sustainability

MDPI

Article

A Data-Driven Approach for Assessing Sea Level Rise Vulnerability Applied to Puget Sound, Washington State, USA

Ian Miller [1,*], Avery Maverick [2], Jim Johannessen [2], Chloe Fleming [3] and Seann Regan [3]

[1] Washington Sea Grant, Port Angeles, WA 98362, USA
[2] Coastal Geologic Services, Bellingham, WA 98225, USA
[3] CSS-Inc., under NOAA National Centers for Coastal Ocean Science Contract No. EA133C-1384, Fairfax, VA 22031, USA
* Correspondence: immiller@uw.edu

Abstract: Sea level rise (SLR) will exert pressures on assets with social value, including things such as infrastructure and habitats, in the coastal zone. Assessing and ranking the vulnerability of those assets can provide insights that support planning and projects that can reduce those vulnerabilities. In this study, we develop a quantitative, data-drive framework for calculating a sea level rise vulnerability score, using publicly available spatial data, for 111,239 parcels in Puget Sound, Washington State, USA. Notably, our approach incorporates an assessment of coastal erosion, as well as coastal flooding, in an evaluation of the exposure of each parcel, and impacts to habitats are quantified alongside impacts to existing infrastructure. The results suggest that sea level rise vulnerability in Puget Sound is widely distributed, but the overall distribution of scores is heavily skewed, suggesting that adaptation actions directed at a relatively small number of parcels could yield significant reductions in vulnerability. The results are also coupled with a concurrently developed social vulnerability index, which provides additional insight regarding those people and places that may be predisposed to adverse impacts from SLR-related hazards. We find that the proposed approach offers advantages in terms of advancing equitable SLR-related risk reduction, but also that the results should be carefully interpreted considering embedded assumptions and data limitations.

Keywords: sea level rise; vulnerability; climate; resilience; coastal management; coastal policy; GIS; spatial analysis

check for updates

Citation: Miller, I.; Maverick, A.; Johannessen, J.; Fleming, C.; Regan, S. A Data-Driven Approach for Assessing Sea Level Rise Vulnerability Applied to Puget Sound, Washington State, USA. *Sustainability* **2023**, *15*, 5401. https://doi.org/10.3390/su15065401

Academic Editors: Peter Sheng, Trevor Meckley, Karen Thorne and Vladimir Paramygin

Received: 7 December 2022
Revised: 11 March 2023
Accepted: 16 March 2023
Published: 18 March 2023

1. Introduction

Sea level is rising at a globally averaged rate of approximately 1 foot/century (3 mm/yr), but with regional variations [1]. Regional sea level projections for Washington State [2], on the west coast of the United States (U.S.), suggest that accelerated rates of sea level rise are expected. Sea level rise exacerbates and worsens the impacts of existing coastal hazards, leading to increases in coastal flooding frequency and magnitude [3], accelerated coastal erosion [4], and saltwater intrusion into groundwater [5]. These hazards enhance risks to infrastructure, ecosystems, and cultural values, and ultimately can compromise community well-being [6]. The identification and prioritization of sea level rise vulnerabilities can help to direct attention or resources to places, people, or assets along the coast where impacts associated with sea level rise are likely to be greatest [7]. Approaches to reduce vulnerabilities can forestall future impacts and reduce overall adaptation costs, and integrating insights derived from the assessment of vulnerability into planning processes can help to build overall climate resilience in coastal areas [8].

The concept of identifying, prioritizing, and addressing vulnerabilities is applied in many fields, including emergency management [9], food distribution markets [10], and cybersecurity defense [11], as a means for efficiently reducing risk. The concept has been advanced to support climate adaptation planning [12], in which vulnerability is conceptualized as a function of three components: (1) exposure, or the presence of people, assets, and ecosystems in places where they can be adversely affected by hazards; (2) sensitivity, or the degree to which a system, population, or resource might be affected by the hazard; and (3) adaptive capacity, which characterizes the ability of a person, asset, or system to adjust to a hazard or cope with change. The assessment of vulnerability in climate adaptation settings often involves characterizing one or more of these three components of vulnerability for assets of concern. Assessments of vulnerability to sea level rise, for example, can focus on classes of coastal assets such as shorelines [13], coastal ecosystems [14,15], transportation infrastructure [16], and vulnerable human populations [17], or can be multi-faceted and consider a variety of assets important to a community [18].

The approach used for evaluating vulnerability components, and ranking or quantifying vulnerability itself, can also vary across a spectrum ranging from qualitative [19] to semi-quantitative [20] or quantitative [18]. Each approach can leverage the input of stakeholders or local experts, though the type of feedback solicited from stakeholders varies in each approach. The results of vulnerability assessments may therefore enjoy the credibility and buy-in associated with participatory planning [21,22], but are often limited in scope, either spatially or in terms of the types of assets or values that can be considered, simply because of the limitation on the number of perspectives that can be feasibly considered in workshop settings. In some instances, sea level rise vulnerability has been assessed semi-qualitatively at larger scales (i.e., for entire nations [23]) by leveraging expert elicitation and written survey results.

Quantitative, or data-driven, frameworks for the assessment of vulnerability that support climate adaptation are becoming more common [24]. These quantitative approaches offer several advantages over more qualitative approaches: They can be easily replicated and updated, and they are not limited by the reach of the expertise of the convened working group [25]. Quantitative approaches and frameworks for the assessment of sea level rise vulnerability also facilitate the consideration of very narrowly defined impact pathways associated with sea level rise driven hazards. Wang and Marsooli [26], for example, examined human safety vulnerabilities to storms as the sea level rises by coupling hydrodynamic model outputs with models defining how humans physically cope in potentially dangerous overland flows.

Quantitative approaches, though, are limited by the availability of data appropriate for the assets under consideration, or the scale at which the results of the assessment may be applied. The Coastal Vulnerability Index (CVI), for example, is one of the earliest quantitative vulnerability frameworks for sea level rise [27] and ranks the exposure of shorelines to erosion or flooding. The CVI has proven to be useful for managing coasts [28] but is limited in that it does not consider the distribution of infrastructure, critical habitats, or people in the coastal landscape. The results of the CVI, therefore, need to be further interpreted to determine where coastal changes co-occur with assets of value [23]. Data resolution can also limit the application of data-driven assessments of vulnerability to sea level rise. Fleming et al. [18], for example, implemented a powerful multi-hazard GIS-based assessment evaluating the climate vulnerability of areas in Los Angeles County, CA. Their framework relies to a large degree on data compiled for the U.S. Census and is therefore limited in resolution to census block groups, which may represent many thousands of people across many hundreds of square kilometers.

In 2018, the U.S. Environmental Protection Agency's (EPA) Puget Sound National Estuary Program funded a project selected from the Puget Sound Action Agenda, titled "Prioritizing Sea Level Rise Exposure and Habitat Sensitivity Across Puget Sound" [29], to develop a sea level rise vulnerability analysis to support restoration and land-use planning in Puget Sound, Washington (Figure 1). This project will be referred to in this manuscript as "the project" or "the study".

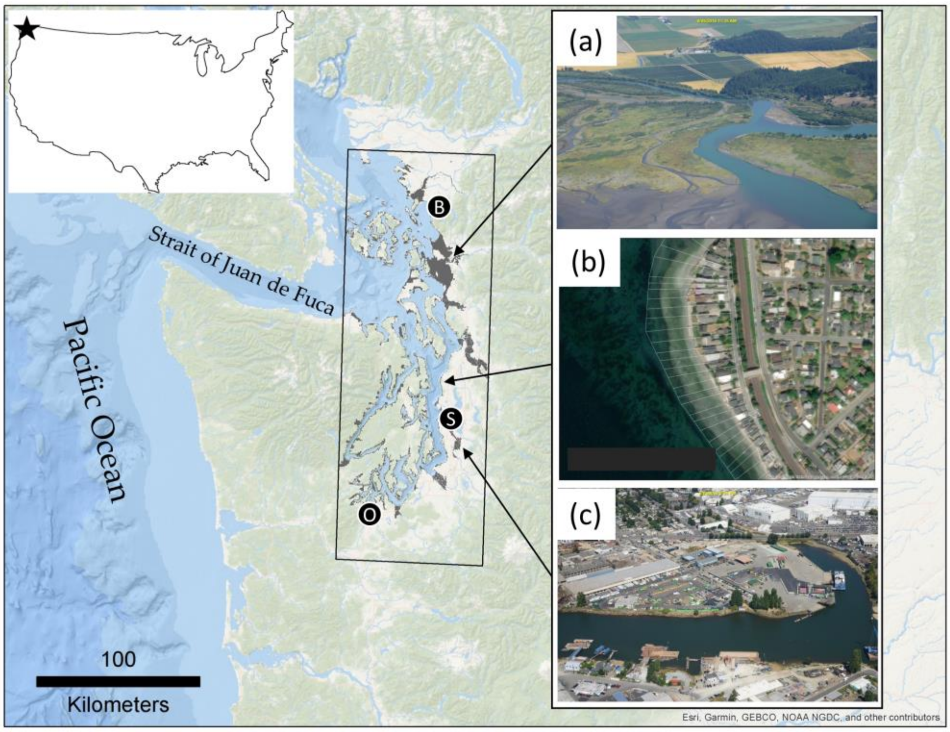

Figure 1. Overview map of the study area (black rectangle on map) in Puget Sound, Washington State, USA, and images of locations discussed in the text, including (**a**) the Skagit River delta, (**b**) parcels including portions of the intertidal area near Edmonds, Washington, and (**c**) the Duwamish River delta in Seattle. Aerial oblique images of the Skagit and Duwamish River deltas are from imagery collected by the Washington Department of Ecology in 2017. Three of Puget Sound's coastal cities, Bellingham (B), Seattle (S), and Olympia (O), are marked on the map with black circles for geographic reference.

