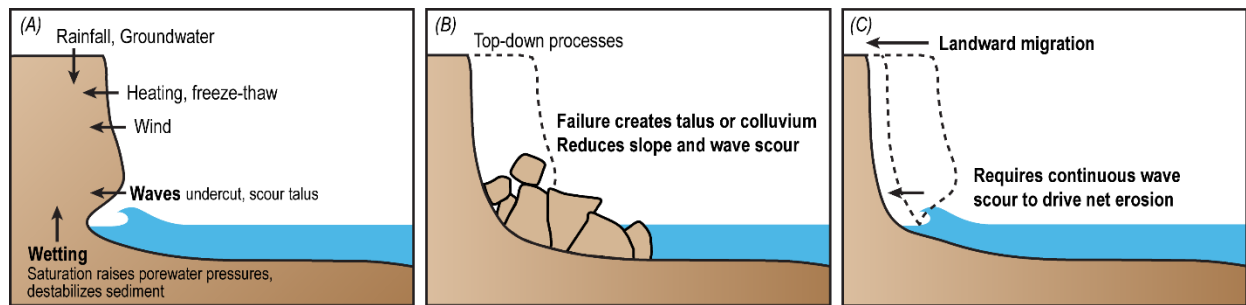


Figure 1. Conceptual diagram illustrating factors that drive bluff retreat and the two factors (**bold**) accounted for in this study (A), the reduction in slope and erosion with only top-down processes (B), and the requirement for wave scour processes to redistribute colluvium undercut and oversteepen bluffs to drive net landward migration (C).

The rate of global sea level rise has doubled since the 1970s and is anticipated to accelerate in the coming decades, reaching 3–5 times the historical rate by 2150 (Sweet et al., 2022). The rate of relative sea level rise (with respect to land) varies spatially on scales of 1-100s of kilometers associated with localized faulting, subsidence, and regional to global vertical land motions (Newton et al., 2021). The influence of tides, storm surge, and waves also can vary at similarly fine spatial scales affected by shoreline orientation to wave climate (Barnard et al., 2017; Sweet et al., 2024). Sea level rise is expected to enhance wave and storm impacts at higher profile elevations through flooding and coastal erosion, which are expected to be relatively higher in microtidal rather than macrotidal regions of the world where storm waves can co-occur more frequently at a given tidal elevation (Vitousek et al., 2017). Projected acceleration of sea level rise and differences in relative rates of sea level rise are a growing concern for bluff change in settings like the Pacific Northwest where vertical land movements are highly variable.

Sea level rise in the Pacific Northwest is projected to reach 0.5–1.0 m by 2080–2130 for a range of quantified likelihoods (Miller et al., 2018). Global Climate Models (GCMs) and regional downscaling indicate that frequency and intensity of storms and precipitation associated with atmospheric rivers are also projected to increase through the year 2100 (Mass et al., 2022; Guo et al., 2024). While the climate models do not indicate marked changes in atmospheric pressure patterns and wind speeds that generate

waves, annual to decadal shifts in wind direction are likely to occur as observed in the past (Crosby et al., 2023; Grossman et al., 2023) and modulate wave incidence angle on the shore, leading to changes in erosion patterns. The anticipated increase in rainfall intensity is expected to lead to 120–150% higher peak stream flows by the year 2100 (Mauger et al., 2015). Intense and/or long-duration rainfall saturating soils are expected to destabilize steep, poorly consolidated hillsides and coastal bluffs (Mirus et al., 2018).

Past numerical modeling efforts of long-term (decadal) bluff change and erosion include a range of statistical, process-based, and mass-conservation approaches of varying sophistication; a thorough review is provided by Limber et al. (2018). Most existing bluff retreat models are transect-based, one-dimensional (1D) formulations that evaluate statistical relationships between average erosion rate and/or dynamic processes accounting for the effects of water levels, wave energy, wave runup, shoreline orientation, slope, beach width, and other factors. However, Limber et al. (2018) noted that these formulations generally do not include details of cliff collapse mechanisms or account for fine temporal scales of morphological change important to coastal evolution. Commonly, these models are validated with measured historical rates then perturbed to evaluate anticipated linear (Hapke & Plant, 2010; Revell et al., 2011; Ruggiero et al., 2001; Sallenger et al., 2002; Young et al., 2016) and exponential (Hackney et al. 2013, 2015) sea level rise trajectories on erosion rates. More recently, Vitousek et al. (2017, 2023) have added substantial physical complexity to 1D shoreline modeling approaches to capture along and cross-shore processes and use satellite-derived shorelines to calibrate parameters and reduce uncertainty. Conservation of mass approaches that balance estimates of bluff retreat with sediment production required to maintain beach stability continue to evolve and represent historical changes at multiple temporal and spatial scales (Wolinsky and Murray, 2009; Ortiz & Ashton, 2016; Appleton et al., 2026). Most models have treated geologic controls on bluff recession with a coefficient to represent erodibility or hardness (Marani et al., 2011) because suitable metrics have been sparse for widespread model integration and highlight the need to fill this information gap.

