Prioritizing Sea Level Rise Exposure and Habitat Sensitivity Across Puget Sound

Final Technical Report
EPA's National Estuary Program Near-Term Action 2018-0685

Prepared for the Puget Sound National Estuary Program
Prepared by Coastal Geologic Services, Inc., April 2022

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Prioritizing Sea Level Rise Exposure and Habitat Sensitivity Across Puget Sound, Final Technical Report

Prepared for the Puget Sound National Estuary Program

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Executive Summary

Sea level rise (SLR) will subject Puget Sound shores to a change in the magnitude and frequency of coastal flooding, with cascading effects of accelerated erosion, habitat loss, and other impacts at the local scale. Prior regional investigations of the extent of coastal flooding and historical patterns of erosion have been conducted across the region in a variety of temporal and spatial extents, but primarily at local or shoreline reach scales. Previous studies have not mapped to the parcel scale or integrated the number of datasets that the current effort has to provide a comprehensive analysis of likely future vulnerability.

The recent release of updated sea level rise projections and high resolution topobathymetric data for the Puget Sound region allowed for a new quantitative analysis of SLR-related hazards at a finer spatial scale. The goal of this project was to construct, calculate, and map a SLR vulnerability index for the greater Puget Sound shore (including north to the Canadian border and west to Port Angeles) that includes both coastal infrastructure and habitat sensitivity at the parcel scale. Our assessment was based on a quantitative vulnerability framework, which defines vulnerability as a function of exposure and sensitivity. The exposure index, which incorporates coastal flooding and erosion, was coupled with a sensitivity index which integrated infrastructure and coastal habitats into a total vulnerability index.

Here we present the methods and results of the assessment, intended to inform local hazard planning and habitat restoration efforts, and include a vulnerability assessment of 111,249 parcels within the Puget Sound coastal study area using SLR projections out to 2100. These results are also coupled with a complementary social vulnerability index developed concurrently by partners at NOAA's National Centers for Coastal Ocean Science (NCCOS), which provides additional insight about people and places that may be predisposed to adverse impacts from SLR-related risks.

Over fourteen existing datasets were incorporated, along with the creation of five new inundation layers. Our methods and results were created through engagement with a broad Advisory Group, including over 20 email updates, three presentations, and many other individual communications. The deliverable is a geodatabase including all input data, inundation layers, intermediate analysis layers, and a parcel layer with 12 scores associated with vulnerability, including one social vulnerability scores from our NCCOS partners.

We find that our approach allows the ranking of parcels in a way that considered both present and future potential coastal flooding, the impact to existing infrastructure and habitats, and community resilience, but acknowledge that data limitations and assumptions incorporated into the approach should be considered when interpreting the results.

Introduction and Purpose

The purpose of this report is to provide a final-project technical summary on NTA 2018-0685: "Prioritizing Sea Level Rise Exposure and Habitat Sensitivity Across Puget Sound", with a focus on datasets, technical approaches, and results. The appendix also contains a *Geodatabase User Guide* for the project Geodatabase and a *Summary of Reviewer Comments*. We first describe the overall conceptual model guiding the quantitative estimation of vulnerability for coastal parcels on Puget Sound and then describe the technical methods of the three project phases (the "Exposure Assessment", the "Sensitivity Assessment" and the "Vulnerability Assessment").

We also present example maps showing the results for better visualization of the framework. The conceptual framework, data sources, and scoring schemes outlined in this report were all worked out by the project team initially, then circulated for input and additions to the project Advisory Group in a series of group emails and other communication. The input from the Advisory Group was reconciled and incorporated into the approaches outlined herein.

This project has been funded wholly or in part by the United States Environmental Protection Agency under assistance agreement PC-01J22301 through the Washington Department of Fish and Wildlife.

Project Advisory Group

This project was guided by a multi-agency group that consisted of professionals from a range of disciplines focused on restoration and protection in the Puget Sound region, hereafter referred to as the Advisory Group. Advisory group members included representatives from several state and federal agencies (Table 1).

Engagements with the Advisory Group came from monthly email updates soliciting feedback and technical advice, individual emails, or phone calls between the project team to specific member of the Advisory Group, and three formal meetings. In total, 112 engagements with the Advisory Group were documented (see Communications Summary report). There were also two outreach/communication events led by Washington Sea Grant that were not with the Advisory Group, that were used to gather feedback from an additional 55 people.

Table 1. Advisory Group members.

Advisory Group Member	Title
Kevin Zerbe	Washington Emergency Management Division Natural Hazards Mitigation Strategist
Harriet Morgan	University of Washington Climate Impacts Group Researcher
Bobbak Talebi	Senior Coastal Planner, Washington Department of Ecology
Travis Ball	Hydraulic Engineering Section Chief, US Army Corps of Engineers, Seattle District
Tish Conway-Cranos	Nearshore Science Manager, Washington Department of Fish and Wildlife
Jay Krienitz	Program Director, Washington Department of Fish and Wildlife
Thomas (T.J.) Moore	Geospatial Coordinator, Lynker/CSS Team, on contract to NOAA's Office for Coastal Management – West Coast Region
John Lovie	ETI Consulting and Habitat Strategic Initiative Advisory Team
Cynthia Catton	Environmental Planner at Washington Department of Natural Resources (DNR), and Habitat Strategic Initiative
Nicole Faghin	Coastal Management Specialist, Washington Sea Grant
Melissa Watkinson	Equity, Access and Community Engagement Lead, Washington Sea Grant
David Trimbach	Research Associated, OSU
Chloe Fleming	NOAA National Centers for Coastal Ocean Science
Seann Regan	NOAA National Centers for Coastal Ocean Science

Overall Conceptual Model

The goal of this project was to couple recently developed localized sea level rise (SLR) projections from the Washington Coastal Resilience Project team (Miller et al., 2018), high resolution land elevation data from the United States Geologic Survey for Puget Sound (Tyler et al., 2020), and other publicly-available regional data in GIS to perform a quantitative assessment of SLR vulnerability for Puget Sound shores.

The overall framework for the quantitative estimation of vulnerability used in this project can be simply written as Vulnerability = Exposure + Sensitivity, which we are modifying from the approach described in the *US Climate Toolkit*[1,2]. This framework is applied to "assets," and for this project we are viewing the central "asset" under consideration to be 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.

Exposure Assessment

The objective of the first phase (the "Exposure Assessment") was to determine which "assets", or parcels, are exposed to coastal flooding and erosion, exacerbated by sea level rise using a quantitative approach. Another objective of the first phase was to assign a unique score to each asset, so we can determine which parcels are most exposed, and which are less.

[1] Exposure: Explore Hazards | U.S. Climate Resilience Toolkit
[2] Sensitivity and Vulnerability: Assess Vulnerability & Risk | U.S. Climate Resilience Toolkit

Sensitivity Assessment

The second phase was focused on the sensitivity of the chosen assets (the "Sensitivity Assessment"), or parcels, to the selected hazards. Sensitivity is defined here as the degree to which a parcel is susceptible to impacts due to coastal flooding. Put more simply, how much does flooding damage something that we care about on or related to the parcel? In this project, sensitivity had two components that were incorporated into an overall quantitative sensitivity score: first, parcel sensitivity associated with impacts to infrastructure, and second, parcel sensitivity associated with impacts to coastal habitats.

Vulnerability Assessment

The final phase (the "Vulnerability Assessment") combined the assessed exposure and sensitivity on each parcel to prioritize and rank parcels according to how likely and how severe direct sea level rise impacts may be on each parcel. It is important to note here that the conceptual framework for assessing vulnerability that we used in this project typically includes a third element, adaptive capacity, which is intended to assess the degree to which the exposure or sensitivity of a parcel may be reduced. For example, relocating or elevating a building to above expected flood levels are instances of adaptive capacity, which reduces vulnerability. While this is an important element in the assessment of vulnerability, we did not have the capacity to include adaptive capacity in this project.

In lieu of an adaptive capacity assessment, researchers at the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Coastal Ocean Science (NCCOS) partnered with our team to develop a complementary social vulnerability assessment for communities within the Puget Sound region. Their approach applied part of NCCOS's vulnerability assessment framework through application of a regionally modified Social Vulnerability Index (SoVI) for Zip Code Tabulation Areas (ZCTAs) within the Puget Sound watershed, using a principal components analysis on a suite of variables known to influence social vulnerability. Since social vulnerability is an estimate of the potential predisposition of communities to be adversely affected by coastal impacts such as SLR, its inclusion allows for the identification of potential areas where co-benefits of efforts such as restoration may occur. This is especially important for management communities seeking to prioritize efforts in the region. For more information of NCCOS's methodology and results see their technical report (Fleming and Regan, 2022).

Spatial Data Selection

Compilation of data for this project began with a literature review of existing approaches and datasets used to assess sea level rise vulnerabilities at a variety of spatial scales and regions. We also solicited input from the Advisory Group on available datasets and summarized selected datasets into two interim technical summary documents, which were reviewed by the Advisory Group.

Acceptance Criteria

The acceptance criteria for datasets in this analysis are described in detail in the *Quality Assurance Project Plan* (Miller et al., 2020), and are summarized as follows:

- Publicly available or are intended to be released for public use
- Cover the entire study area
- Obtained from authoritative sources that have undergone a documented quality assessment
- Less than 10-years old, if possible
- Resolution that is appropriate to the scale of the project

We did not have the capacity to build new datasets, collect field data, or compile datasets from counties, cities, municipalities, or similar entities.