The objectives of the project included:

1. Develop a data-driven framework, implementable in GIS and easily updateable as new data become available, for calculating an index of sea level rise vulnerability across a large spatial area (Puget Sound, Washington State).
2. Incorporate multiple hazards (erosion and flooding) into the assessment of sea level rise exposure.
3. Assess the sensitivity of the built and natural environment and include both in an overall evaluation of vulnerability.
4. Calculate results at scales appropriate for coastal decision-making. In the case of this project, a unique vulnerability index was calculated for every parcel within a sea level rise risk zone identified for Puget Sound (Figure 1).
5. Integrate measures of social vulnerability into an overall assessment of sea level rise vulnerability.

In this paper, we contribute to the literature on approaches for assessing sea level rise vulnerability by summarizing the methodology developed for this project and its results (for more detail, see Coastal Geologic Services et al. [30]). Puget Sound is also a geographically and geomorphologically diverse landscape, with low-lying deltas, steep bluff-backed shorelines, and agricultural, industrial, residential, and natural shoreline uses (Figure 1). Studies like this one, which attempt to evaluate vulnerability across a geographically diverse landscape, are rare. We also analyze elements of the quantitative methodology employed in the project to better understand the implications of the quantitative models employed.

2. Materials and Methods

2.1. Engagement and User-Community Input

A project advisory group of nine individuals provided feedback and advice during the development and implementation of this sea level rise vulnerability study. Members were recruited based on their expertise in habitat assessment and restoration, spatial analysis, and coastal policy in Puget Sound, and represented a cross-section of federal and state agencies, local governments, and engaged citizens. The advisory group was engaged approximately monthly via email and phone during the project and provided input on the selection of data and scoring and weighting approaches as they were developed. Additionally, three remote workshops were organized during the study to discuss methodology, determine data inputs, and present results.

2.2. Data Selection Criteria

Three data selection criteria enhanced the credibility and repeatability of the results: Included datasets needed to be (1) publicly available, (2) less than 10-years old and/or obtained from authoritative sources, and (3) regional in spatial scale with spatial bounds that included our entire study area. This final criterion acknowledged that the project lacked the capacity to assemble datasets that might be available for parts of Puget Sound, but unavailable in a consistent format for the entire region. Most counties in Puget Sound, for example, collect data on the type and condition of septic systems in their respective geographies. Those data, though, are not complete nor compiled into a single, regionally consistent database, and our project budget did not provide the capacity to collect and merge those datasets.

The study area for the project was developed by applying the data selection criteria described above to the selection of a digital elevation model [31], and then clipping a publicly available parcel database for Washington State [32] to the boundaries of the selected elevation dataset. The parcel layer was further refined by removing any parcels for which all parts of the parcel were more than 200 feet from the shoreline [33] and the minimum elevation on the parcel was greater than 30 feet relative to the North American Vertical Datum of 1988 (NAVD88). The intention of this refinement was to exclude parcels from the analysis that will not be feasibly impacted by sea level rise by 2100. Importantly, though, this refinement step was designed to include in the analysis parcels in Puget Sound that are at high elevation but close to the shoreline (for example, on coastal bluffs), and may be subject to impacts associated with erosion exacerbated by sea level rise.

Finally, the parcel database was manually trimmed to exclude areas that were represented as hydro-connected to marine waters in the elevation dataset but contained significant flow control structures. In the case of Puget Sound, this led to the exclusion of Lake Washington and Lake Union near Seattle, which are hydraulically disconnected from Puget Sound by a set of locks.

2.3. Vulnerability Framework

The overall framework for the quantitative estimation of vulnerability used in this project can be simply written as Vulnerability = Exposure + Sensitivity, modified from the approach described in the U.S. Climate Resilience Toolkit's "Steps to Resilience" [12]. This framework was applied to "assets," and for this project, the central "asset" was coastal and near-coastal parcels in Puget Sound that may be exposed to coastal flooding or erosion by 2100. The project framework lends itself to a three-phase project approach to include an exposure assessment phase, a sensitivity assessment phase, and a vulnerability assessment phase. Each is described in the sections below.

2.4. Exposure Assessment

Two hazards were accounted for in this exposure assessment: coastal flooding driven by tides, storm surges, and rising sea level, and coastal erosion. The coastal flooding exposure index was quantified by summing the percentage of each parcel under each of five inundation layers representing five different inundation scenarios (Table 1). Each inundation layer was constructed using spatially varying relative sea level projections for Washington State for the RCP8.5 emissions scenario [2] added to a 20-year return frequency, extreme coastal water level scenario for Puget Sound [34].

Table 1. Five different scenarios used to construct inundation layers. Sea level changes are drawn from [2] and vary spatially across the study area. The extreme coastal water level magnitude is drawn from [35] and is 2.9 ft above the local Mean Higher High Water tidal datum in Puget Sound.

Scenario	Sea Level Change Scenario	Sea Level Change Magnitude (ft)	Extreme Water Level Scenario (ft MHHW)
1	None	0.0	+2.9
2	2050, 50th percentile, RCP8.5	0.5–1.0	+2.9
3	2050, 1st percentile, RCP8.5	1.2–1.7	+2.9
4	2100, 50th percentile, RCP8.5	1.7–2.2	+2.9
5	2100, 1st percentile, RCP8.5	4.5–5.0	+2.9

The coastal erosion potential index evaluated the relative likelihood of erosion occurring on a given parcel and was calculated for every parcel with a marine shoreline, using an approach modified from Coastal Geologic Services et al. [35]. While the application of a physically based predictive erosion model would be preferred, no such model exists for the study area. Coastal erosion potential was evaluated based on a multiplicative combination (Table 2) of a shoreline type [35] ranking and the 1st percentile of significant wave height based on modelled historic waves [36], normalized to a range of 0–5. The coastal erosion potential index for parcels without a marine shoreline was zero.

Table 2. Scoring approach for the coastal erosion potential index, using shoretype mapping for Puget Sound [35], and the 1st percentile of the distribution of significant wave height, in feet, drawn from wave climatology modelling [36].

Shoretype Description	Shoretype Value	1st Percentile of H_s (ft)
No Appreciable Drift (NAD)-Bedrock	0	0-Max
No Appreciable Drift (NAD)-Low Energy	1	
No Appreciable Drift (NAD)-Modified Delta	2	
No Appreciable Drift (NAD)-Artificial, Pocket Beach, Transport Zone or Accretion Shoreform	3	
Feeder Bluff	4	
Feeder Bluff Exceptional	5	

Both the coastal flooding index and the coastal erosion potential index were summed to calculate the exposure score for each parcel (Figure 2). The resulting exposure score has a range of 0–10.

2.5. Sensitivity Assessment

Two separate sensitivity indices were evaluated: infrastructure sensitivity and habitat sensitivity (Figure 2). An infrastructure sensitivity index relatively ranks the potential impacts of flooding and erosion on buildings, roads, and critical infrastructure on or near a parcel. A habitat sensitivity index provides a quantitative assessment of the potential for existing coastal habitats to migrate on the parcel as sea level rises. These are described in more detail below.

2.5.1. Infrastructure Sensitivity Index

The infrastructure sensitivity index was derived from three index components: a "parcel infrastructure" component to relatively rank parcels based on the configuration of buildings on each parcel, an "accessibility reduction" component to characterize if transportation paths into and out of the parcel are compromised by flooding, and an "agricultural lands" component to represent possible negative effects of inundation or groundwater-flooding on existing agricultural lands.