In 2018, a comprehensive analysis of historical bluff retreat conducted across the Puget Sound region found that bluff retreat rates have ranged 0.3–1.0 m/year since the early 1900s (MacLennan et al., 2018). That study also developed a multivariate regression model that helped explain 30–40% of the variance in historical bluff retreat due to tide range, fetch (exposure to waves), and categorical parameterizations of bluff geology and shore type. Uncertainty in past bluff positions associated with aerial photo interpretation, bluff crest and toe elevations relative to tidal datums, and geology were identified as important information needs for improving the model (MacLennan et al., 2018). Most of these data needs were met through completion of a 1-m, seamless topo-bathymetric digital elevation model (Tyler et al., 2020) and regional water level and wave historical re-analyses and future projections to 2100 (Grossman et al., 2023; Crosby et al., 2023; Parker et al., 2026a) to support implementations of the U.S. Geological Survey Coastal Storm Modeling System (CoSMoS) across the Salish Sea. Little (2024) removed site-specific parameters and replaced fetch with offshore wave power derived from the CoSMoS water level and wave hindcasts (Crosby et al., 2023; Grossman et al., 2023). These changes increased the explanatory power of the multivariate regression of MacLennan et al. (2018) and enabled historical erosion reconstructions more broadly alongshore.

This paper describes the development of a bluff retreat model and data outputs accounting for the contributions of coastal processes through, (1) high water levels that saturate sediment and elevate porewater pressures to thresholds for failure, and (2) wave energy that scours, undercuts, and oversteepens bluffs and redistributes sediment temporarily accumulated at their base, which resets the system for undercutting. We also describe the integration of quantitative measures of the geological control of sediment cohesion that modulates both saturation and erodibility. After a description of the model configuration and validation, we show how the model is implemented to assess potential changes in erosion rate with sea level rise. Lastly, we apply the developed model to assess future cliff hazards across Puget Sound, which have been identified as important information needs for land and resource

managers to inform general hazard planning, ecosystem assessments, and protection of human lives (MacLennan et al., 2018).

2 Material and methods

2.1 Model Design and Overview

The bluff model workflow consists of four principal steps: (1) model configuration and compilation of historical bluff retreat and model input data, (2) development of a multivariate regression model to reconstruct historical observed erosion, (3) implementation of the multivariate regression model regionally to reconstruct historical rates where observations do not exist, and (4) projections of anticipated future changes to bluff positions associated with sea level rise (Figure 2). Modeling of anticipated future bluff change rates and positions made use of the multivariate regression and three cross-shore evolution formulations of Limber et al. (2018) that were integrated into an ensemble mean projection with associated uncertainty. The multivariate regression model was developed and implemented in Python, using the SciPy (Virtanen et al., 2020) and Statsmodels libraries for statistical analysis (Seabold and Perktold, 2010). The computed future bluff crest positions were output as Geographic Information System (GIS) shapefiles to support assessments of bluff hazard exposure and vulnerability assessments and made publicly available in (Grossman et al., 2026a and 2026b).