The study area for this project is bounded by the extend of the USGS's 1-m resolution topobathymetric model of Puget Sound (Tyler et al., 2020) (Figure 1). The approximate bounds are Port Roberts and Blaine in the north, Olympia in the south, and Dungeness Spit in the west.

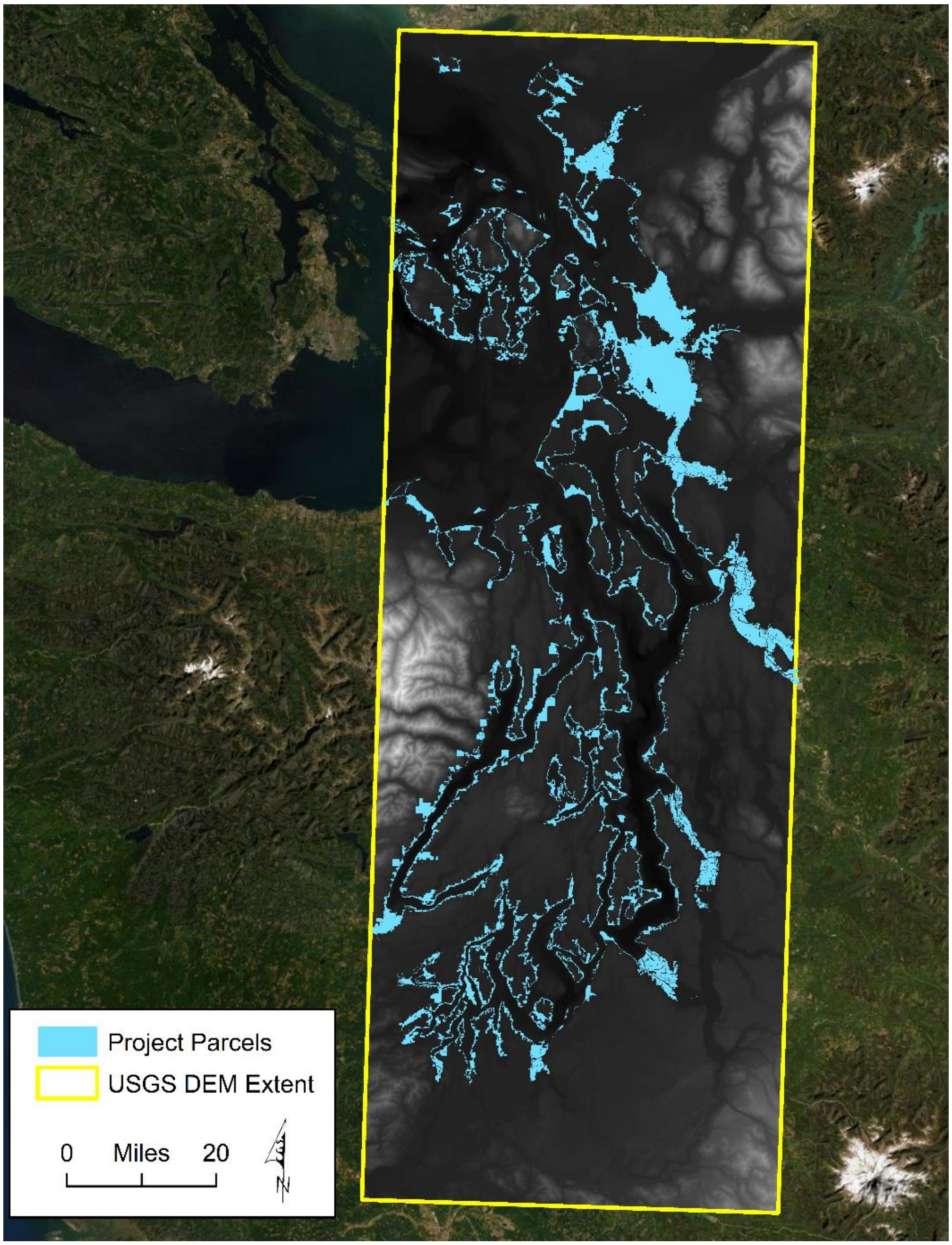

Figure 1. Map of the study area showing parcels to be assessed. Boundary defined by the USGS Puget Sound elevation model and project parcel layer from Beach Strategies marine parcel layer with parcels from Rogers and Cooke, 2012.

Parcel Layer

Coastal parcels in this study are derived from *Beach Strategies* (Coastal Geologic Services, 2017), which were initially obtained and updated from the Washington Statewide Parcel Database (Rogers and Cooke, 2012). The parcel layer was subsequently expanded from the Beach Strategies layer to include parcels that were either 200 FT from the ShoreZone shoreline (WDNR, 2001) or encompassed elevations of 30 FT or less (based on Tyler et al., 2020) and were hydro-connected to Puget Sound. We treated the Ballard Locks as a topographic boundary to water inundation and therefore manually excluded all parcels past the locks along Lake Union and Lake Washington that were hydro-connected to Puget Sound in our selected DEM.

The expanded parcels were pulled from the Washington Statewide Parcel Database to allow compatibility with the Beach Strategies parcel database. The final project parcel database includes 111,239 parcels or just over twice the amount as the Beach Strategies parcel layer (Figure 1). A breakdown of the parcel layer by county is shown in Figure 2. Note that Clallam County was only partially included in the project, as the topobathymetric DEM ends just west of Dungeness Spit.

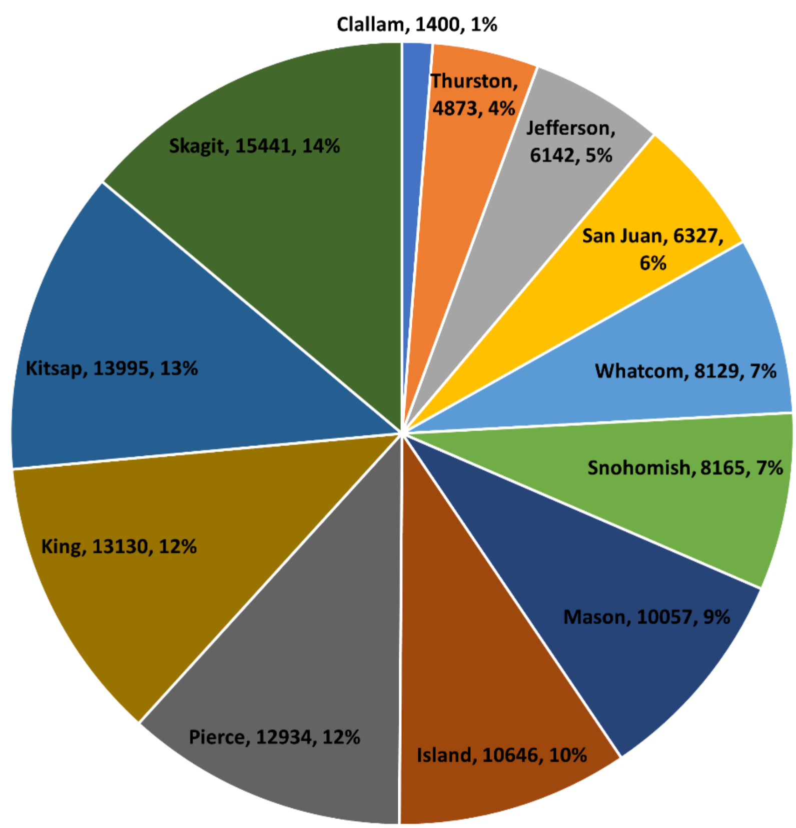

Figure 2. Parcels broken down by county with parcel count and percent within the parcel layer labeled.

Compatibility with Beach Strategies

The *Prioritizing Sea Level Rise and Habitat Sensitivity Across Puget Sound Geodatabase* is designed to be compatible with the WDFW Estuary and Salmon Restoration Program *Beach Strategies Geodatabase* (Coastal Geologic Services, 2017). The original parcel identifier (PolyID) from the Washington Statewide Parcel Database was retained in both the *Beach Strategies* parcel layer as well as this projects parcel layer. This enables the user to have the ability to join the attributes within the *Beach Strategies* database in ArcGIS using the "Join" feature. Additionally, both geodatabases have the same spatial projection making them easily overlayed and compared. More information on spatial projections for the geodatabase can be found in Appendix B: *Geodatabase User Guide*.

Methods

Inundation Scenarios

To assess the vulnerability of sea level rise on Puget Sound parcels, we chose to model inundation for five scenarios (Table 2). First, we opted to model inundation during an extreme coastal water level event relative to Mean Higher High Water (MHHW; 1983-2001 epoch) and settled on the use of the 20-year return frequency still water level as calculated in Miller et al. (2019) after testing several coastal flooding conditions (e.g., highest astronomical tide, 50-year, 100-year). These current conditions provide a baseline to compare future sea level rise extreme coastal water level conditions.

Table 2. Inundation scenarios modeled.

Inundation Scenarios
MHHW + extreme water level scenario (20-yr; 2.9 FT)
MHHW + extreme water level scenario + 50% SLR 2050
MHHW + extreme water level scenario + 1% SLR 2050
MHHW + extreme water level scenario + 50% SLR 2100
MHHW + extreme water level scenario + 1% SLR 2100

The sea level rise scenarios chosen rely on the localized and probabilistic relative sea level rise projections published by Miller et al., 2018[3]. Projections are provided at 171 locations along Washington's coastline. At each location, estimates of vertical land movement and associated uncertainty were combined which led to different estimates of relative sea level rise.