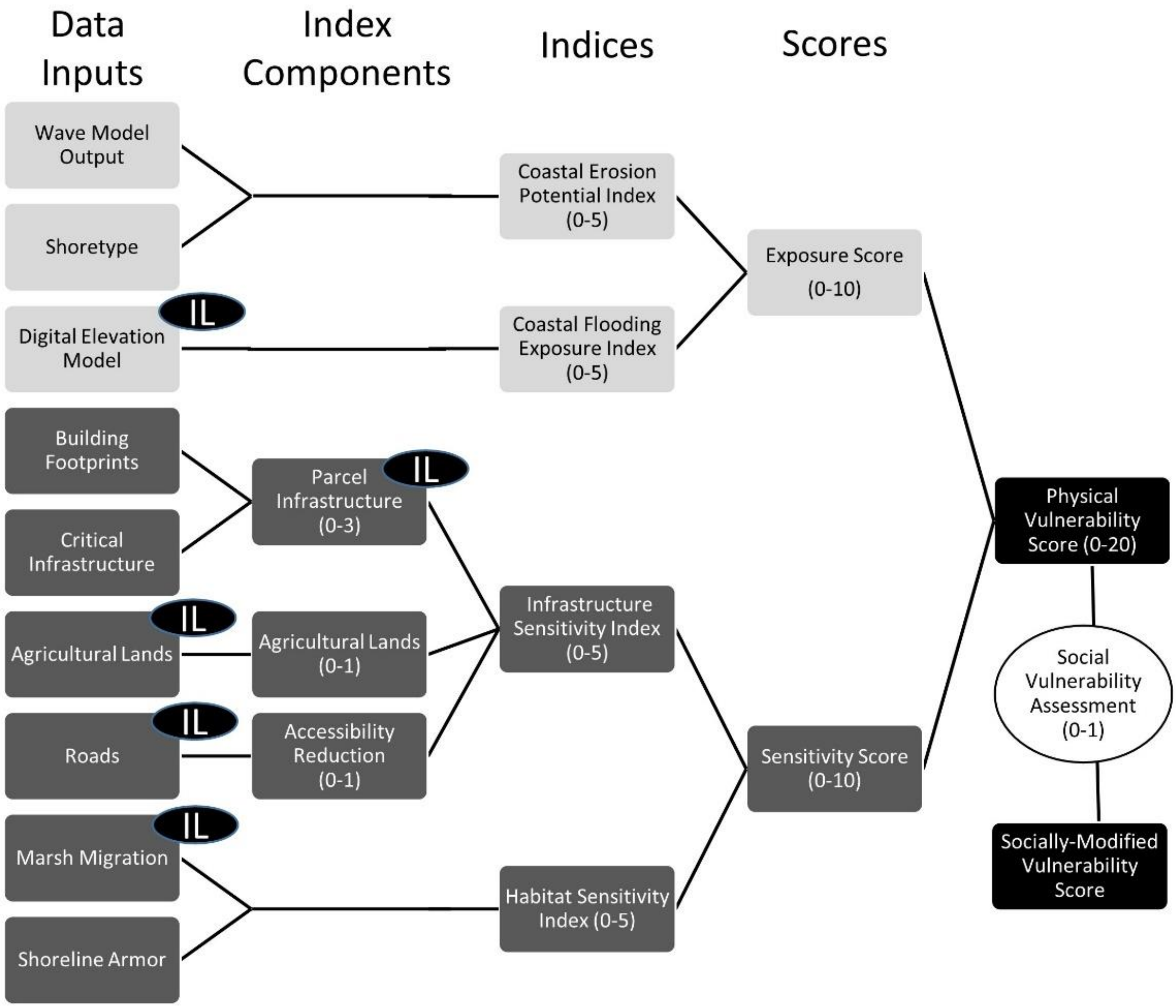

Figure 2. Model framework identifying data inputs and derived components, indices, and four primary results scores for exposure, sensitivity, physical vulnerability, and socially-modified vulnerability. The "IL" in the black oval designates where the five inundation layers developed for this project (Table 1) intersect with other datasets. Specific details regarding, and citations for, individual datasets shown here as "data inputs" are not included for brevity, but are described in [30].

The parcel infrastructure component for the infrastructure sensitivity index was based on mapped building footprints [37]. Building footprints were modified for this analysis in three ways:

(1) In some instances, building footprints slightly overlapped parcel boundaries, and these small overlaps were assumed to be an artifact of the process by which building footprints were derived from aerial photography. Building footprints that overlapped parcel boundaries were clipped to the boundaries of parcels.
(2) To remove any small residuals of clipped buildings from the step above, as well as very small structures, any building footprint with an area of <18.6 m^2 (200 ft2) was removed from the building footprint database.
(3) Critical infrastructure data [38], served as a series of points, was manually related to the building footprint layer, such that individual building footprints could be identified as schools, emergency response facilities, public transportation facilities, or other facilities associated with critical community services.

The parcel infrastructure component was calculated by summing the percentage of building area in each parcel inundated to a depth of >0.15 m (0.5 ft) under each of the five inundation scenarios (Table 1), with a 10% addition (scaled using input from the advisory group) to the score for buildings categorized as critical infrastructure. The resulting values were normalized to a range of 0–3. An inundation depth threshold was applied in this analysis step to reflect the relatively greater damage to roads and buildings associated with deeper inundation [39].

The accessibility reduction component was calculated to reflect potential impacts to ingress or egress from a parcel due to flooding, and it evaluated the percent of road length [40] within a defined distance of each parcel [30] inundated to depths greater than 0.15 m (0.5 ft) under each of the five inundation scenarios (Table 1). The five calculated percentages for each inundation scenario were summed and normalized to a range of 0–1.

The agricultural lands component characterized the degree to which parcels with agricultural uses may be negatively influenced by flooding as sea level rises, and parcels were characterized as agricultural in an agriculture database maintained by Washington State [41]. The agricultural lands component was calculated as the percentage of a parcel with agricultural uses inundated under each of the five scenarios (Table 1) and was normalized to a range of 0–1.

The resulting infrastructure sensitivity index for each parcel is a sum, in a range between 0–5, of the parcel infrastructure score, the accessibility reduction score, and the agricultural lands score.

2.5.2. Habitat Sensitivity Index

The sensitivity of coastal habitats in Puget Sound was evaluated under the assumption that those habitats will migrate in response to sea level rise [42] in the absence of topographic controls. The scoring approach for habitat sensitivity calculated a change in percent cover in each parcel of four habitat classes (Brackish/Transitional Wetland, Estuarine Wetland, Unconsolidated Shore, Palustrine Emergent Wetland) that were mapped for different sea level rise scenarios [43] and were connected to the five inundation scenarios selected for this project (Table 1). For shorelines backed by coastal bluffs, the sum of the percentage change in area of habitats was modified with a multiplier, intended to represent impacts to habitat-forming processes associated with erosion of coastal bluffs [44]. The multiplier was selected based on the presence or absence of armoring and the presence or absence of building footprints on the parcel (Table 3). Additional details on the calculation of the habitat sensitivity index are provided in [30].

Table 3. Selection criteria for a multiplier applied to the habitat sensitivity index, based on the shoreform mapped to the parcel and the presence or absence of shoreline armoring and development on the parcel.

Shoreform	Armored	Un-Armored	Developed	Un-Developed	Index Multiplier
Non-bluff	X	X	X	X	1
Bluff-backed	X		X		1.4
		X	X		1.2
	X			X	1.2
		X		X	0.8

The habitat sensitivity indices for all parcels were normalized to a scale between 0 and 5. The final sensitivity score for every parcel was calculated by summing the separate infrastructure and habitat sensitivity indices.

2.6. Vulnerability Scores

A physical vulnerability score for each parcel is the sum of the separate exposure score and infrastructure sensitivity score (Figure 2). While the concept of adaptive capacity is often a component of vulnerability [34], quantitative estimates of adaptive capacity at the resolution of parcels were infeasible in this analysis. Instead, a social vulnerability index was developed for zip code tabulation areas in the Puget Sound drainage basin [45]. This regionally modified social vulnerability index [46] used a principal components analysis on 50 chosen variables, such as median income, average family size, and percentage of households without access to a vehicle, which resulted in seven components contributing to social vulnerability that highlighted concepts such as diversity and urbanity, housing and infrastructure, and life satisfaction and belonging. Social vulnerability was scaled to a range between 0 (low social vulnerability) and 1 (high social vulnerability), and social vulnerability scores were then uniformly assigned to all parcels within each zip code tabulation area. With advisory group feedback, we chose to add these social vulnerability index scores to the raw physical vulnerability index scores for each parcel, with a weighting coefficient of 10, to offer a socially-modified vulnerability index. The intent of this approach was to provide insight regarding how community characteristics may act to reduce or enhance the vulnerability of individual parcels, but note that this approach provides a very incomplete perspective on the various individual attributes that contribute to vulnerability at the scale of parcels.

3. Results

The overall distribution of exposure, sensitivity, and physical vulnerability scores of the 111,239 parcels analyzed in this study are heavily skewed towards zero (Table 4), suggesting that the combination of topography, the distribution of habitats, and the distribution of built environment elements (such as buildings and roads) lead to a concentration of vulnerability in a relatively small number of parcels in Puget Sound. On the other side of the distribution of physical vulnerability scores, 961 parcels, 0.9% of the total, have a physical vulnerability score above 15, out of a maximum of 20 (Table 4). Our approach for integrating a social vulnerability index to generate an optional "socially-modified" vulnerability score for every parcel changed the score distribution considerably, narrowing and centralizing the overall distribution of scores such that only two parcels in the study area have a socially-modified vulnerability score of zero, and only 796 fall into the upper quartile of the range (Table 4).

Table 4. Descriptive statistics for the distribution of exposure, sensitivity, physical vulnerability, and socially-modified vulnerability scores within the study area.

Component	Zero	Median	Top Quartile
Exposure	35,704 (32.1%)	1.1 out of 10	118 (0.1%)
Sensitivity	13,307 (12.0%)	1.9 out of 10	525 (0.5%)
Physical Vulnerability	12,055 (10.8%)	3.5 out of 20	961 (0.9%)
Socially-modified Vulnerability	2 (0.0%)	7.9	796 (0.7%)

3.1. Exposure

Exposure to hazards exacerbated by sea level rise was evaluated here by summing separate indices for coastal erosion potential (Figure 3, left panel) and coastal flooding (Figure 3, middle panel). This approach resulted in a spatial distribution of the highest exposure scores in parcels that are flooded across a range of present and future inundation scenarios and are wave-exposed, with shorelines that are easily eroded (Figure 3, right panel).

The two indices of exposure were weighted equally in the summed exposure score; therefore, parcels that are ranked high for coastal flooding exposure can rank low for coastal erosion potential, and vice versa. For example, some parcels on large, low-lying river deltas, such as that of the Skagit River (Figure 1), are modelled to be entirely flooded during all inundation scenarios but have a coastal erosion score of zero as they are not directly exposed to wave energy. The relative distribution of the two indices suggests that for most parcels, one or the other of the two hazards predominate, with more parcels in Puget Sound having higher coastal flooding index values than high coastal erosion potential values (Figure 4).