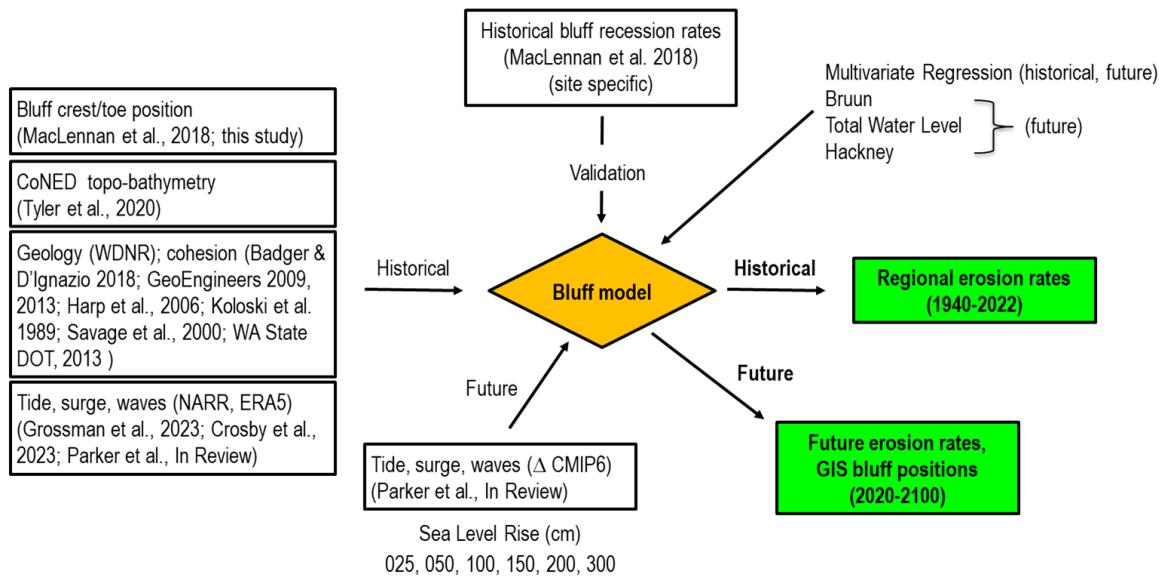


Figure 2. Model workflow showing data (white boxes) used by bluff model (diamond) for simulations and validation of regional historical erosion rates and future change in bluff retreat rates and bluff positions (green boxes).

2.2 Model configuration and data inputs

Model configuration was initiated with construction of cross-shore model transects alongshore and mapping baseline bluff crest and toe positions and cross-shore transects to compute bluff change. Cross-shore (1D) modeling transects extending from approximately -20 m landward to +50 m (NAVD88) on land as defined by the USGS CoNED 1-m digital elevation model (Tyler et al., 2020) were generated using the USGS Digital Shoreline Analysis System (Himmelstoss et al., 2021). Transects were generated at validation sites and every 25 m alongshore orthogonal to the shoreline and attributed with ID number and a group ID number defining continuous reaches of bluffed shoretypes. Approximately 15% of the autogenerated set of model transects were manually edited where extreme shoreline curvature led to transect crossings. Elevations along each transect were then sampled from CoNED at its native resolution of 1 m.

The positions and elevations of the top (crest) and base (toe) of coastal bluffs were determined through automation by extracting inflection points along the cross-shore model transects from the 1-m

CoNED DEM (Tyler et al., 2020) using the USGS Cliff Feature Delineation Tool (Seymour et al. 2020) and iBluff open-source R package for geomorphic analysis of coastal bluffs/cliffs (R Core Team, 2024; Palaseanu-Lovejoy, 2023). Approximately 90% of the bluff crests and toes were captured by the automated CFDT and iBluff tools; the remaining ~10% of picks were manually revised where the automation identified multiple inflection points or faulty locations were generated where morphology was complex, highly modified, or the highly curved shoreline resulted in crests or toes crossing those of neighboring transects. Manual revisions of the baseline bluff crest or toe positions were interpolated at most 50-m alongshore consulting imagery from the U.S Department of Agriculture Farm Service Agency (2025), U.S. Geological Survey plane cam (Ritchie et al., 2025), or Washington State Coastal Atlas (Washington State Department of Ecology, 2025). In select cases where the natural bluff toe was buried, graded, or artificially elevated above the influence of coastal processes due to land use modifications, we instead delineated the bluff toe across the developed coastal plain at the elevation contour of the adjacent bluff toe or the maximum inundation extent of the highest (3 m) CoSMoS SLR scenario to capture anticipated coastal erosion effects. Transects were then attributed with transect number, latitude, longitude, and elevation of the bluff crest and toe, transect bearing, and placeholders for filenames, station codes, and boundary conditions associated with CoSMoS historical reanalysis and projected future water level and wave time-series outputs. Placeholders for published geologic parameters were also attributed to each transect.

2.3 Multivariate regression and model validation of historical bluff change

This study built upon the multivariate regression model of MacLennan et al. (2018) that captured 41.5% of the variance in measured long-term average bluff retreat rates across Puget Sound. That model relied on categorical definitions for variables “Shoretype,” “Surface Geology,” “Measurement Feature,” “Tide Range,” and “Fetch.” “Shoretype” characterized the shore as stable, erosional, or accretionary and was used to qualify erosional shorelines and regression coefficients used in the analysis. “Surface

Geology” in the MacLennan et al. (2018) model was prescribed with four categorical values as a surrogate for low, low to moderate, moderate to high, or high geologic susceptibility to erosion, based on the similarity in sediment composition of mapped geologic units. “Measurement Feature” primarily represented the level of uncertainty in erosion rate with those derived from repeat field surveys of bluff crest distance to control monuments, which are substantially lower than values derived from digital aerial photography interpretation. “Tide Range” was derived from astronomic predictions, and “Fetch Distance” was implemented as the maximum distance that waves may propagate to a bluff site and served as a proxy for wave energy (MacLennan et al., 2018). The remaining unexplained variance was attributed to other processes (e.g., rainfall) and uncertainty in modeled data and processes in particular wave energy and geologic controls on bluff recession.