The assessment also gave a range of projection magnitudes based on the likelihood for a given emissions scenario that sea level rise will reach or exceed a certain level relative to the present. Inundation scenarios were developed for the 50% and 1% probability of exceedance, or the percent chance that absolute sea level will rise by at least that amount. The 50% exceedance scenarios were chosen to analyze a moderate scenario, or a "likely" range. In contrast, the 1% exceedance scenarios were chosen to analyze a more extreme scenario, but with a lower likelihood.

All projections are associated with an RCP 8.5 or high emissions scenario for 2050 and 2100. Using specific scenarios, rather than incremental steps in sea level rise, allows us to get a more realistic sense of the vulnerability of parcel through time. It is important to note, though, that since the outcome of this project was an assessment of *relative* exposure to coastal flooding within Puget Sound the results should be relatively insensitive to the choice of emissions scenario, likelihoods, or extreme water level scenario.

Building the Inundation Layers

The inundation layers were created by Coastal Geologic Services using NOAA's Office for Coastal Management Coastal Inundation Mapping methods in ArcMap 10.8.1. These are the same methods that were used in the creation of NOAA's Sea Level Rise Viewer[4]. The GIS methods are outlined in the NOAA

[3] https://wacoastalnetwork.com/chrn/research/sea-level-rise/
[4] https://coast.noaa.gov/slr/

document “Detailed Methods for Mapping Sea Level Rise Inundation”[5]. The basics steps of this methodology are as follows:

1) Create a MHHW tidal surface raster from VDatum relative to the NAVD88 vertical datum for the entire project area
2) Add the desired magnitudes of sea level rise and/or extreme still water levels to create a raster with flood elevation values
3) Subtract the flood elevation raster from the topobathymetric model of Puget Sound (digital elevation model)

Locations (raster cells) where the flood elevation values are greater than the surface elevation are modeled as inundated. The difference in elevations is the inundation depth.

For our analysis we chose to create a MHHW tidal surface raster with a cell size of 250 FT using NOAA’s Vertical Datum Transformation (VDatum) tool for ASCII File Conversion[6]. VDatum does not perform conversions into inland areas, therefore we extrapolated the VDatum conversion values inland so that our water surface representing tidal variability covered the entire project area. We used the *Euclidean Allocation* tool in ArcGIS because it extends the conversion values inland without interpolating new values.

In NOAA’s methodology, they use a single value for sea level rise across their project area and simply add that to the MHHW tidal surface to get flood elevation. To account for the spatially varying relative sea level rise projections across the study area as well as the 20-year extreme still water level magnitude, we created polygon layers based on the boundaries of projected sea level rise geographies from Miller et al., 2018. These boundaries for projected sea level rise extend throughout the project area, however they are not continuous and have gaps in several locations. We manually filled in the gaps by using the adjacent projection values and in some cases averaging two adjacent values. Each sea level rise scenario has a polygon shapefile in the geodatabase, with the boundaries and values of the projected sea level used across the study area for the creation of the inundation layers. See the *Geodatabase User Guide* for these layer names.

Once the values of 20-year extreme still water and sea level rise projections were added to the MHHW tidal raster for each scenario, inundation layers were created by using the *Raster Calculator* in ArcGIS with this conditional statement:

Con(“Flood Elevation Raster” >= “DEM”, “Flood Elevation Raster”-“DEM”)

Where “DEM” represents the topobathymetric DEM of Puget Sound. In this step we set the output raster cell size to the “Same as layer DEM” so that the inundation layer has the same resolution as the DEM rather than the flood elevation raster. This outputted raster layers where inundation was mapped everywhere the surface elevation was lower than the flood elevation, with the cell value being the depth in feet. This results in some areas modeled as inundated that are not physically connected to Puget Sound waters but represent low-lying areas.

[5] https://coast.noaa.gov/data/digitalcoast/pdf/slr-inundation-methods.pdf
[6] https://vdatum.noaa.gov/

Our final step was to extract the hydrologically connected areas into a separate layer, using the *Region Group* tool in ArcGIS. This tool only works on integer rasters, therefore a few processing steps were necessary to use this tool. We used a model created by NOAA in ArcGIS Model Builder to perform the required steps to run the *Region Group* tool as shown in Figure 3.

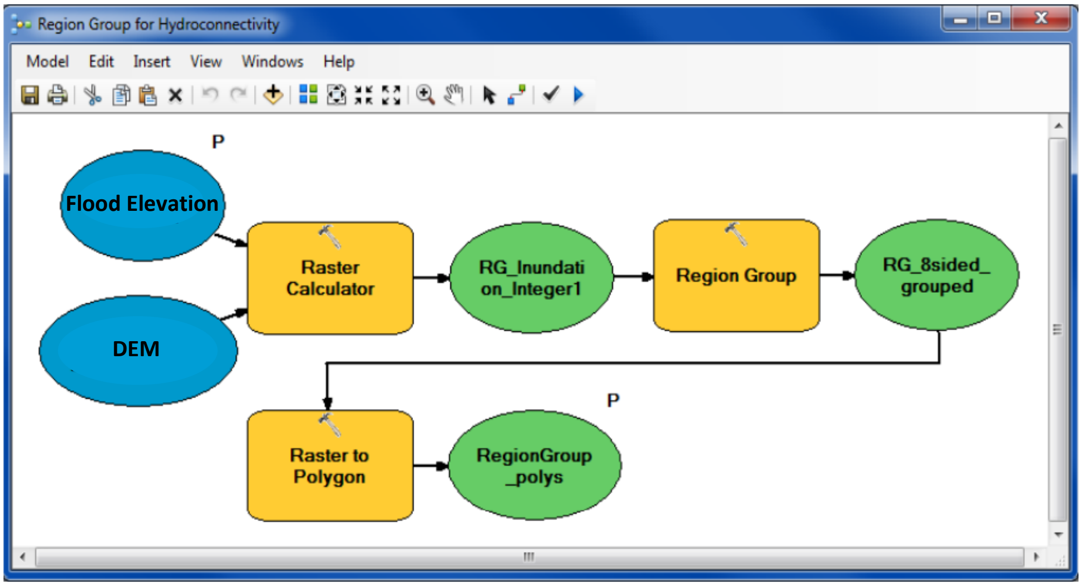

Figure 3. ArcGIS Model Builder model used to map hydro-connected inundation areas.

This model outputted polygon layers with many different features within them. The feature with the largest shape area (layer attribute "Shape_Area"), represents the hydrologically connected inundation polygons. However, in some cases diagonally connected cells were converted into separate features even though they were connected in the raster. To select all polygons representing hydrologically connected inundation, we used the *Select by Attributes* tool under the table option of the attribute table to select all polygons with the same "grid_code" value as the value of the largest feature in the table (e.g., "grid_code" = 1). These polygon features were then exported and are the final inundation polygons found in the project geodatabase.

Exposure Assessment

The exposure assessment focused on present and future coastal flooding potential on each parcel, as well as an assessment of the coastal erosion potential on each parcel. The intent was to develop a score that summarizes the relative differences in exposure to these hazards through time. The exposure assessment was broken down into separate estimates of a Coastal Flooding Exposure and Coastal Erosion Potential score, as described in the following sections.

Selected Input Data

based on our acceptance criteria for datasets and our proposed exposure indices, the datasets found in Table 3 were selected for this assessment.

Table 3. Exposure datasets utilized.

Dataset	Source	Description
Inundation Layers	Coastal Geologic Services (2022)	Inundation layers created for this project. Inputs into the creation of these layers included the Topobathymetric model of Puget Sound (Tyler et al., 2020), 20-year extreme still water level magnitude (Miller et al., 2019), relative sea level rise projections (Miller et al., 2018), and VDatum tidal values (NOAA, 2013).
Shoretype (Attribute of parcels)	Beach Strategies (Coastal Geologic Services, 2017)	Shoretypes for all coastal parcels. Up to six shoretypes possible for each parcel and includes the shoretype length.
1st Percentile Significant Wave Height (Points)	PNNL (Yang et al., 2019)	High-resolution wave modeling study using unstructured-grid Simulating Waves Nearshore (UnSWAN) to simulate wave climate within the Salish Sea. Model domain covers the entire Salish Sea with a grid cell resolution of about 200 m inside Puget Sound. Model outputs include the top percentiles (i.e., 5%, 1%, and 0.1%) of hourly significant wave height, peak period, and wave direction. Dataset not yet publicly available.

Coastal Flooding Exposure

This approach was intended to quantitatively score a parcel's flood exposure in a way that considers both present and future potential coastal flooding. The approach evaluates the percentage of a parcel's area inundated under each of five scenarios, outlined in Table 4. Each parcel's initial flood score (out of a total possible of 500) was normalized to a floating-point scale between 0-5.

Table 4. Coastal Flooding Exposure score approach.

Inundation Scenario	% of Parcel Inundated
MHHW + extreme water level scenario (20-yr; 2.9 FT)	0-100
MHHW + extreme water level scenario + 50% SLR 2050	0-100
MHHW + extreme water level scenario + 1% SLR 2050	0-100
MHHW + extreme water level scenario + 50% SLR 2100	0-100
MHHW + extreme water level scenario + 1% SLR 2100	0-100
Flooding Score = SUM(% parcel inundated for 5 scenarios)* *Normalized 0-5	

The *Clip* tool was utilized to cut the parcel layer with each of the inundation layers to find the area of each parcel inundated. These areas were joined and added to the final parcel layer (see *Geodatabase User Guide* for details). If there was no inundation on a parcel, the "Shape_Area" attribute was set to "<null>". Null values were set equal to zero to allow calculation of the flooding score using the *Field Calculator* tool.