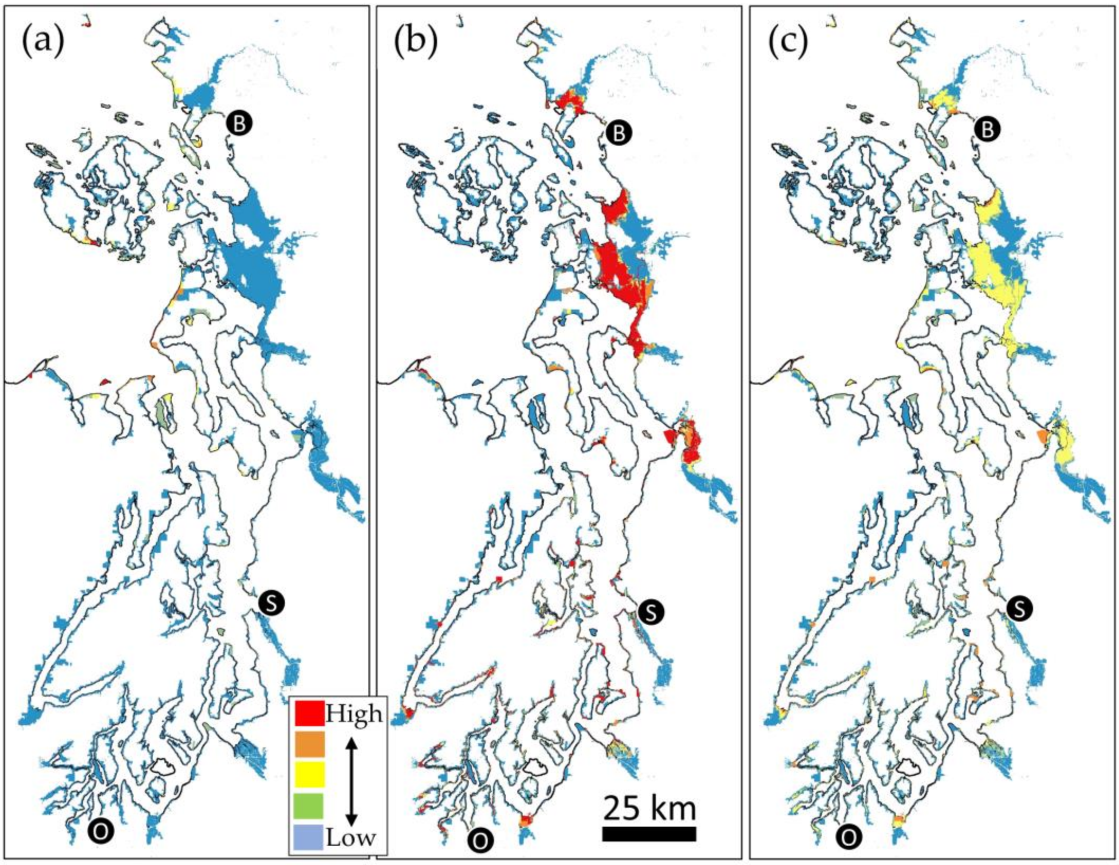

Figure 3. The spatial distribution of the (**a**) coastal erosion potential index, (**b**) coastal flooding index, and their sum, (**c**) the exposure score. Parcels are colored according to their score, where the range of possible scores are binned into five categories in equal intervals. Three of Puget Sound's coastal cities, Bellingham (B), Seattle (S), and Olympia (O), are marked on the map with black circles, and also in Figure 1, for geographic reference.

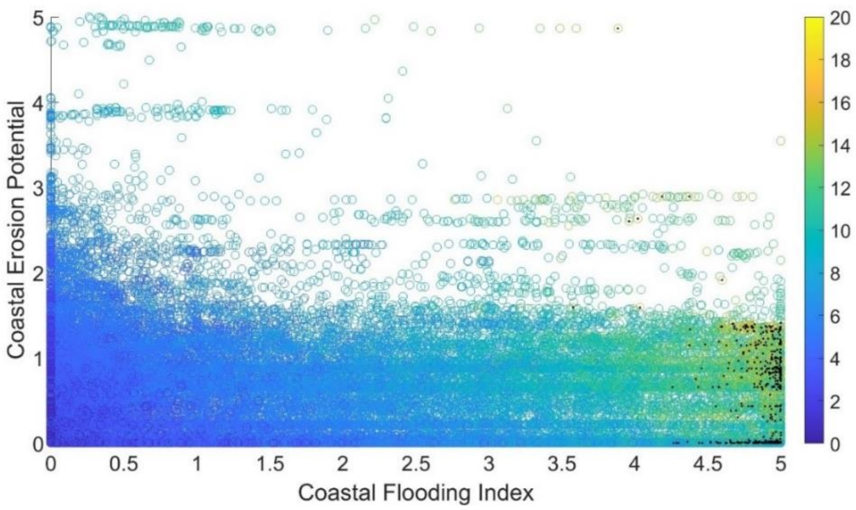

Figure 4. Patterns of exposure in Puget Sound illustrated by plotting the two exposure indices against each other. For context, the symbols are colored according to their physical vulnerability score, with the 961 parcels in the top quartile of the range (physical vulnerability score > 15) additionally marked with a black dot.

3.2. Sensitivity

The sensitivity index represents the degree to which assets of value on a parcel may be negatively affected by either flooding or erosion and is comprised of separate infrastructure and habitat sensitivity indices. The highest infrastructure sensitivity index values are heavily concentrated on large river deltas within Puget Sound (Figure 5b), probably because agricultural uses on a parcel factored into the score through an agricultural lands index, and many large river deltas on Puget Sound, are heavily agricultural (Figure 2). This assumption is supported by the generally broader distribution of high parcel infrastructure index component scores, which identified the presence of flood-impacted buildings on a parcel, across Puget Sound (Figure 5a). In other words, the highest scores for infrastructure sensitivity would be assigned in this assessment to flood-exposed parcels that include both buildings and agricultural lands. High habitat sensitivity scores are also relatively broadly distributed along the shoreline of Puget Sound (Figure 5, right panel), but with a relatively narrower overall distribution (in other words, fewer parcels were assigned high scores) as compared to other components of sensitivity evaluated in this study.

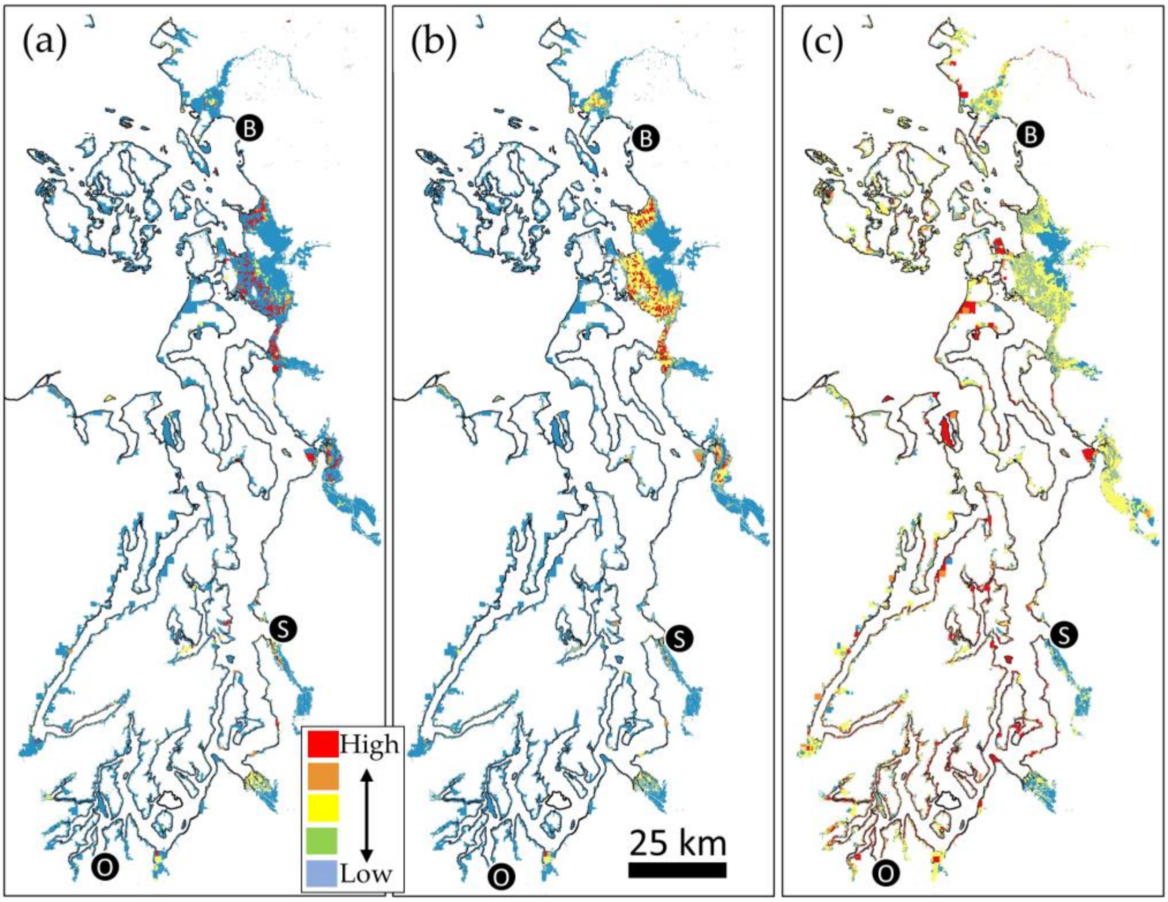

Figure 5. Distribution of the (**a**) parcel infrastructure index component, (**b**) infrastructure sensitivity index, and (**c**) habitat sensitivity index. Parcels are colored according to their score, where the range of possible scores are binned into five categories in equal intervals. Three of Puget Sound's coastal cities, Bellingham (B), Seattle (S), and Olympia (O), are marked on the map with black circles, and also in Figure 1, for geographic reference.