In this study, we revised the multivariate regression in a more quantitative manner to account for the effects of coastal processes and geologic variability and to enable model application regionally beyond sites containing existing historical bluff rate data. First, we removed the categorical parameters. Second, we replaced tide range for each model transect with a water-level parameter defined as the 95th percentile non-tidal residual (NTR) normalized by water-level range. The NTR/water-level range parameter captures the relative influence of extreme events associated with storm surge that raise water levels and through prolonged wetting help to drive shoreline change above and beyond their semi-equilibrium state shaped by average condition modulated by tides alone. Each year, NTRs including regional inverse barometric pressure effects and remote sea level anomalies that penetrate into the Salish Sea, elevate water levels ~30–40% of the time and up to 1.0 m above the predicted tides (Grossman et al., 2023; Soontiens et al., 2016). We also included the skew of water levels (e.g., tide+NTR) to account for spatial variability across the complex estuary domain. Water levels, tides, and NTRs were derived from a 1940-2022 reanalysis of Salish Sea water levels and wave climate (Parker et al., 2026b). The reanalysis was

forced by the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis – Fifth Generation (ERA5) (Hersbach et al., 2020).

Third, we replaced fetch distance with offshore cumulative wave power filtered for water levels within the upper 1/3 of the tide range at each site. The offshore wave power has been found to capture the effects of wave scour at the base of bluffs (Adams et al., 2025; Earlie et al., 2015); offshore wave power is used here to avoid the high and uncertain computational challenges associated with computing wave runup and energy flux of short period ($\sim 4\text{--}6$ sec) waves across the highly variable slope and roughness of the region's mixed-sediment beaches. A simpler offshore cumulative wave power metric is also more accessible to a broader user base and has more straightforward refinement than wave runup or energy flux above the base of bluffs. Wave power was computed following the standard formulation following (Tucker and Pitt, 2001):

$$WP = \frac{1}{64\pi} \rho g^2 H_s^2 T_m \quad (\text{kW/m}) \quad (1)$$

where ρ =density of seawater (1000 kg/m^3), g =acceleration due to gravity (9.8 m/s^2), H_s = significant wave height and T_m = mean wave period. Cumulative wave power was summed for all water levels within the upper 1/3 of the tide range to represent wave energy that can reach the upper beach and is consistent with observations of predominant active extreme beach change (Miller et al., 2011). We included wave power skew to capture effects of asymmetry in their distributions which varies spatially across the complex shoreline morphology of the study domain (Crosby et al., 2023; Grossman et al., 2023; Parker et al., 2026b; Yang et al., 2019).

Lastly, we replaced the four categorical bins of geology of MacLennan et al. (2018) representing potential erodibility with published median cohesion values for glacial sediments across the region (Savage et al., 2000; Harp et al., 2006; GeoEngineers 2009, 2013; Koloski et al. 1989; Badger & D'Ignazio

2018; Washington State Department of Transportation, 2013) that can be correlated to mapped alongshore geology (Washington State Department of Natural Resources, 2026). Geologic units across the study domain were differentiated into 7 groups defined by the midpoint of the range in cohesion for each similar glacial deposit lithology and age (Table 1) as follows in decreasing order of cohesion; Vashon till, glaciolacustrine deposits, glaciomarine drift, pre-Fraser fine grained glacial deposits, advanced and recessional outwash deposits, pre-Fraser coarse grained glacial deposits, and alluvium, colluvium, or landslide deposits.

Table 1. Cohesion values for geologic units of coastal bluffs in Puget Sound.

Bin	Geology	Cohesion (kPa)			
		Min	Max	Mid	Range
1	Glaciolacustrine of the Lawton Clay Member of Vashon Drift and Possession Drift	0	144.0	72.0	144.0
2	Glacial Till, weathered Till, Vashon Till, Vashon subglacial meltout, pre-Olympia glacial till	0	192.0	96.0	192.0
3	Glaciomarine Drift	19.0	48.0	33.5	29.0
4	Pre-Fraser Fines, Pre-Olympia fines, Olympia Fines	29.0	29.0	29.0	0
5	Pre-Fraser and Pre-Olympia coarse glacial deposits, Possession Drift of Easterbrook et al. (1967)	19.0	19.0	19	0
6	Advance outwash, Overridden Advance Outwash, Esperance Sand Member of Vashon Drift, Recessional outwash, Pre-Vashon	0	48.0	24.0	48.0
7	Alluvium, Landslides	0	24.0	12.0	24.0