The Flood Exposure Scores were normalized to a score from 0-5 using a standard min-max normalization:

$$Normalized\ Score = \frac{m - r_{min}}{r_{max} - r_{min}} \times (t_{max} - t_{min}) + t_{min}$$

m = "raw" score
r_{min} = minimum of measurements
r_{max} = maximum of measurements

t_{max} = minimum of the range of the desired target scaling
t_{min} = maximum of the range of the desired target scaling

Coastal Erosion Potential

There is no comprehensive historical erosion data for Puget Sound, and no modeling basis from which current or future physical rates of erosion can be estimated in Puget Sound. We therefore opted to develop a "coastal erosion potential" score for each parcel that was modified from one developed as part of the *Beach Strategies* project (Coastal Geologic Services, 2017).

The *Beach Strategies* project calculated a erosion potential as the sum of binned categories of shoretype and fetch distance. We modified that approach in four ways (Table 5). First, we replaced fetch distance with modeled extreme wave heights derived from updated wave modeling for Puget Sound conducted as part of the Washington State Resilience Project (Yang et al., 2019), specifically utilizing the 1% annual modeled significant wave height, in feet. Next, we multiplied a binned shoretype value and the modeled wave height (rather than adding), which has the effect of widening the distribution of scores, and weighting wave height as a driver of coastal erosion. We separated bedrock shorelines (which should have very low erosion potential) into its own shoretype category, rather than lumping them into the "low energy" category as was the case in the *Beach Strategies* project. This has the effect of ensuring that bedrock shorelines with high wave exposure are not erroneously assigned a high erosion potential score. Finally, we moved accretion shoreforms to the value of 3 category (from 2), to increase the erosion potential for these usually low-lying dynamic shorelines.

Table 5. Coastal Erosion Potential approach.

Coastal Erosion Potential		
Shoretype	**Value**	**Wave Height FT (Hs 1%)**
No Appreciable Drift (NAD)-Bedrock	0	0 – Max
No Appreciable Drift (NAD)-Low Energy	1	
Modified, NAD-Delta	2	
NAD-Artificial, Transport Zone, Pocket Beach, Accretion Shoreform	3	
Feeder Bluff	4	
Feeder Bluff Exceptional	5	
Erosion Potential Score = Shoretype Value x Wave Height (FT)* *Normalized 0-5		

Shoretype in the *Beach Strategies* geodatabase were mapped at a minimum length of 20 FT, and some parcels are mapped with multiple shoretypes. Where this occurred in this analysis, we used the highest shoretype value from Table 5 for that parcel. For example, if the dominant shoretype for a parcel was accretion shoreform, but there was a section of feeder bluff, the assigned shoretype value for the parcel was 4 for feeder bluff.

The wave height data from PNNL was interpolated from points to a raster using the ArcGIS geoprocessing *Inverse Distance Weighted (IDW)* technique with a cell size of 200 FT. The highest wave height cell value within each parcel was chosen as the input for this analysis and assigned to each parcel. This was accomplished by first using the *Zonal Statistics* tool with the parcel layer as the input feature, the interpolated wave height layer as the input value raster, and the statistics type set to maximum. This outputted a raster layer with only the maximum wave height cell within each parcel. Next, we used the

Raster Calculator to determine which cells correspond to the highest elevation found within each parcel with the following conditional statement:

Con(“HsFT_IDW”== “Max_Hs_Zonal_Stats”, “HsFT_IDW”)

Then the *Raster to Point* tool was utilized to turn the output raster from the previous step into a point feature class. Finally, the max wave height value was assigned by using the *Spatial Join* tool with the parcel layer as the target feature, the join feature as the point layer from the previous step, one to one join operation, and the match option being “closest geodesic.”

We chose this approach rather than simply finding the spatially closest wave height point from the original data because there were several places, mainly along spits with water and wave data on the shore side in bays, where a parcel has two points very close to the parcel with widely different wave height values. An example of this is Dungeness Spit, where on the west side of the spit wave heights were ~5 FT, whereas on the east side of the spit, wave heights were only ~0.5 FT. Interpolating the values and finding the maximum value insured that no erroneously small or large values were assigned to a given parcel.

Unlike the flood exposure scoring approach described above, the coastal erosion potential approach does not explicitly incorporate potential changes in rates of erosion that may be driven by sea level rise. We also do not incorporate specific rates of erosion into our analysis. We simply do not have the data or models available for the complex Puget Sound shore to do either. However, our approach is grounded in the assumption that places that are most likely to erode now will erode first and fastest as sea level rises, and presents a useful approach for evaluating the relative erosion potential along the Puget Sound shore.

All parcels without a direct marine shoreline were assigned a score of zero for erosion potential. These parcels are not considered to be impacted by current coastal erosion as they are not on the waterfront and do not experience direct wave action.

As with the Coastal Flooding Score, we normalized the score to a scale of 0-5 using the methods described in the *Coastal Flooding Exposure* section above.

Total Exposure

Our approach was to weight both the Coastal Flooding Exposure and Coastal Erosion Potential scores equally, and simply sum them to arrive at a Total Exposure score and normalize the results on a floating-point scale between 0-10. We decided to default to equal weighting after discussion with the Advisory Group.

$$Total\ Exposure = Coastal\ Flooding\ Exposure\ (0-5) + Coastal\ Erosion\ Potential\ (0-5)^*$$

*Normalized 0-10

Sensitivity Assessment

The sensitivity assessment is broken down into two fundamental pieces: a “Infrastructure Sensitivity” score and a “Habitat Sensitivity” score. The Infrastructure Sensitivity focuses on assessing whether infrastructure will be negatively impacted by sea level rise and is further broken down into:

- *Parcel Infrastructure Score* which assesses buildings and critical infrastructure on each parcel
- *Accessibility Reduction Score* assesses coastal flooding on roads *adjacent* to each parcel

- *Agricultural Lands Score* assesses coastal flooding on parcels mapped as agricultural by the USDA

The Habitat Sensitivity score evaluates how habitat area changes on a parcel under projected sea level rise.

The intent was to develop an integrated score to quantify the relative differences in sensitivity of parcels to sea level rise through time.

Selected Input Data

We selected the datasets listed in Table 6 for assessing sensitivity to sea level rise.

Table 6. Sensitivity datasets utilized.

Dataset	Source	Description
Building Footprints (polygons)	(Microsoft, 2018)	building footprints leveraging artificial intelligence (AI) to identify and map structures using aerial imagery.
Critical Facilities (points)	Layers from WA Geospatial Open Data Portal & HAZUS Data	Hospitals, Airports, Schools from WA Geospatial Open Data Portal and Communication, electric power, natural gas, oil, potable water, wastewater, bus, rail facilities, police, medical care, fire station, emergency operations centers from HAZUS database.
Roads (polylines)	OpenStreetMap	Built by community of mappers that contribute and maintain data about roads. Contributors use aerial imagery, GPS devices, and low-tech field maps to verify that OpenStreetMap is accurate and up to date.
Agricultural Lands (polygons)	WSDA	Agricultural land use geodatabase. Includes crop and irrigation type.
Sea Level Rise Marsh Migration (Raster)	NOAA Office for Coastal Management	Integrated C-CAP and elevation data to map potential changes to marsh environments from sea level rise. Module within the NOAA sea level rise viewer.
Shoreline Armoring (polygons)	Beach Strategies (Coastal Geologic Services, 2017)	Armor length assigned to each parcel in the database.
Shoretype (polygons)	Beach Strategies (Coastal Geologic Services, 2017)	Shoretypes assigned to each parcel in the database.

Infrastructure Sensitivity

The Infrastructure Sensitivity score was evaluated with three components which are described below: the Parcel Infrastructure Score, the Accessibility Reduction Score, and the Agricultural Lands Score.

Parcel Infrastructure

This approach was intended to quantitatively score the inundation potential of buildings on a parcel in a way that incorporates both present and future potential coastal flooding. The approach evaluates the percent of buildings area (Microsoft, 2018) inundated under each of the inundation scenarios above a depth of 0.5 FT (Table 2).

An inundation threshold of 0.5 FT was selected and vetted by the Advisory Group, and is intended to acknowledge the importance of flood depth in creating adverse and negative impacts during coastal flooding events. We created these inundation layers by using the *Raster Calculator* tool to extract depths > 0.5 FT, then converted them to polygons using the *Raster to Polygon* tool. We then used the same methods outlined in the *Inundation Scenarios* section to extract the hydro-connected polygons. These layers can be found in the geodatabase (see *Geodatabase User Guide* for layer names).

Building footprints sometimes overlap parcel boundaries, which can reflect either errors in the parcel lines or building footprints data, or can reflect real circumstances on the ground. In these cases, we divided the building footprints at the parcel boundaries and assessed what parts of the building are fully within the parcel boundaries. We used the ET Wizards Tool (an extension of ArcGIS in lieu of 3D Analyst) *Intersect Polygons* with the input as the Washington Building (Microsoft, 2018) and the parcels as the intersect layer. Where these splits occurred, they often left small slivers of building footprints in parcels, which could lead to erroneously high scores or assign a parcel as developed. To correct for this, we chose to only analyze inundation for building footprints that were >200 square feet (SF). This both helped reduced those leftover slivers of buildings footprints as well as took out any very small buildings (presumably structures like sheds) from the analysis. To do this we used the *Select by Attributes* tool under the table option of the attribute table to select all polygons with an area greater than 200 SF.

Many parcels included multiple building polygons which we grouped by parcel, using the *Dissolve* tool (based on PolyID, with "create multipart features" checked) in order to simplify the calculation of building area.