3.3. Vulnerability

The physical vulnerability score is a sum of the separate exposure and sensitivity scores (Figure 2). While there is a concentration of those parcels on the large river deltas (such as the Skagit River delta; Figure 1), we also find parcels with high physical vulnerability scattered broadly along the shoreline of the entire study area (Figure 6, left panel). The integration of a social vulnerability index to calculate a "socially-modified" vulnerability index shifts the geographic distribution of the highest vulnerability, elevating vulnerability in certain areas such as in the urban deltas of the Duwamish (Seattle) and Puyallup (Tacoma) Rivers (Figure 6).

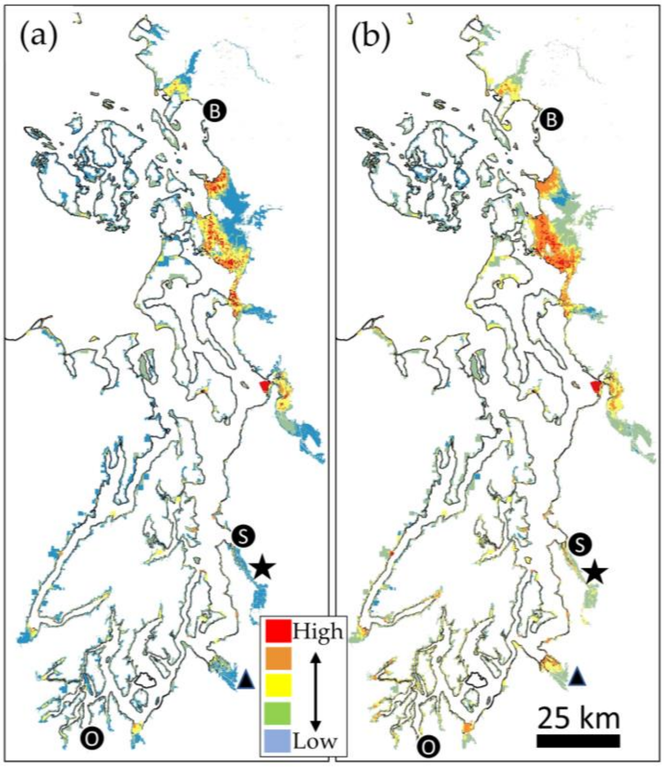

Figure 6. The spatial distribution of (**a**) physical vulnerability and (**b**) socially-modified vulnerability scores in Puget Sound. Parcels are colored according to their score, where the range of possible scores are binned into five categories in equal intervals. The Duwamish River delta and the Puyallup River delta, discussed in the text, are marked with a black star and black triangle, respectively. Three of Puget Sound's coastal cities, Bellingham (B), Seattle (S), and Olympia (O), are marked on the map with black circles, and also in Figure 1, for geographic reference.

4. Discussion

4.1. Key Insights

Three key insights emerged during this investigation of sea level rise vulnerability in Puget Sound, Washington. First, we found that quantitative approaches for evaluating sea level rise vulnerability can provide insights useful in management and decision-making contexts. Feedback from the project advisory group, as well as coastal planners and managers engaged in briefings after the analysis was completed, demonstrated an interest in, and a desire to access, the results. The feedback from those stakeholders, however, suggests a desire to modify the results by changing weightings or excluding various indicators or scores to tune the results for different applications. An interactive version of our database was outside of the scope of this project, but tools that allow users to interact meaningfully with sea level rise vulnerability data would enhance the usability of analyses such as those within this study.

Next, the skewness of the distribution of vulnerability score suggests that meaningful adaptation gains can be made in Puget Sound by focusing on a relatively small number of parcels. While additional validation of our results is warranted, only 961 parcels fell into the top quartile of the range of physical vulnerability scores, and only 796 fell into the top quartile of the range of socially modified vulnerability scores (Table 4). This suggests that relatively modest investments in adaptation measures, such as parcel acquisition, land-use conversion, or other actions, can reduce the impact of sea level rise in the Puget Sound region.

Finally, the inclusion of coastal erosion potential as an index, as well as the development and integration of a habitat sensitivity index in the overall evaluation of sensitivity, provide a broader perspective on vulnerability to sea level rise than investigations of flooding impacts to only infrastructure or habitat. For example, vulnerability to sea level rise in a landscape such as Puget Sound is not confined to low-lying developed areas, such as deltas, but can be found more broadly distributed on the landscape, including on shorelines backed by coastal bluffs, and even on undeveloped or lightly developed parcels. This insight acknowledges the broad range of services that shorelines provide and is crucial to the management of coastal areas.

4.2. The Impact of Data Limitations

The indices and scores derived in our assessment have important embedded assumptions and limitations that should be considered when interpreting the results and when developing similar assessments. A key limitation for data-driven projects such as this is the availability and quality of input data. Sea level rise projections, for example, are a key input to this analysis, but are uncertain [2], and updating the analysis as projections change would be useful. Another example of a data limitation is illustrated by the parcel infrastructure component of the infrastructure sensitivity score (Figure 5, left panel). The purpose of this index component was to characterize the relative sensitivity of buildings on a parcel, and our approach quantified the percentage of a building footprint inundated at modelled depths > 0.15 m (0.5 ft). This approach has a variety of important limitations because the building footprint layer includes no attributes that might be used to evaluate likely damages associated with flooding (e.g., building value, construction type, first floor elevation).

Our approach for evaluating the sensitivity of buildings also biases the potential damages to structures towards those associated with flooding and away from those associated with coastal erosion. A building footprint sitting on a parcel on a rapidly eroding coastal high bluff would, in our analysis, have a parcel infrastructure score of 0, even while there is a real and serious risk of damage to the structure. The consequences, we believe, manifested as an overall concentration of higher physical vulnerability index scores in those parcels with higher coastal flooding indices (Figure 4), and likely underestimate the vulnerability on parcels with high coastal erosion potential. This shortcoming could be addressed with a physically based predictive erosion model, which does not exist for the shorelines of Puget Sound at the time of publication.

4.3. The Impact of Assumptions

What we characterize as "assumptions", or ways in which social values and perceptions of importance are embedded in scores, are primarily due to choices made regarding calculating, weighting, and normalizing indices and scores. Two examples illustrate the impact of these choices. First, while the decision to use parcels as the spatial scale of analysis was rooted in an interest to make the results relevant to management decisions in Puget Sound, this decision has important implications for the scores themselves. Parcels in Puget Sound can include intertidal areas (Figure 1) or can, in some cases, be entirely located within the intertidal zone. In those instances, our approach for calculating a coastal flooding index should be expected to over-estimate a parcel's actual vulnerability to coastal flooding. We could not evaluate the sensitivity of our results to this assumed bias, but in future analyses would recommend that parcels be clipped to exclude intertidal area or revise the index to account for the change in flooded area across scenarios, rather than the total flooded area.

Parcels also vary considerably in size, which could potentially bias the coastal flooding index calculated in this analysis. For example, it is less likely for a large parcel to be entirely inundated than a smaller one, which could lead to a bias towards higher coastal flood index values, and therefore higher exposure and vulnerability, for smaller parcels. Our results suggest that there is not a systematic bias in coastal flooding index values with parcel size (Figure 7), but the implications of analysis methodologies on overall results should be carefully considered and communicated to users wherever possible.

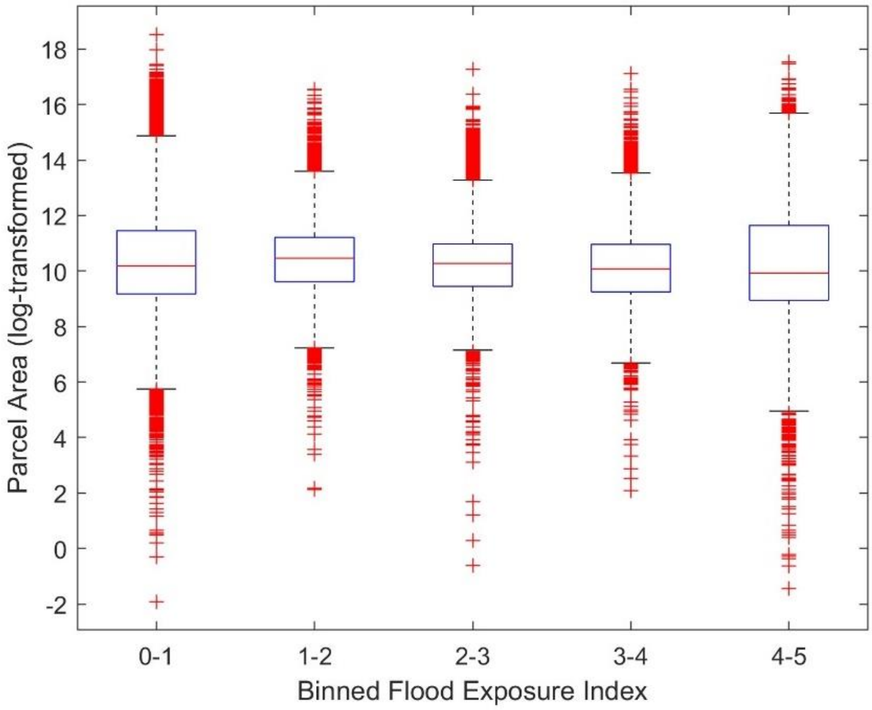

Figure 7. The distribution of log-transformed parcel areas in five coastal flood exposure index bins.