Conceptually, these modifications address the two principal physical coastal processes driving basal bluff erosion: (1) saturation that leads to bluff failure when sufficient pore-water pressures destabilize slopes, and (2) wave scour that undercuts, oversteepens, and removes colluvium from bluff systems. We tested more than 1,000 combinations of water level and wave power metrics, including specific

percentiles, ranges, exceedances above elevation thresholds, and recurrence magnitudes for statistical correlation power to explain the variability of the published long-term erosion rate data of MacLennan et al. (2018). The multivariate regression accounting for these potential physical processes with the highest explanatory power was:

$$EPR=B0+B1*NTR_{95}/WL_{range}+B2*WL_{skew}+B3*WP_{cum}+B4*WP_{skew}+B5*Cohesion+B6*Cohesion_{range}$$

where,

EPR is the end-point (average) rate of bluff change in meters per year, NTR_{95} is the 95th percentile non-tidal residual in meters (m), WL range is the water level range, WL_{skew} is skew of water levels (unitless), WP_{cum} = cumulative wave power in kilowatts per meter (kW/m) computed using Equation 1 when water levels are within 67% of the tide range, WP_{skew} (unitless) is the wave power skew, and cohesion and cohesion range prescribed in kilopascals (kPa). The coefficients for the Puget Sound model are as follows: $B0=6.76$, $B1=6.77$, $B2=13.95$, $B3=2.58e-7$, $B4=0.90$, $B5=-0.097$, and $B6=0.06$. Normalized coefficients showed that wave power and cohesion are the dominant terms and an order of magnitude greater influence than water level on EPR. Validation was based on testing model skill of the best estimate compared with the 57 directly measured mean historical bluff retreat values revisited and reported in MacLennan et al. (2018) that were initially surveyed by Kueler (1979, 1988). Uncertainty was propagated through all computations with the 95% prediction interval based on 1,000 bootstrap (Efron 1979) iterations of uncertainty in water levels (0.30 m), wave heights (0.25 m), wave period (1.3 sec), and cohesion (23 kPa).

2.4 Regional Model

The revised multivariate regression model eliminated the site-specific “Measurement Feature” parameter requirement and enabled application of the regression to reconstruct historical erosion rate where input “forcing” data for water level, wave power, and cohesion exist. The new multivariate

regression model was therefore implemented regionally at 25-m-spaced model transects alongshore to reconstruct and establish historical bluff retreat rates based on the 80-year historical 1940–2022 ERA5 reanalysis of water levels and waves (Parker et al., 2026b) and assuming no change in sea level. Model output at each model transect therefore represents the average historical bluff retreat rate over the period 1940–2022. This provided important baseline boundary condition data to assess spatial variability in bluff retreat. It also facilitated assessment of impending effects of sea level rise on bluff retreat rate and landward migration of the bluff crest.

2.5 Process-based model of future bluff change

We assessed potential future change in bluff retreat rate and bluff position based on the ensemble mean projection of the revised multivariate regression model and the 1D Bruun, Hackney, and Total Water Level (TWL) formulations following the workflow and uncertainty analyses of Limber et al. (2018) applied to the California coast. The multivariate regression and 1D models were forced by water level and wave power parameters derived from hydrodynamic simulations (Parker et al., 2026b) for the discrete plausible sea level rise scenarios of 0.25, 0.5, 1.0, 1.5, 2.0 and 3.0 m by 2100 of the USGS CoSMoS modeling framework (Barnard et al., 2014) and informed by the suite of SLR projections for the U.S. West Coast of Sweet et al. (2022). Further, these scenarios included forecasted changes in meteorological conditions and forcing on extreme events derived from the World Climate Research Programme (WCRP) outputs of the 7 High Resolution Model Intercomparison Project (HighResMIP~v1.0) CMIP6 global climate models (Voldoire, 2018; Haarsma et al., 2016) that assessed a range of greenhouse gas emission scenarios. The future water levels and wave metrics were implemented after computing the ensemble mean difference between future and historical simulations of water levels and waves for all 7 individual CMIP6 GCMs applied to the ERA5 reanalysis at each quantile.

In addition to the multivariate regression model, the Bruun, Total Water Level (TWL), and Hackney 2013 cross-shore evolution formulations with wide use in the field of morphological change modelling, independently assess the linear and non-linear effects of accelerating sea level on historical erosion rates following Limber et al. (2018). Closure depth for the Bruun formulation, defined as the depth offshore beyond which sediment transport and bottom elevation changes due to wave action are insignificant, was based on the mean closure depth determined for each model transect elevation profile and significant wave height and period of the 1940-2022 wave reanalysis (Parker et al., 2026b). For the Bruun rule, we assumed 50% of the sediment eroded from bluffs remained in the nearshore zone. For the TWL model, mean wave runup was used and computed using Stockdon et al. (2006) from the water level and wave time-series reanalysis (Parker et al., 2026b). For the Hackney 2013 model, mean accumulated wave energy was also computed from the water level and wave time-series reanalysis (Parker et al., 2026b). These model boundary conditions were derived and imposed for each transect alongshore for existing and future sea level position to determine the extent that differences in closure depth, total water level, and wave energy associated with greater water level due to sea level rise will affect bluff retreat relative to historical rates.