To find the building area inundated under each scenario, we used the *Intersect* tool, with the building layer and inundation layer polygons with the 0.5 FT depth threshold. The resulting parcel areas were added to the parcel attribute table and use to calculate the parcel infrastructure score using the approach outlined in Table 7. Scores were normalized to a range between 0-3.

To represent the additional importance of critical infrastructure (Table 6), we increased the Parcel Infrastructure Score by 10% for parcels that included certain types of mapped critical infrastructure. The critical infrastructure building layer within the geodatabase (CritInf_Buildings.shp) was created by first compiling the point layers from the sources listed in Table 6. As the points were not always directly on a building polygon or there were multiple buildings related to a specific critical infrastructure type (e.g., schools), the team manually selected building polygons associated with critical infrastructure points. The attributes of the point layer information were then joined with the building polygon. The parcel was categorized as critical if the parcel intersected with the critical infrastructure building polygon using the *Select by Location* tool. Once the bonus was applied, scores were renormalized from 0-3.

Note that if a parcel had no building footprint on the parcel, the parcel was assigned a score of 0.

Table 7. Parcel Infrastructure Score approach.

Inundation Scenario	% of building area inundated >0.5 FT
MHHW + extreme water level scenario (20-yr; 2.9 FT)	0 - 100
MHHW + extreme water level scenario + 50% SLR 2050	0 - 100
MHHW + extreme water level scenario + 1% SLR 2050	0 - 100
MHHW + extreme water level scenario + 50% SLR 2100	0 - 100
MHHW + extreme water level scenario + 1% SLR 2100	0 - 100
Score* = sum (% buildings area inundated for 5 scenarios)** *Critical Infrastructure Bonus Score = Score x 1.1** **Normalized to 0-3	

Accessibility Reduction

This approach analyzes the percent of roads inundated above a threshold within a buffer area around each parcel. We set a depth threshold for flooding on roads of >0.5 FT, based on NOAA's National Weather System flood safety information guidelines[7] The following summarizes their guidelines:

- 0.5 FT = loss of control and stalling most passenger cars
- 1 FT = can float most vehicles
- 2 FT = can carry most vehicles

For each parcel we defined a buffer area, set in consultation with the Advisory Group, to perform the analysis based on if the parcel is within a rural or urban area (2010 US Census Data). The following are the defined buffer areas:

- Rural = 1 mile
- Urban = 0.25 miles

To create the buffer layer, we created a new field in the attribute table of the parcel layer to denote the buffer distance, then used the *Buffer* tool with the parcel layer as the input and the distance set to the buffer distance field, with all other options set to default.

For each inundation scenario, the roads layer (OpenStreetMap) was intersected with the > 0.5 FT inundation depth polygons using the *Pairwise Intersection* tool in ArcGIS Pro Version 2.7.4. This tool was chosen over the *Intersection* tool in ArcMap as the intersections are computed on pairs of features rather than all combination of features as in the *Intersection* tool, which significantly improves processing speed. This outputted roads segments within each parcel buffer area that is inundated and also retained the PolyID of the parcel.

Using the roads lengths from the previous step, the scores were calculated with the approach outlined in Table 8, and normalized from 0-1.

Table 8. Accessibility Reduction Score approach.

Inundation Scenario	% of road length inundated >0.5 FT depth threshold within distance buffer
MHHW + extreme water level scenario (20-yr; 2.9 FT)	0 - 100
MHHW + extreme water level scenario + 50% SLR 2050	0 - 100
MHHW + extreme water level scenario + 1% SLR 2050	0 - 100
MHHW + extreme water level scenario + 50% SLR 2100	0 - 100
MHHW + extreme water level scenario + 1% SLR 2100	0 - 100
Score = sum (% roads inundated for 5 scenarios)* *Normalized to 0-1	

Agricultural Lands

This approach analyzed the percent of an agricultural parcel that are inundated under each inundation scenario. Parcels were categorized as agricultural if they intersected with the Washington State Department of Agriculture (WSDA) Agricultural Lands layer (polygon) using the *Select by Location* tool.

[7] Turn Around Don't Drown (weather.gov)

The WSDA Agricultural Lands layer was created by WSDA specialist and was obtained through windshield surveys, producers, aerial and satellite imagery, USDA NASS Cropland Data Layer and other sources to identify agricultural land use. The crop data is classified by several categories crop types:

- Berry
- Cereal Grain
- Commercial Tree
- Developed
- Flower Bulb
- Green Manure
- Hay/Silage
- Herb
- Melon
- Nursery
- Oilseed
- Orchard
- Other
- Pasture
- Seed
- Shellfish
- Turfgrass
- Vegetable
- Vineyard

For this analysis we chose to use all crop types *except* shellfish in the definition of agricultural lands, as our focus was to try to identify parcels that might be adversely impacted by processes like soil salinization or groundwater flooding. Shellfish were excluded because they are farmed on intertidal lands which are already, by definition, subject to daily inundation.

For this analysis we chose to use all crop types *except* shellfish in the definition of agricultural lands, as our focus was to try to identify parcels that might be adversely impacted by processes like soil salinization or groundwater flooding. Shellfish were excluded because they are farmed on intertidal lands which are already, by definition, subject to daily inundation.

Rather than intersecting these parcels again with the inundation layers as was completed in the Coastal Flooding Exposure Score, we simply pulled the inundation areas from the Flood Exposure Score analysis for the parcels categorized as agricultural (parcel attribute field “AgLand” = 1). Using these areas, the scores were calculated with the approach outlined in Table 9.

Table 9. Agricultural Lands Score approach.

Inundation Scenario	% of Agricultural Parcel Inundated >0.0 FT
MHHW + extreme water level scenario (20-yr; 2.9 FT)	0-100
MHHW + extreme water level scenario + 50% SLR 2050	0-100
MHHW + extreme water level scenario + 1% SLR 2050	0-100
MHHW + extreme water level scenario + 50% SLR 2100	0-100
MHHW + extreme water level scenario + 1% SLR 2100	0-100
Agricultural Lands Score = sum (% parcel inundated for 5 scenarios)* *Normalized 0-1	

Similarly, to the Accessibility Reduction Score, the Agricultural Lands Score was normalized to a score from 0-1 rather than 0-3 as the Parcel Infrastructure Score was. While agricultural areas are sensitive to flooding of sea water, we already captured the coastal flooding of these parcels in the exposure assessment. This scoring allows a way to increase the sensitivity score of these parcels, without completely double counting their coastal flooding score. All non-agricultural parcels were assigned a score of 0, or low sensitivity.

Infrastructure Sensitivity

The Infrastructure Sensitivity Score is a sum of the three previous scores to have a score that ranges from 0 to 5.

$$Infrastructure\ Sensitivity\ Score =$$

$$Parcel\ Infrastructure\ Score\ (0-3) + Accessibility\ Reduction\ Score\ (0-1) + Agricultural\ Lands\ Score\ (0-1)^{*}$$

*Normalized to a score from 0-5

Habitat Sensitivity

The ability of a coastal habitat to migrate landward as sea level rises was identified as the most important process driving the sensitivity of coastal habitats in Puget Sound. While vertical accretion rates in coastal marshes of the Pacific Northwest are typically relatively high (Thorne et al., 2018), and will likely help vegetated areas along coasts persist through some sea level change (Kirwan et al., 2016), ultimately the room for habitats to migrate upward controls expected future patterns of distribution (i.e., Kairis and Rybczyk, 2010). The ability for the many barrier beaches protecting marsh areas to persevere with substantial sea level rise is not at all a certainly, and has not been well studied. We decided to craft our parcel habitat sensitivity score around comparing the changing area of habitat within a parcel using our selected sea level rise scenarios compared to current conditions.

Several studies have focused on habitat migration with data for the Puget Sound region, mainly concentrating on marsh migration in low lying areas, such as C-CAP Wetland Potential, SLAMM, and NOAA's Sea Level Rise Viewer Marsh Migration tool. After considering several datasets for this analysis we chose to utilize the Marsh Migration dataset within the NOAA Sea Level Rise Viewer[8]. These data are publicly available, cover the entire study region, and have an appropriate resolution for this analysis. The C-CAP Wetland Potential data was only available in a 30-meter resolution and did not have any other habitats besides wetlands or allow us to understand how habitats may change under different magnitudes of sea level rise. The SLAMM models did not have coverage beyond some large river deltas and would have been a very large undertaking to try to expand to the entire study area.

Marsh Migration Tool Use Methods

The process to create the Marsh Migration dataset can be described generally as a modified bathtub (inundation) approach that attempts to account for local and regional tidal variability. The NOAA methodology consisted of creating several tidal surfaces (MLLW, MTL, MHW, MHHW, MHWS (mean high water spring)), plus a surface above MHWS at each 0.5 FT increment of sea level rise, then combining those with the C-CAP landcover data classes to model the potential changes. The changes to the land cover are driven directly by those surface thresholds shown in Figure 4 below.