Another important example of the way in which decisions regarding calculating scores may influence the results in this assessment is illustrated by the decision to sum exposure and sensitivity to calculate physical vulnerability, versus using a multiplicative approach. We investigated the influence of the two calculations and found that the multiplicative approach created even greater skewness in physical vulnerability scores and lowered the vulnerability scores for those parcels in the middle of the range (Figure 8). Summing exposure and sensitivity, though, has its own implications, in that a parcel can have a non-zero vulnerability score even where either the exposure index or sensitivity index is zero. While theoretically inconsistent with some definitions of vulnerability, the chosen summation approach was selected by both the project team and the advisory group to acknowledge the limitations of our data (i.e., we are likely to imperfectly assess either exposure or insensitivity) as well as to acknowledge the role that social organizations, such as communities and neighborhoods, play in driving vulnerability [46]. For example, some burden may be placed on parcels with no exposure or sensitivity if an adjacent or nearby parcel is impacted by hazards exacerbated by sea level rise. The implications of this decision, though, are important. In our analysis, 36,956 parcels, or 33% of the total, have either an exposure or sensitivity index of zero, whereas only 12,055 (10.8%) parcels have both an exposure and sensitivity index of zero. The difference between those two values, 24,901 parcels (20.2%), may therefore be mischaracterized as having some vulnerability despite having either zero exposure or zero sensitivity.

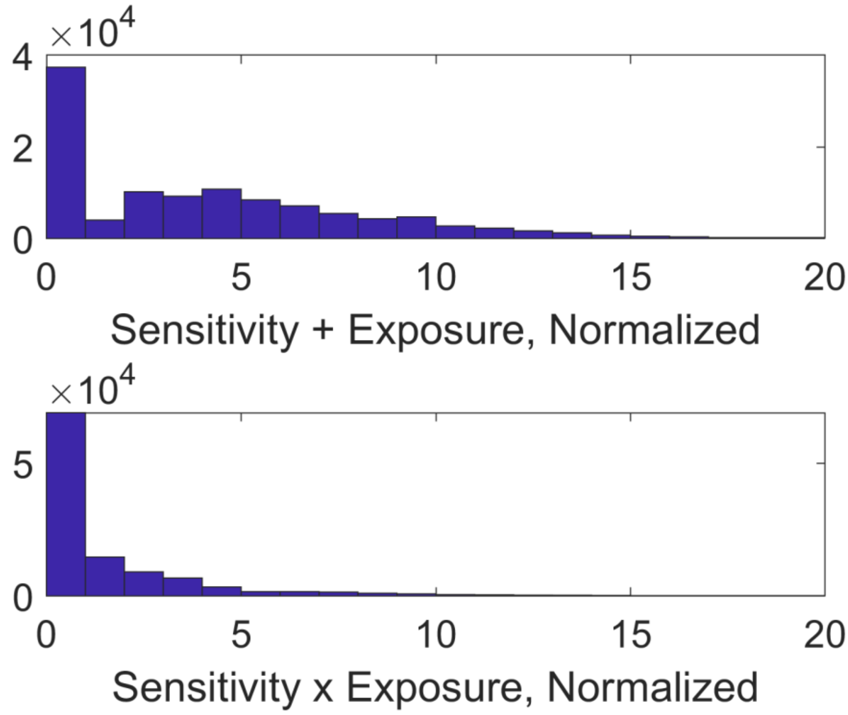

Figure 8. Distributions of the vulnerability score resulting from two different approaches for calculating vulnerability from exposure and sensitivity scores; summing exposure and sensitivity scores (**top panel**) or multiplying exposure and sensitivity scores (**bottom panel**).

We employed two approaches to limit the impact of these assumptions and limitations. First, the project was conceived and led by a team that lives in Puget Sound, works professionally in disciplines associated with coastal management, and who proposed the project with a sense for the goals and priorities of coastal stakeholders. This approach is notable in that an argument can be made that many of the elements of the vulnerability framework of Fleming et al. [17] are associated with building a shared understanding of value that, in our case, may have been embedded in the project conception. Next, the advisory group convened to support this project carefully considered and advised the project team on the implications of embedded assumptions of selected methodologies and relied heavily on their feedback to "get it right."

One way to address the limitations described in the section above would be to independently evaluate sea level rise vulnerability on parcels in Puget Sound and compare those results to those presented here. No validation process was conducted as part of this analysis, and the validation of a relatively abstract concept like vulnerability is difficult to conceptualize. An independent assessment of the vulnerability of parcels in Puget Sound, or even an independent quantitative framework for evaluating that vulnerability, would be a valuable contribution.

4.4. Potential Planning and Policy Applications

While deriving insights regarding the nature of vulnerability in a coastal landscape is valuable, finding applications for those insights in planning and/or policy contexts was an important goal for the project team and for the funders of this assessment. This project was funded and conducted with coastal management in mind and was oriented towards applications in coastal management settings. The choice to analyze parcels was made to support decisions that restoration practitioners and coastal planners often make regarding where and how to design projects or implement management policies and which landowners to engage as partners. Both the physical and socially-modified vulnerability indices may be useful within these management contexts. For example, a parcel or group of parcels with high physical vulnerability might be targeted for restoration efforts, especially if it is a key ecological area or serves as a buffer to inland areas with higher socially-modified vulnerability. On the other hand, a parcel or group of parcels with moderate to high physical and socially-modified vulnerability might be targeted for restoration or adaptation actions that restore ecological function but also provide mental health or community well-being improvements, especially in underserved communities [17,47].

To illustrate other possible applications, we discuss three potential use cases for the data and insights derived from this project, noting that there are certainly more not explored in this paper. Some of the proposed applications described below leverage our indices, or index components, rather than scores, and therefore avoid some of the limitations and assumptions described above.

First, the data compiled for this analysis would support the identification of impact thresholds for planning approaches such as Dynamic Adaptive Policy Pathways [48], which is a useful approach for climate adaptation planning in large, complex geographies [49]. Using the dataset compiled for this project, for example, we can identify flooding scenarios that lead to relatively large increases in parcel flooding or building interactions (Figure 9). These insights can then be used to tie adaptive pathways to observed sea level changes.

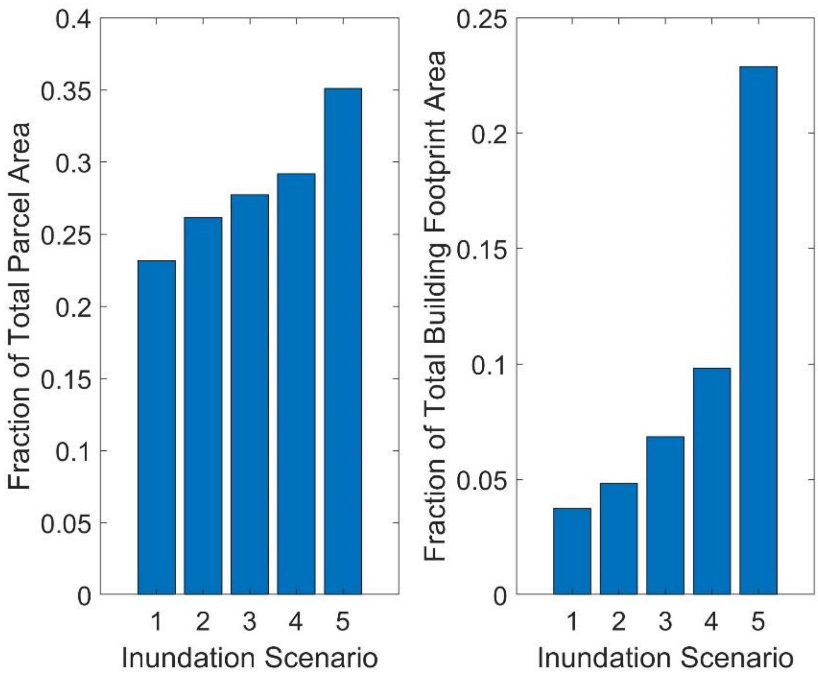

Figure 9. Fraction of the total region-wide parcel area in our study area (**left panel**) and building footprint area (**right panel**) inundated under each of the five flooding scenarios (Table 1) modelled during this project.

Next, the data and analyses compiled during this project could aid in identifying parcels to target for resilience investments that provide long-term benefits. Miller et al. [50] show, for example, that investments in measures that reduce the damage of existing buildings to flooding (e.g., elevating or flood-proofing structures) are not warranted where there is an erosion risk or are less beneficial where impacts to surrounding services (e.g., routes of ingress or egress) are relatively high. The data in this analysis could be leveraged to identify parcels where those conditions are or are not met and optimize investments of time and money into those actions.

Finally, the exposure and sensitivity scores calculated in this project can provide a foundation for economic impact analyses, such as those described in NOAA's Economic Framework for Coastal Community Infrastructure [51]. Accounting for financial costs and benefits in climate-related decisions is especially important in the context of large expenditures on infrastructure, and easy-to-access tools that can aid in those decisions are in demand [51]. The types of data compiled in projects like the one described here link almost seamlessly with economic analysis frameworks and are enhanced when combined with additional local datasets (if combined, for example, with county assessor data for parcel or structure value).

5. Conclusions

We present a first-of-its-kind sea level rise vulnerability analysis for Puget Sound, Washington State, in which a vulnerability score was developed for 111,239 parcels, calculated from separate exposure and sensitivity scores. This approach demonstrates the feasibility of conducting vulnerability assessments at relatively large spatial scales (i.e., across Puget Sound), but at a relatively granular spatial resolution (parcels) that is relevant to management and decision-making by land-use planners, landowners, restoration practitioners, hazard planners, and other local decision-makers. Quantitative approaches such as the one described here can help to address limitations associated with more traditional, qualitative, or semi-qualitative vulnerability assessment processes by reducing barriers to access vulnerability information.