The multivariate regression computes the bluff recession rate for each discrete position in sea level rise and therefore does not require a time step for computation. In contrast, the 1D formulations of Limber et al. (2018) were implemented in 20-yr increments to better account for variations in the acceleration of sea level rise toward the year 2100 following Vitousek et al. (2017). Model outputs of each formulation were then combined into an ensemble mean best estimate and 95% uncertainty for each 20-year time-step using a pair-wise weighted mean following Limber et al. (2018). For each sea level scenario, the change in bluff crest position from the baseline position was calculated by multiplying the derived annual time-varying recession rates (e.g., from each 20-year period) and the number of years spanning baseline to 2100. The future bluff crest positions along with the 95-percentile confidence interval

computed from a 1000-iteration bootstrapping of model and data error terms described in section 2.3 were then mapped in GIS as a polyline and polygon, respectively.

3 Results or outputs

3.1 Model validation

Comparison of projected mean historical bluff retreat rates based on our new multivariate regression model with the observed historical bluff retreat rates reported in MacLennan et al. (2018) shows our revised model has high skill at predicting bluff retreat rates. The revised multivariate regression has a correlation coefficient (R^2) of 0.60, and the reconstructed mean bluff retreat rates are right-skewed in distribution similar to the observational data (Figure 3). The revised model slightly overpredicts lower observed bluff retreat rates and slightly underpredicts the highest observed bluff retreat rates. The increase in the overall model correlation and integration of quantitative metrics for the influence of water levels and wave energy and geologic controls on bluff failure and recession represent an advancement toward a physically based model. The revised model leaves some variability unexplained which is likely related to processes including rainfall- and groundwater driven saturation (Mirus et al., 2018), freeze-thaw effects, and other land disturbances that destabilize steep slopes and contribute to long-term bluff change. We note the model does not account for the presence of shoreline armor, mechanisms driving deep-seated landslides, or vertical land movements, the latter because uncertainty in elevations from digital elevation models and future water levels are greater than the potential changes associated with vertical land movements.

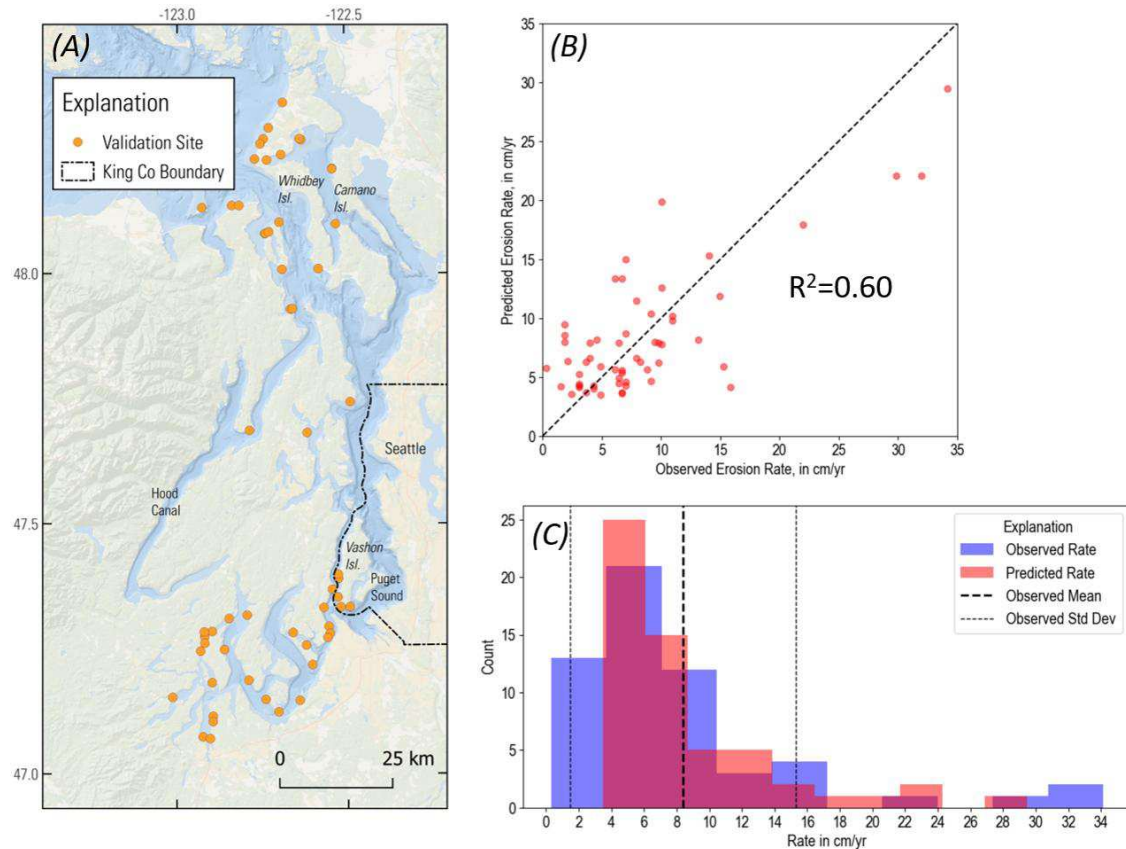


Figure 3. Map showing validation site locations of MacLennan et al. (2018) (A), plots showing model skill in terms of R^2 of historical rate predictions in cm/yr compared with measured erosion rates at the validation sites (B) and the distribution of predictions relative to observations (C) with similar right-skew and slight overprediction of lowest bluff retreat rates and slight underprediction of highest erosion rates. Base map from Esri and its licensors, copyright 2022.