[8] https://coast.noaa.gov/slr/#/layer/mar/0/-12721665.867601521/5804130.1214256175/4/satellite/71/0.8/2050/interHigh/midAccretion

The habitat classes in the Marsh Migration data were consolidated from the original 2016 C-CAP landcover classifications and used as the initial or current land cover condition and include:

- Developed High
- Developed Medium
- Developed Low
- Developed Open Space
- All Uplands
- Palustrine Wetlands – Forested
- Palustrine Wetlands – Scrub/Shrub
- Palustrine Wetlands – Emergent
- Brackish/Transitional Wetland
- Estuarine Wetland
- Unconsolidated Shore
- Open Water

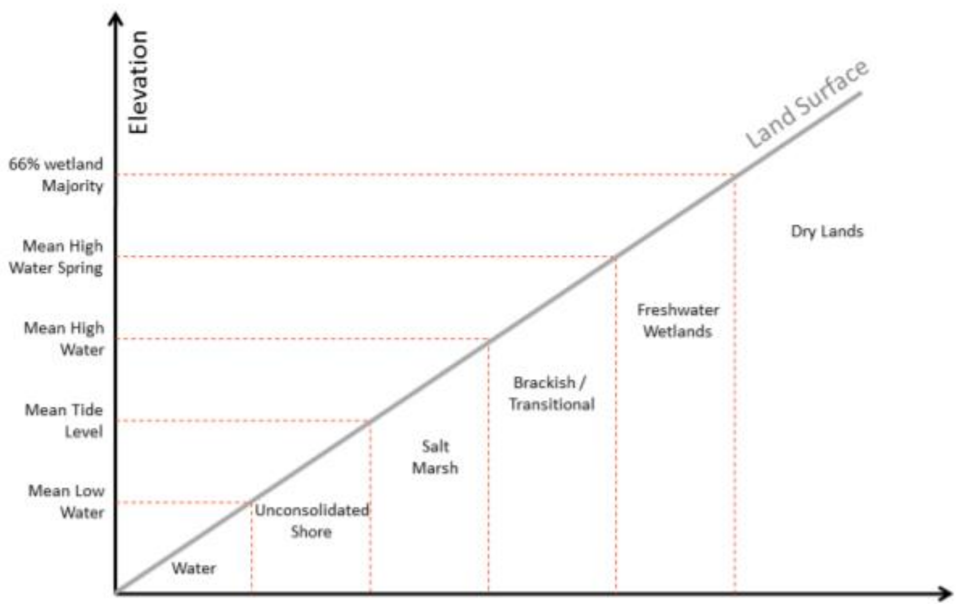

Figure 4. Wetland and landcover elevation thresholds used to model landcover migration with sea level rise[9].

Our methodology for assessing habitat sensitivity involved finding the area within a parcel that was classified as the selected coastal habitats from the NOAA Marsh Migration layers for each of the sea level rise scenarios. The coastal habitats that we assessed from the dataset include:

- Brackish/Transitional Wetland
- Estuarine Wetland
- Unconsolidated Shore
- Palustrine Emergent Wetland

It is important to note that the Marsh Migration data maps habitats based on 0.5 FT increments of sea level rise while our sea level rise projection scenarios vary in elevation across the study area. To account for this, we found the Marsh Migration layer (layers are in 0.5 FT increments) that is closest to the projected sea level rise magnitude above mean high water spring (MHWS) tidal level different geographic areas in the larger study area. Then we mosaic these together to make a new Marsh Migration layer for each of the sea level rise scenarios.

[9] https://coast.noaa.gov/data/digitalcoast/pdf/slr-marsh-migration-methods.pdf

Mean high water spring is defined by NOAA as the highest predicted tide during May-June of a year and varies across the study area. NOAA's VDatum tool does not have a vertical datum conversion for MHWS, therefore we assigned each spatial extent within the sea level rise projection polygons (see *Inundation Scenarios* section) a MHWS value. The highest predicted tide between May-June for the year 2021 were calculated for nine NOAA tide gauge station spanning the study area, including Cherry Point, Friday Harbor, Port Townsend, Seattle, Tacoma, Olympia, Union, La Conner, and Port Angeles. Each polygon within the sea level rise projection polygon was assigned a MHWS value based on their location relative to the nine tide gauges and their subbasin. In some cases, the MHWS value was averaged between two stations for a polygon. The tide gauge stations as well as the assigned MHWS value are within the attribute table for the sea level rise projection layer (see the *Geodatabase User Guide*).

The difference between MHHW and MHWS was added to the sea level rise magnitude (Marsh Migration layers are mapped relative to MHHW) for each of the polygons and then rounded to the closest 0.5 FT interval (field "pMHWS_rnd" in the sea level rise projection layer). These values were used to extract the appropriate marsh migration layer for each of the polygon boundaries within each inundation scenario. These layers were then converted from raster to polygons using the *Raster to Polygon* tool, with only the four selected habitats.

The layers generated in the previous step, which represent predicted habitat areas during each of the inundation scenarios, were then clipped with the inundation polygons. This was to account for inundation blockages within the elevation model.

Shoretype Use

Bluff-backed parcels (feeder bluffs: FB, FBE, FB-T, and transport zones: TZ) were treated slightly differently in order to acknowledge the important role that erosion is likely to play on those shoreforms to maintain habitat as sea level rises (Bruun, 1962; Johannessen and MacLennan, 2007; Raymond et al., 2018). Scores on bluff-backed shorelines are weighted for factors that will decrease or increase the ability for habitat to migrate.

The presence or absence of hard armor or development on a bluff parcel was chosen as factors to weigh the final habitat sensitivity score of a parcel (Table 10). The armor data comes from the *Beach Strategies* database (Coastal Geologic Services, 2017) which was mapped along the ShoreZone shoreline without any additional information on the armoring such as hard armor type, configuration, or elevation. Parcels were categorized as armored if it contained any length of armor, given that the Beach Strategies armor mapping had a minimum mapping length of 20 FT (Beach Strategies parcel layer attribute "SumLenArmor"). Parcels were categorized as developed if they contained a building polygon of greater than 200 SF (Microsoft, 2018). The following summarizing the weighting factors for bluff parcels:

- Presence of hard armor or development (likely that the bluff will be unable to erode) – increase score by 20%
- Presence of hard armor and development (very likely that the bluff will be unable to erode) – increase score by 40%
- Absence of hard armor and development (possible that the bluff will be able to erode) – decrease score by 20%

Parcels with armor and/or development will likely decrease the ability of coastal habitats to migrate and decrease the ability of that parcel to contribute habitat-forming sediments to the coastal zone (Johannessen and MacLennan, 2007), and so an increase in the sensitivity of the parcel was deemed appropriate. The decrease in a parcel sensitivity due to the absence of armor and development is to account for potential bluff recession and associated habitat migration that is not taken into account in the static elevation model that the Marsh Migration layers were built on. Weighting for these factors is somewhat arbitrary but was vetted by the Advisory Group.

Non-bluff shoreforms are not weighted in a similar way to bluff-backed shorelines because an assumption was made that shore armor and development are much less likely to be effective against stopping sea level rise and marsh migration into the future compared to higher elevation bluff shoreforms, and because those shoreforms do not contribute habitat-forming sediments to the coastal zone as they erode.

Table 10. Habitat Sensitivity Score approach.

Shoreforms	Armored	Unarmored	Developed	Undeveloped	Score
Non-bluff Shoreforms (AS, PB, PB-A, NAD-A, NAD-B, NAD-D, NAD-LE)	X	X	X	X	=SUM(% change in area)*
Bluff Shoreforms (FBE, FB, FB-T, TZ)	X		X		= SUM(% change in area)*1.4*
		X	X		= SUM(% change in area)*1.2*
	X			X	= SUM(% change in area)*1.2*
		X		X	=SUM(% change in area)*0.8*
*Normalized from 0-5					

Scoring Approach

The proposed Habitat Sensitivity score is summarized in Table 10 and was calculated based on the conditions of the parcel. Inherently, this scoring method will give a higher numeric score to parcels that have an increase in habitat size with sea level rise—or what we would categorize as "low sensitivity." To account for that, scores are first normalized and then reverse scaled (i.e., 5 – Score, for a scale from 0-5). This score was then multiplied by the weighting factor and renormalized to a scale of 0 to 5. Lastly, parcels that do not have any area of habitat currently or during sea level rise scenarios were assigned a score of 0 or "low sensitivity."

Aside from the weighting given to bluff-backed shoreforms, this analysis does not directly take into account any dynamic response of the landscape as sea level rises. The Marsh Migration data does have an option for the selection of an accretion rate, but we chose to not include an accretion rate into our analysis for the following reasons:

- Accretion rates are likely highly variable in space and time across our study area, and are largely undocumented.
- Accretion rates in the marsh migration layer are used to modify the relative sea level scenario across the entire layer. Therefore, applying an accretion rate to an entire layer may

misrepresent where and how sediment accretes on the landscape in a way that may influence the persistence of coastal habitats.

- Our analysis is intended to identify relative differences in the likelihood that habitats can migrate, so the overall scores should be relatively insensitive to small modifications in the sea level scenarios we've used for assessing inundation (i.e., Table 9).

Total Sensitivity Score

The Total Sensitivity Score was a simple summation of the Infrastructure and Habitat Sensitivity Score, with equal weighting. The final scores were normalized on a scale from 0-10.

$$Total\ Sensitivity\ Score = Infrastructure\ Sensitivity\ Score + Habitat\ Sensitivity\ Score^{*}$$

*Normalized to a score from 0-10

Vulnerability Assessment

The vulnerability assessment was broken down into a "Physical Vulnerability" and "Socially Modified Vulnerability Score." Physical Vulnerability incorporates the scores from the Exposure and Sensitivity assessment and the Socially Modified Vulnerability score adds in the social vulnerability score ("WAV" score) derived from NCCOS's work (Fleming and Regan, 2022).