The results suggest that parcels in Puget Sound vary widely in their vulnerability and that investments directed towards the relatively small number of parcels with the highest vulnerability could yield significant benefits and reduce Puget Sound's overall vulnerability. We also found that parcels with the highest vulnerability are not found only on Puget Sound's large river deltas or on low elevation shorelines but are more broadly distributed on the landscape, including relatively high-elevation parcels with eroding shores. This conclusion illustrates the importance of accounting for multiple hazards exacerbated by sea level rise, not just flooding, when assessing vulnerability. The calculation and inclusion of an equally weighted habitat sensitivity index in our vulnerability score recognizes the habitat values of shorelines and can provide particularly important insights to adaptation planning processes that seek broad benefits. Related to this, we argue that while physical vulnerability mapping is useful for applied management efforts, the integration of social data further highlights areas of potential co-benefit. For example, restoration efforts directed at physically and socially vulnerable parcels may bolster both natural ecosystems and community well-being.

This analysis contributes to the growing literature describing approaches for evaluating vulnerability to climate impacts in the Puget Sound region of the U.S. and beyond. As such, it is important to recognize the various limitations and assumptions embedded in the analysis. Limitations are often a function of data availability and quality, and analyses such as those presented here will improve as new and/or improved datasets become available. Assumptions that influence results are primarily associated with how indicators are calculated, how they are weighted as scores, and how indices are developed. Making results available in a format that permits end-users to modify those calculations or weightings is desirable.

Author Contributions: Conceptualization, I.M. and J.J.; methodology, I.M., A.M., J.J., C.F. and S.R.; formal analysis, A.M., C.F., I.M. and S.R.; data curation, A.M. and I.M.; writing—original draft preparation, I.M. and A.M.; writing—review and editing, I.M., A.M., J.J, C.F. and S.R.; funding acquisition, I.M. and J.J. All authors have read and agreed to the published version of the manuscript.

Funding: This project was funded primarily by the United States Environmental Protection Agency under assistance agreement PC-01J22301 through the Washington Department of Fish and Wildlife, with additional support from the National Science Foundation, award # 2103713, "The Cascadia Coastlines and People Hazards Research Hub".

Informed Consent Statement: Not applicable.

Data Availability Statement: A geodatabase of input data and results described in this manuscript, the technical report cited in the text (Coastal Geologic Services, et al., 2022 [30]), and high resolution results maps can be downloaded from https://wacoastalnetwork.co/puget-sound-parcel-scale-sea-level-rise-vulnerability-assessment/ (accessed on 1 December 2022).

Acknowledgments: The approaches used in this study are based in part on intellectual contributions made by Abraham Im and Quince Hara, students in the Spring 2020 Geography 469 course at the University of Washington, and Robert Knapp and Hansi Hals of the Jamestown S'Klallam Tribe, and especially Emily Mastrianni, who led the development of a pilot parcel-scale vulnerability analysis for the Dungeness River delta in Washington State. We also relied heavily on the contributions of our project advisory group, including Kevin Zerbe (Washington Emergency Management Department), Harriet Morgan and Tish Conway-Cranos (Washington Department of Fish and Wildlife), Bobbak Talebi (Washington Department of Ecology), Travis Ball (US Army Corps of Engineers), Thomas Moore (NOAA Office of Coastal Management), Nicole Faghin (Washington Sea Grant), John Lovie, and David Trimbach. Their contributions and insights to this project were invaluable. Finally, the project managers for the project also shaped the approach and analysis, and include Jennifer Griffiths, Cynthia Catton, and Matthew Lurie, with the Washington Department of Fish and Wildlife. Finally, Jackson Blalock (Washington Sea Grant), provided important manuscript reviews and feedback.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Nerem, R.S.; Beckley, B.D.; Fasullo, J.T.; Hamlington, B.D.; Masters, D.; Mitchum, G.T. Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 2022–2025. [CrossRef] [PubMed]
2. Miller, I.M.; Morgan, H.; Mauger, G.; Newton, T.; Weldon, R.; Schmidt, D.; Welch, M.; Grossman, E. Projected Sea Level Rise for Washington State—A 2018 Assessment. A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, University of Oregon, University of Washington, and US Geological Survey; Prepared for the Washington Coastal Resilience Project. 2018. Available online: https://wacoastalnetwork.com/research-and-tools/slr-resources/ (accessed on 17 October 2022).
3. Vitousek, S.; Barnard, P.; Fletcher, C.H.; Frazer, N.; Erikson, L.H.; Storlazzi, C. Doubling of coastal flooding frequency within decades due to sea-level rise. *Sci. Rep.* **2017**, *7*, 1399. [CrossRef] [PubMed]
4. Vitousek, S.; Barnard, P.L.; Limber, P.; Erikson, L.H.; Cole, B. A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change. *J. Geophys. Res. Earth Surf.* **2017**, *122*, 782–806. [CrossRef]
5. Befus, K.M.; Barnard, P.L.; Hoover, D.J.; Hart, J.A.F.; Voss, C.I. Increasing threat of coastal groundwater hazards from sea-level rise in California. *Nat. Clim. Change* **2020**, *10*, 946–952. [CrossRef]
6. Graham, S.; Barnett, J.; Fincher, R.; Hurlimann, A.; Mortreux, C.; Water, E. The social values at risk from sea-level rise. *Environ. Impact Assess. Rev.* **2013**, *41*, 45–52. [CrossRef]
7. Moser, S.C.; Ekstrom, J.A. A Framework to Diagnose Barriers to Climate Change Adaptation. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 22026–22031. [CrossRef]
8. Magnan, A.K.; Oppenheimer, M.; Garschagen, M.; Buchanan, M.K.; Duvat, V.K.E.; Forbes, D.L.; Ford, J.D.; Lamber, E.; Petzold, J.; Renaud, F.G.; et al. Sea level rise risks and societal adaptation benefits in low-lying coastal areas. *Sci. Rep.* **2022**, *12*, 10677. [CrossRef]
9. Emergency Preparedness Demonstration Project. Community Based Vulnerability Assessment: A Guide to Engaging Communities in Understanding Social and Physical Vulnerability to Disasters. 2009. Available online: http://srdc.msstate.edu/readycommunity/files/mdc_vulnerability_assessment.pdf (accessed on 5 October 2022).
10. Food and Drug Administration (FDA). Vulnerability Assessments of Food Systems: Final Summary Report, June 2009–February 2012. 2012. Available online: https://www.fda.gov/media/84376/download (accessed on 5 October 2022).
11. Cybersecurity and Infrastructure Security Agency (CISA). CISA Stakeholder-Specific Vulnerability Categorization Guide. 2022. Available online: https://resources.sei.cmu.edu/library/asset-view.cfm?assetid=653459 (accessed on 5 October 2022).
12. United States Global Change Research Program (USGCRP); US Climate Resilience Toolkit: Steps to Resilience. 2016. Available online: https://toolkit.climate.gov/#steps (accessed on 15 November 2022).
13. Meyers, M.R.; Barnard, P.L.; Beighley, E.; Cayan, D.R.; Dugan, J.E.; Feng, D.; Hubbar, D.M.; Iacobellis, S.F.; Melack, J.M.; Page, H.M. A multidisciplinary coastal vulnerability assessment for local government focused on ecosystems, Santa Barbara area, California. *Ocean. Coast. Manag.* **2018**, *182*, 104921. [CrossRef]
14. D'Acunto, L.E.; Romañach, S.S.; Haider, S.M.; Hackett, C.E.; Nestler, J.H.; Shinde, D.; Pearlstine, L.G. *The Everglades vulnerability analysis—Integrating ecological models and addressing uncertainty*; U.S. Geological Survey Fact Sheet 2021–3033; U.S. Geological Survey: Washington, DC, USA, 2021. Available online: https://pubs.usgs.gov/fs/2021/3033/fs20213033.pdf (accessed on 15 November 2022).
15. Lentz, E.E.; Stippa, S.R.; Thieler, E.R.; Plant, N.G.; Gesch, D.B.; Horton, R.M. *Evaluating Coastal Landscape Response to Sea-Level Rise in the Northeastern United States—Approach and Methods, version 2.0, December 2015*; U.S. Geological Survey Open-File Report 2014–1252; U.S. Geological Survey: Washington, DC, USA, 2015. Available online: https://pubs.usgs.gov/of/2014/1252/pdf/ofr2014-1252.pdf (accessed on 10 March 2022).