3.2 Model outputs

The model outputs include a best estimate of the future bluff crest position and 95% prediction uncertainty envelope for each plausible USGS CoSMoS sea level rise scenarios of 0.25, 0.5, 1.0, 1.5, 2.0, and most extreme condition for risk management (e.g., 3.0 m) to occur by 2100 (Figure 4). The bluff crest projections are published as GIS polyline shapefile and the 95% prediction uncertainty envelope as GIS polygon shapefile. The region between the maximum uncertainty and the toe of the bluff is also published as the “hazard erosion zone” as GIS polygon shapefile for each scenario. Outputs for each county also include the baseline bluff crest position and model transects as GIS polyline shapefile and baseline bluff

toe positions at each transect as GIS point shapefile. The timing imposed for the sea level rise scenarios for the rate calculations is assumed 2100 for all scenarios, but additional sea level rise scenarios and timing can be implemented as desired.

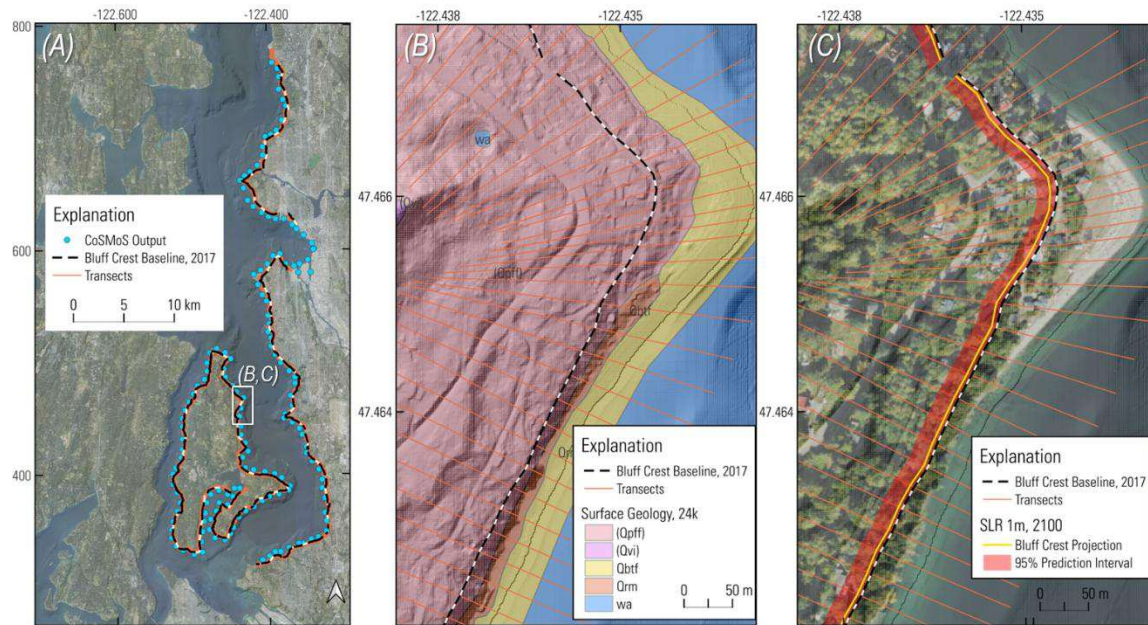


Figure 4. Maps showing example coverage of model projections at three spatial scales; county scale (A), subcounty scale (B) as indicated in A, and kilometer scale (C) as indicated in B, sequentially resolving the 25-m spaced model transects, hydrodynamic and geologic boundary conditions, and resulting future bluff crest and uncertainty predictions, along with baseline bluff crest used to initiate the model. Base from Microsoft product screen shot(s) reprinted with permission from Microsoft Corporation.