Physical Vulnerability

The Physical Vulnerability Score was the sum of the Exposure and Sensitivity Scores, each with equal weighting. The breakdown of the full approach is shown in Figure 5 and the equation below.

$$Vulnerability\ Score\ (0-20) = Exposure\ Score\ (0-10) + Sensitivity\ Score\ (0-10)^{*}$$

*Normalized 0-20

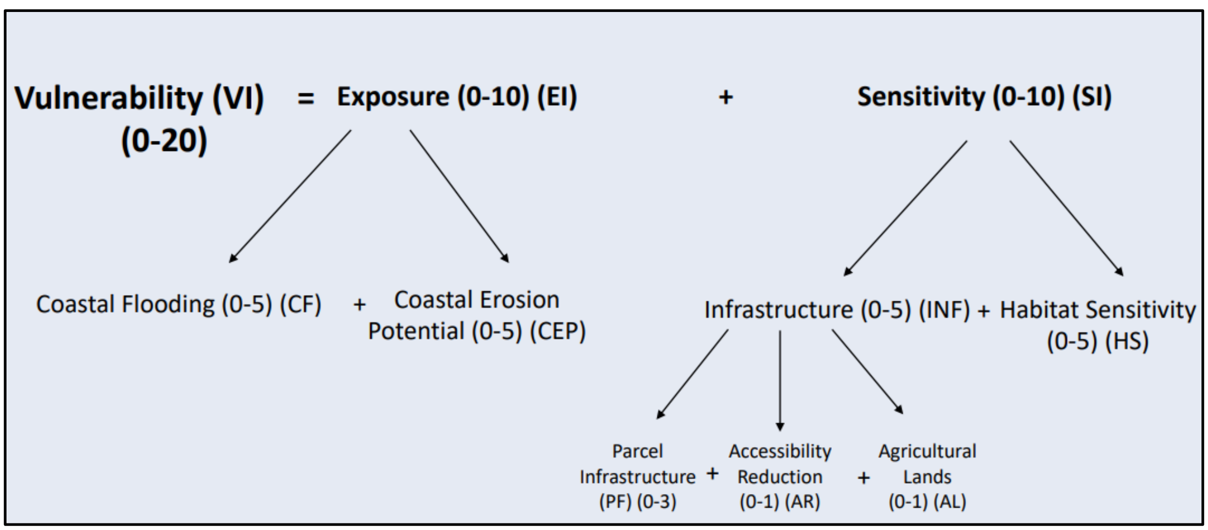

Figure 5. Physical Vulnerability scoring approach.

Socially Modified Vulnerability Score

The Socially Modified Vulnerability Score builds off of the Physical Vulnerability score by simply adding in the scores from NCCOS's work (Fleming and Regan, 2022), applying an equal weight to Exposure, Sensitivity, and Social Vulnerability.

$$Socially\ Modified\ Vulnerability\ Score\ (0-30) =$$
$$Exposure\ Score\ (0-10) + Sensitivity\ Score\ (0-10) + Social\ Vulnerability\ Score\ (0-10)$$

As the original social vulnerability scores were based on zip code tabulated areas rather than parcels and some parcels fell just outside these zip code areas, the *Spatial Join* tool was used with the "closest" option to link the scores to the parcels. To weight the factors equally, we took the original scores that were normalized from 0-1 and renormalized them from 0-10 using a min-max normalization equation. After testing a few different ways to integrate the scores (a multiplication factor, bi-variate approach etc.), we found that the chosen method of integration puts an appropriate relative weight on each of the factors. However, if a user feels that social vulnerability should be weighted more or less than the physical vulnerability factors, weighting factors can be applied to any of the components.

Results

Exposure, Sensitivity, and Vulnerability scores were calculated for 111,239 parcels along Puget Sound shores. Approximately 14 existing datasets were integrated into the analysis, and five new inundation layers were created, one to represent current extreme water level and four for sea level rise scenarios. We had a good deal of participation and feedback from the Advisory Group, initiated by over 20 email updates, three presentations, and many other individual communications.

Results are broken down into Exposure, Sensitivity, Physical Vulnerability, and Socially Modified Vulnerability and summarized below. First, we present maps showing the scores for the entire study region and the top 500 scoring parcels, using equal interval distribution of scores for color bins. Second, we present the breakdown in scores binned into single integers (i.e., 0-1, 1-2) and their associated percentages, and then the results broken down by county. Appendix A shows the results of the different subcomponents of each of the scores are shown for the Tulalip Bay area to provide an example of how the scores combine to arrive at the final vulnerability scores and the vulnerability scores for each county within the study area.

Exposure Assessment

The results of the Exposure Assessment, a function of the Coastal Flooding and Coastal Erosion Potential scores, for the entire project area are shown in Figure 6. The top 500 scoring parcels are also shown (Figure 7) and are spread out across the study area, though clusters of high exposure parcels are found in Whatcom County and west Whidbey Island and along the Seattle to Everett shore. Approximately half (46.5%) of the parcels within the database have the lowest possible exposure (Exposure score = 1; Figure 8). Generally, as the scores increase the percentage or number of parcels within a range decreased. Parcels within the range 7-10 accounted for 2.9% of the data. Only 5 parcels scored >9 and were located on the very exposed west Whidbey Island and west Dungeness Spit shore.

Results broken down by county reveal that for each county approximately 25% to 60% of parcels fall into the least exposed category (Figure 9). Scores between 7-10 made up a small fraction of parcels by county, mostly less than 10% of parcels. A few counties, Clallam, Mason, and Island in particular, stood out as encompassing a greater fraction of highly exposed parcels (though only eastern Clallam County parcels were scored). San Juan County had the smallest percentage of top scoring parcels, due to prevalence of bedrock/high elevation parcels.

The Coastal Flood Exposure and Coastal Erosion Potential scores results, as well as the total Exposure scores for the Tulalip Bay area are shown in Appendix A to illustrate in detail how the individual scoring components contributed to the total vulnerability scores. There we see low to moderate scores for the majority of the parcels, especially further landward and higher elevation parcels, and higher scores in low lying coastal parcels.

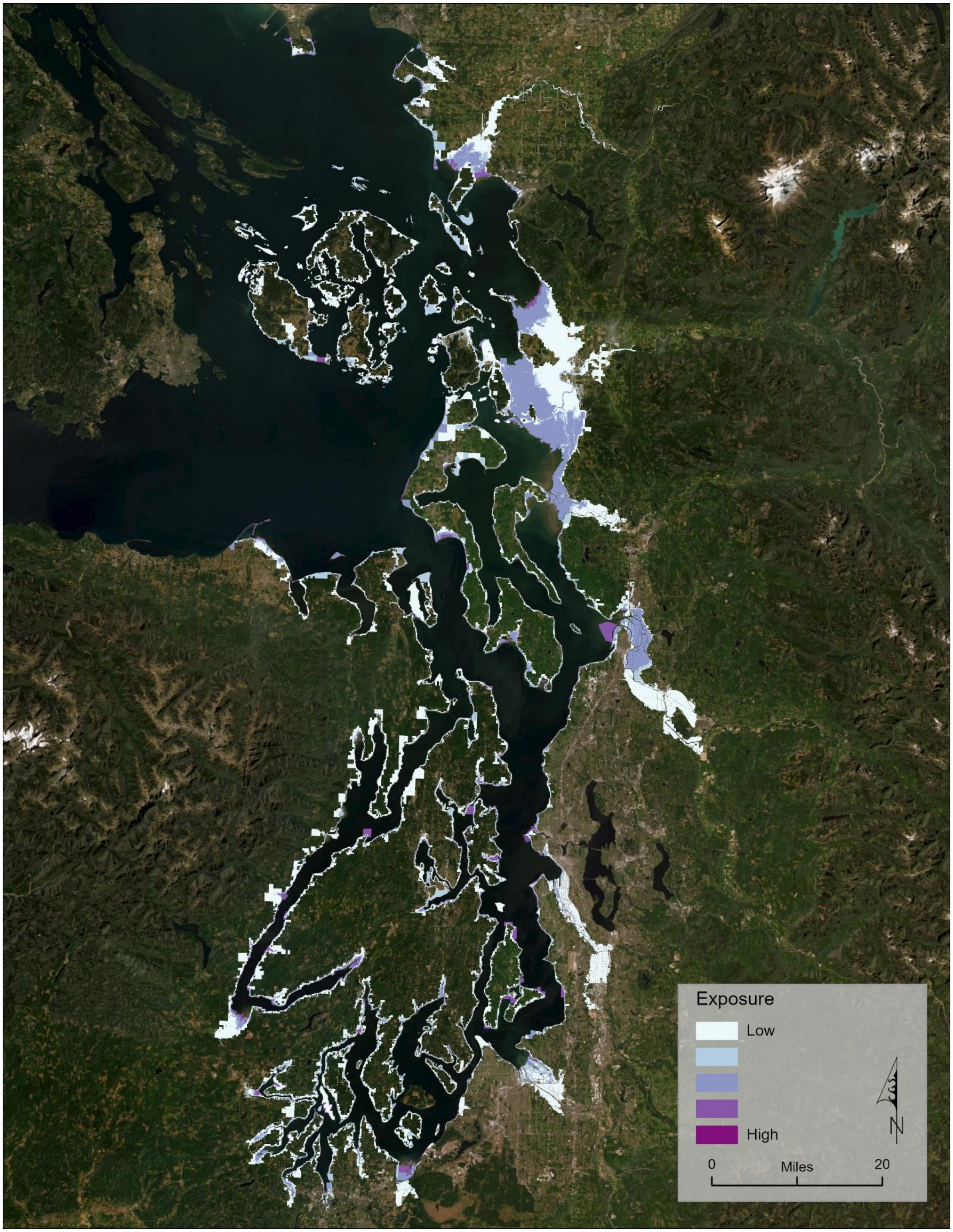

Figure 6. Exposure Score results for the entire project area. Darker colors represent increasing exposure.