16. Filosa, G.; Plovnick, A.; Stahl, L.; Miller, R.; Pickrell, D. *Assessment and Adaptation Framework*, 3rd ed.; FHWA-HEP-18-020; US Department of Transportation, Federal Highway Administration: Washington, DC, USA, 2017. Available online: https://rosap.ntl.bts.gov/view/dot/36188 (accessed on 5 October 2022).
17. US Environmental Protection Agency (EPA). *Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts*; 430-R-21-003; U.S. Environmental Protection Agency, EPA: Washington, DC, USA, 2021. Available online: https://www.epa.gov/cira/social-vulnerability-report (accessed on 6 May 2022).
18. Fleming, C.S.; Regan, S.D.; Freitag, A.; Burkart, H. Indicators and participatory processes: A framework for assessing integrated climate vulnerability and risk as applied in Los Angeles County, California. *Nat. Hazards* **2022**, *115*, 2069–2095. [CrossRef]
19. Stephens, S.H.; DeLorme, D.E.; Hagen, S.C. Coastal Stakeholders' Perceptions of Sea Level Rise Adaptation Planning in the Northern Gulf of Mexico. *Environ. Manag.* **2020**, *66*, 407–418. [CrossRef]
20. Petersen, A.; Hals, H.; Rot, B.; Bell, J.; Miller, I.M.; Parks, J.; Stults, M. Climate change and the Jamestown S'Klallam Tribe: A customized approach to climate vulnerability and adaptation planning. *Mich. J. Sustain.* **2014**, *2*. [CrossRef]
21. Bassett, E.; Shandas, V. Innovation and ClimateAction Planning. *J. Am. Plan. Assoc.* **2010**, *76*, 435–450. [CrossRef]
22. van Aalst, M.K.; Cannon, T.; Burton, I. Community level adaptation to climate change: The potential role of participatory community risk assessment. *Glob. Environ. Chang.* **2008**, *18*, 165–179. [CrossRef]
23. Beeharry, Y.D.; Bekaroo, G.; Bokhoree, C.; Phillips, M.R. Impacts of sea-level rise on coastal zones of Mauritius: Insights following calculation of a coastal vulnerability index. *Nat. Hazards* **2022**, *114*, 27–55. [CrossRef]
24. Bevacqua, A.; Yu, D.; Zhang, Y. Coastal vulnerability: Evolving concepts in understanding vulnerable people and places. *Environ. Sci. Policy* **2018**, *82*, 19–29. [CrossRef]
25. Hooijer, A.; Vernimmen, R. Global LiDAR land elevation data reveal greatest sea-level rise vulnerability in the tropics. *Nat. Commun.* **2021**, *12*, 3592. [CrossRef]
26. Wang, Y.; Marsooli, R. Physical Instability of Individuals Exposed to Storm-Induced Coastal Flooding: Vulnerability of New Yorkers during Hurricane Sandy. *Water Resour. Res.* **2020**, *57*, e2020WR028616. [CrossRef]
27. Thieler, E.R.; Hammar-Klose, E.S. National Assessment of Coastal Vulnerability to Sea-Level Rise: U.S. Atlantic Coast; U.S. Geological Survey, Open-File Report 99-593. 1999. Available online: https://pubs.usgs.gov/of/1999/of99-593/ (accessed on 11 October 2022).
28. Hammar-Klose, E.S.; Pendleton, E.A.; Thieler, E.R.; Williams, S.J. Coastal Vulnerability Assessment of Cape Cod National Seashore (CACO) to Sea-Level Rise; U.S. Geological Survey, Open File Report 02-233. 2003. Available online: https://pubs.usgs.gov/of/2002/of02-233/caco.htm (accessed on 11 October 2022).
29. Puget Sound Partnership. The 2018–2022 Action Agenda for Puget Sound. 2018. Available online: https://www.psp.wa.gov/2022AAupdate.php (accessed on 4 December 2022).
30. Coastal Geologic Services; Maverick, A.; Johannessen, J.; Miller, I.M. Prioritizing Sea Level Rise Exposure and Habitat Sensitivity Across Puget Sound Final Technical Report; Prepared for EPA's National Estuary Program in support of Near-Term Action 2018-0685, Bellingham, WA, USA. 2022, p. 46. Available online: https://wacoastalnetwork.com/puget-sound-parcel-scale-sea-level-rise-vulnerability-assessment/ (accessed on 4 December 2022).
31. Tyler, D.J.; Danielson, J.J.; Grossman, E.E.; Hockenberry, R.J. Topobathymetric Model of Puget Sound, Washington, 1887 to 2017, U.S. Geological Survey Data Release 2020. Available online: https://www.sciencebase.gov/catalog/item/5d72b5dfe4b0c4f70cffa775 (accessed on 7 April 2020).
32. Rogers, L.W.; Cooke, A.G. *Washington State Parcel Database—Parcel Feature Class*; School of Environmental and Forest Sciences, College of the Environment, University of Washington: Washington, DC, USA, 2012; Available online: http://www.ruraltech.org/gis/parcels/ (accessed on 7 April 2020).
33. Washington Department of Natural Resources (WDNR). *Washington State Shorezone Inventory Linear Unit Features (GIS Shapefile), Nearshore Habitat Program*; Washington Department of Natural Resources, Aquatic Resources Division: Olympia, WA, USA, 2012. Available online: https://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science/nearshore-habitat-inventory (accessed on 7 April 2020).
34. Miller, I.M.; Yang, Z.; VanArendonk, N.; Grossman, E.; Mauger, G.S.; Morgan, H. *Extreme Coastal Water Level in Washington State: Guidelines to Support Sea Level Rise Planning*; A Collaboration of Washington Sea Grant, Pacific Northwest National Laboratory and U.S. Geological Survey 2019, Prepared for the Washington Coastal Resilience Project; University of Washington Climate Impacts Group, Oregon State University, University of Washington: Washington, DC, USA, 2019. Available online: https://wacoastalnetwork.com/research-and-tools/slr-resources/ (accessed on 17 October 2022).
35. Coastal Geologic Services; MacLennan, A.; Lubeck, A.; Ode-Giles, L.; Johannessen, J.; Schlenger, P. Beach Strategies for Puget Sound, Phase 2 Summary Report; Prepared for the Estuary and Salmon Restoration Program of the Washington Department of Fish and Wildlife, Bellingham, WA, USA. 2020. Available online: https://salishsearestoration.org/wiki/File:CGS_ESRP_BeachStrategies_Phase2Report_Sept2020_revised.pdf (accessed on 7 April 2020).
36. Yang, Z.; Garcia-Medina, G.; Wu, W.C.; Wang, T.; Leung, L.R.; Castrucci, L.; Mauger, G.S. Modeling analysis of the swell and wind-sea climate in the Salish Sea. *Estuar. Coast. Shelf Sci.* **2019**, *224*, 289–300. [CrossRef]
37. Microsoft. Microsoft Building Footprints—WA. 2018. Available online: https://wiki.openstreetmap.org/wiki/Microsoft_Building_Footprint_Data (accessed on 7 April 2020).

38. Federal Emergency Management Agency (FEMA). HAZUS Inventory Technical Manual: Hazus 4.2 Service Pack 3. 2018. Available online: https://www.fema.gov/sites/default/files/documents/fema_hazus-inventory-technical-manual-4.2.3.pdf (accessed on 5 October 2022).
39. Pregnolato, M.; Ford, A.; Wilkinson, S.M.; Dawson, R.J. The impact of flooding on road transport: A depth-disruption function. *Transp. Res. Part D Transp. Environ.* **2017**, *55*, 67–81.
40. OpenStreetMap Contributors. Washington State Roads. 2015. Available online: https://planet.openstreetmap.org (accessed on 7 April 2020).
41. Washington State Department of Agriculture. Agricultural Land Use Geodatabase. Available online: https://agr.wa.gov/departments/land-and-water/natural-resources/agricultural-land-use (accessed on 7 April 2020).
42. Kairis, P.A.; Rybczyk, J.M. Sea level rise and eelgrass (*Zostera marina*) production: A spatially explicit relative elevation model for Padilla Bay, WA. *Ecol. Model.* **2010**, *221*, 1005–1016. [CrossRef]
43. Office for Coastal Management. NOAA Office for Coastal Management Marsh Migration. Available online: https://www.fisheries.noaa.gov/inport/item/55958.2022 (accessed on 3 March 2021).
44. Limber, P.W.; Barnard, P.L.; Vitousek, S.; Erikson, L.H. A model ensemble for projecting multidecadal coastal cliff retreat during the 21st century. *J. Geophys. Res. Earth Surf.* **2018**, *123*, 1566–1589. [CrossRef]
45. Fleming, C.S.; Regan, S.D. *A Complementary Social Vulnerability Assessment to Support Sea Level Rise Planning in the Puget Sound Region of Washington State*; NOAA Technical Memorandum NOS NCCOS 302: Silver Spring, MD, USA, 2022. Available online: https://repository.library.noaa.gov/view/noaa/37524 (accessed on 4 December 2022).
46. Cutter, S.L.; Boruff, B.J.; Shirley, W.L. Social vulnerability to environmental hazards. *Soc. Sci. Q.* **2003**, *84*, 242–261. [CrossRef]
47. Bowen, K.J.; Lynch, Y. The public health benefits of green infrastructure: The potential of economic framing for enhanced decision-making. *Curr. Opin. Environ. Sustain.* **2017**, *25*, 90–95. [CrossRef]
48. Haasnoot, M.; Kwakkel, J.H.; Walker, W.E.; ter Maat, J. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Glob. Environ. Chang.* **2013**, *23*, 485–498. [CrossRef]
49. Collini, R.C.; Carter, J.; Auermuller, L.; Engemann, L.; Hintzen, K.; Gambill, J.; Johson, R.E.; Miller, I.M.; Schafer, C.; Stiller, H. Guide for the 2022 Sea Level Rise Technical Report; National Oceanic and Atmospheric Administration Office for Coastal Management, Mississippi–Alabama Sea Grant Consortium (MASGP-22-028), and Florida Sea Grant (SGEB 88). 2022. Available online: https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html#application-guide (accessed on 4 December 2022).
50. Miller, I.; Faghin, N.; Fishman, S. Sea Level Rise and Management Options for Washington's shorelines; A Collaboration of Washington Sea Grant and the Washington Department of Ecology; Prepared for the Washington Coastal Resilience Project. 2022. Available online: https://wacoastalnetwork.com/research-and-tools/slr-resources/ (accessed on 4 December 2022).
51. Eastern Research Group, Inc. *What Will Adaptation Cost? An Economic Framework for Coastal Community Infrastructure, Final Report*; Written under Contract for the National Oceanic and Atmospheric Administration, Coastal Services Center; National Oceanic and Atmospheric Administration: Washington, DC, USA, 2013. Available online: https://coast.noaa.gov/data/digitalcoast/pdf/adaptation-report.pdf (accessed on 4 March 2022).