3.3 Data file structure

The model predictions are provided as GIS shapefile with the best estimate future bluff crest position as polyline and the 95% uncertainty envelope and hazard zone as polygons. The baseline crest positions and model transects are served as polylines. The data are georeferenced to UTM Zone 10 relative to the NAD83 horizontal datum, and units are in meters. The file name nomenclature is as follows:

CountyNameBluffModel_Transects.shp (polyline)

CountyNameBluffModel_YYYYBaseline.shp (polyline)

CountyNameBluffModelToePts_YYYY.shp (points)

CountyName_SLRxxx_BluffProjection.shp (polyline)

CountyName_SLRxxx_BluffUncertainty.shp (polygon)

CountyName_SLRxxx_BluffHazZone.shp (polygon)

where,

xxx is the amount of sea level rise in cm, YYYY is the year associated with the data.

The model boundary conditions and projection results are also served for each model transect by county as a csv file. The boundary condition file includes the parameters listed **Table 2**

Table 2. Model boundary condition and change computation file attributes.

Parameter
OutputID
Shore_modified
BluffTop_Elev
BluffTop_UTMX
BluffTop_UTMY
BluffToe_Elev
BluffToe_UTMX
BluffToe_UTMY
Geol_Unit
Geol_Code
Cohesion_MidPoint
Cohesion_Range
DFM_Lat
DFM_Lon
DFM_ID
WavePower_Cum_slr000
WavePower_Skew_slr000
TWL_Range_slr000
TWL_Skew_slr000
Tidal_Range_slr000
NTR95_slr000
NTR95_per_TWLrange_slr000

Bearing
DepthClosure_slr000
BeachWidth_slr000
ActiveSlope_slr000
WavePower_Cum_slr025
WavePower_Skew_slr025
TWL_Range_slr025
TWL_Skew_slr025
Tidal_Range_slr025
NTR95_slr025
NTR95_per_TWLRange_slr025
WavePower_Cum_slr050
WavePower_Skew_slr050
TWL_Range_slr050
TWL_Skew_slr050
Tidal_Range_slr050
NTR95_slr050
NTR95_per_TWLRange_slr050
WavePower_Cum_slr100
WavePower_Skew_slr100
TWL_Range_slr100
TWL_Skew_slr100
Tidal_Range_slr100
NTR95_slr100
NTR95_per_TWLRange_slr100
WavePower_Cum_slr150
WavePower_Skew_slr150
TWL_Range_slr150
TWL_Skew_slr150
Tidal_Range_slr150
NTR95_slr150
NTR95_per_TWLRange_slr150
WavePower_Cum_slr200
WavePower_Skew_slr200
TWL_Range_slr200
TWL_Skew_slr200
Tidal_Range_slr200
NTR95_slr200
NTR95_per_TWLRange_slr200
WavePower_Cum_slr300
WavePower_Skew_slr300
TWL_Range_slr300
TWL_Skew_slr300
Tidal_Range_slr300
NTR95_slr300
NTR95_per_TWLRange_slr300
ErosionRate_SLR000
ErosionRate_SLR000_low

ErosionRate_SLR000_high
ErosionRate_Projected_SLR025
ErosionRate_Projected_SLR025_low
ErosionRate_Projected_SLR025_high
ErosionRate_Projected_SLR050
ErosionRate_Projected_SLR050_low
ErosionRate_Projected_SLR050_high
ErosionRate_Projected_SLR100
ErosionRate_Projected_SLR100_low
ErosionRate_Projected_SLR100_high
ErosionRate_Projected_SLR150
ErosionRate_Projected_SLR150_low
ErosionRate_Projected_SLR150_high
ErosionRate_Projected_SLR200
ErosionRate_Projected_SLR200_low
ErosionRate_Projected_SLR200_high
ErosionRate_Projected_SLR300
ErosionRate_Projected_SLR300_low
ErosionRate_Projected_SLR300_high

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6 Author Contributions

E.E.G. designed the research project, oversaw the Master’s Theses research efforts of C. Little and K. Chiasson, and drafted the manuscript. C. Little and K. Chiasson collated existing data, collected new field measurements, and carried out analyses to evaluate the model, bluff changes at study sites owing to event (storm) and annual change. L. Horner conducted data processing and analysis including the last steps in model refinement. AJM contributed bluff crest mapping and insights on data quality. All authors contributed to the ideas and development of the model and reviewed the manuscript.

7 Data Availability

Data for bluff change projections across the region of Puget Sound in the State of Washington are provided in:

Grossman, E.E., Horner, L., Foxgrover, A.C., and O’Neill, A.C., 2026a, Projections of coastal bluff retreat in Puget Sound, U.S. Geological Survey data release, <https://doi.org/10.5066/P13GUZTZ>.
Grossman, E.E., Horner, L., Foxgrover, A.C., and O’Neill, A.C., 2026b, King County Near- to Medium-term scenarios of coastal bluff retreat: U.S. Geological Survey data release, <https://doi.org/10.5066/P13YR3SH>.

Data for water level and wave hindcast and future projections are provided in:

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Survey data release, <https://doi.org/10.5066/P14VOPEY>.

8 Competing Interests

The authors declare no competing interests.

9 Additional Information

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