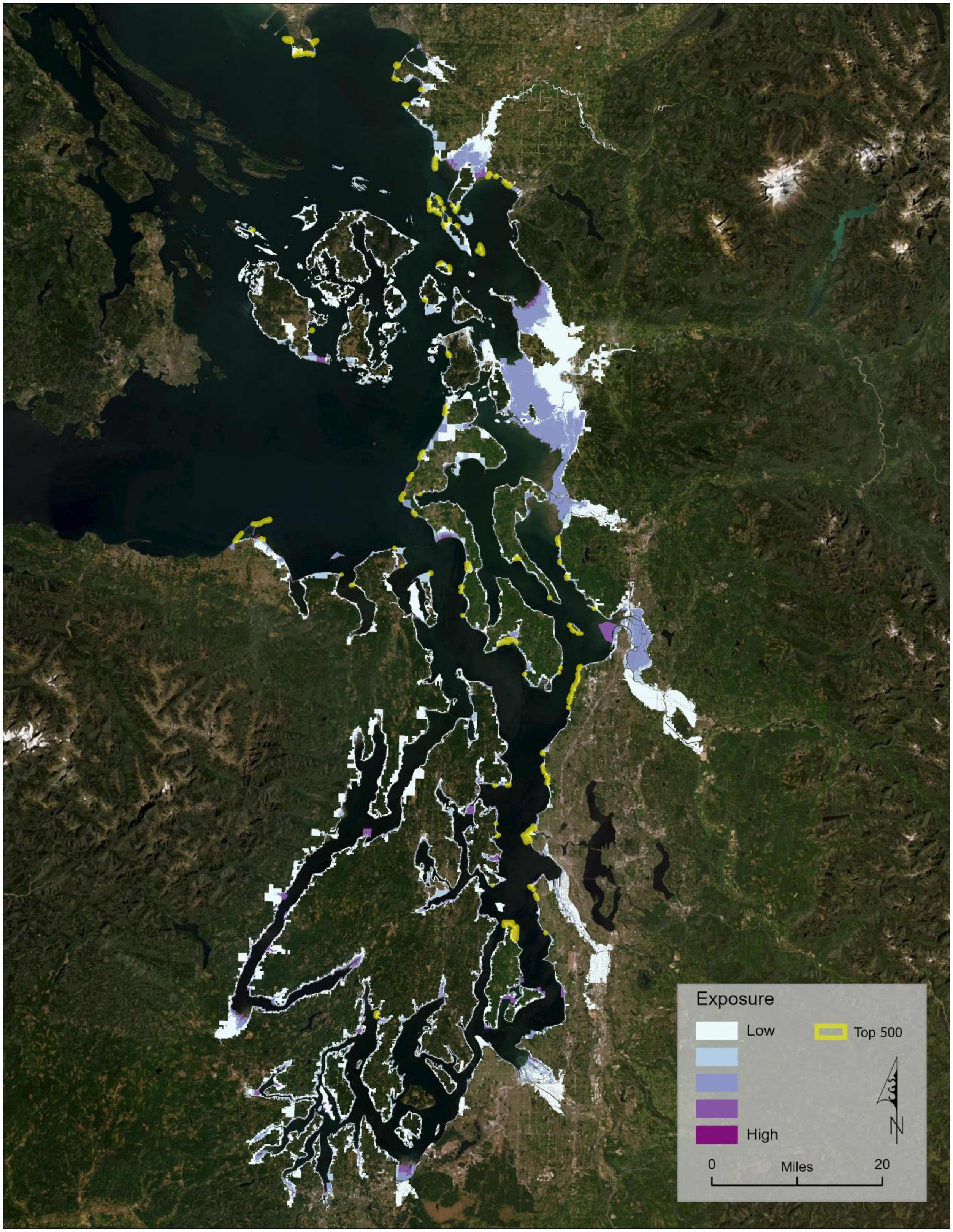

Figure 7. Exposure Score results for the entire project area with the top 500 scoring parcels highlighted in yellow.

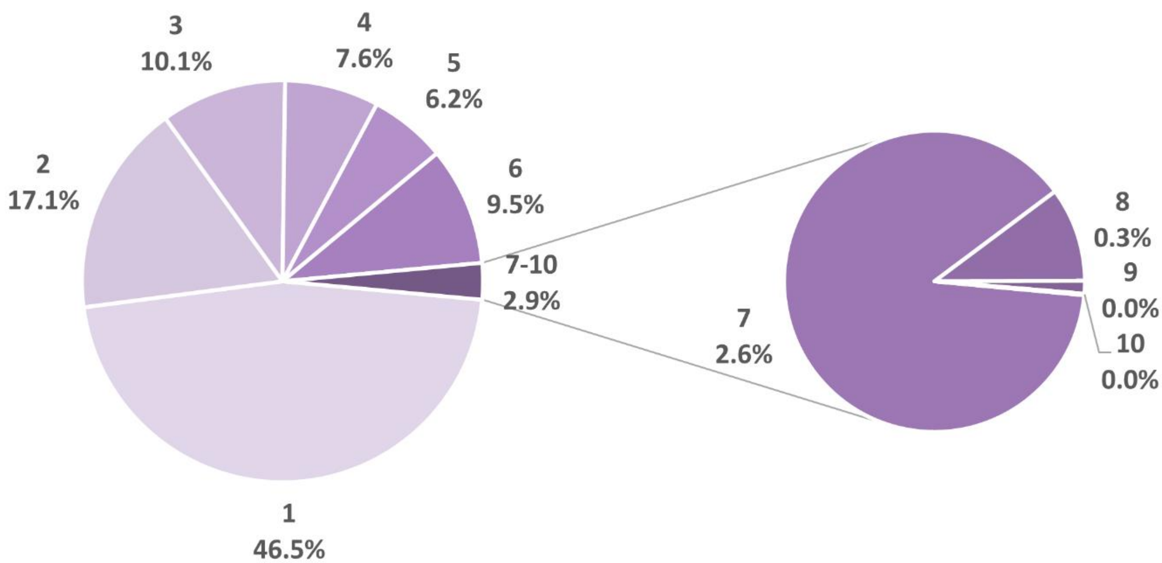

Figure 8. Exposure Score results broken down into binned categories.

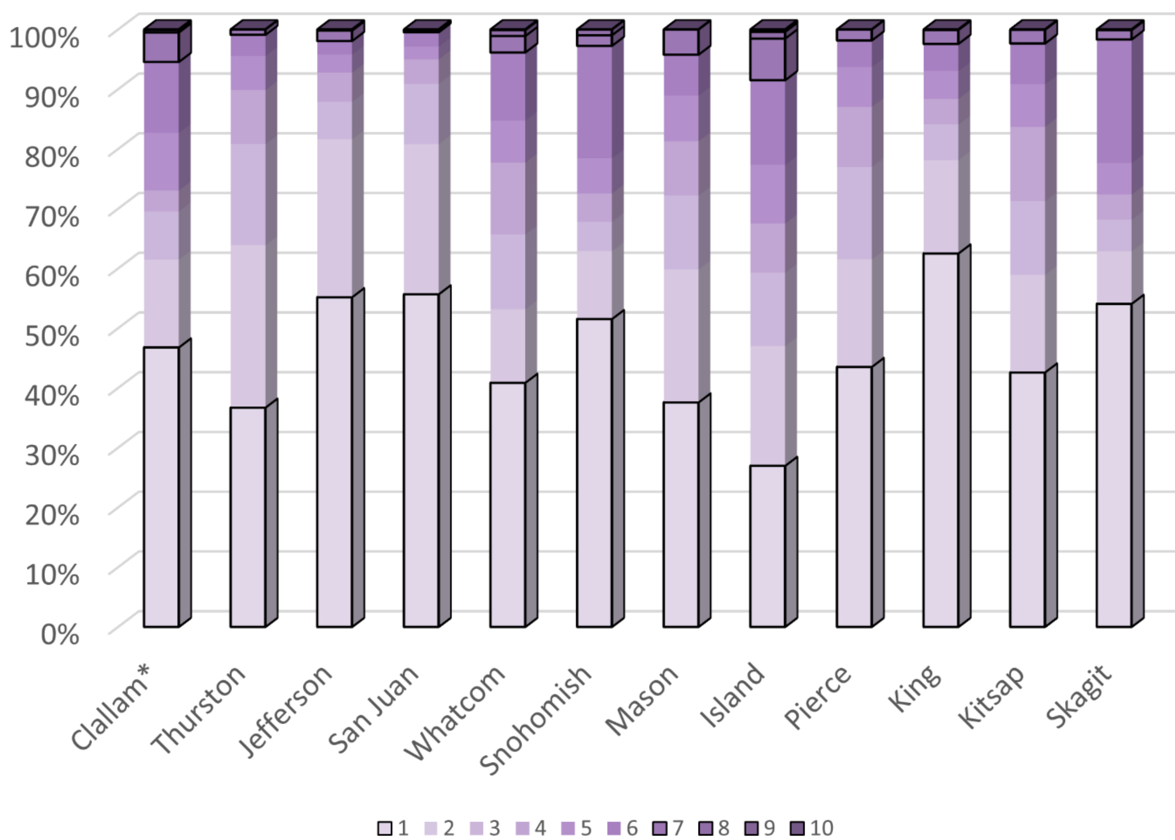

Figure 9. Exposure Score results broken down by county, with percent categories within the lowest binned group (0-1) and the upper three (7-10) categories outlined in black. Note that only a small fraction of Clallam County parcels was included in this study.

Sensitivity Assessment

Sensitivity, a function of the Infrastructure and Habitat Sensitivity Scores, for the entire project area is shown in Figure 10. The top 500 scoring parcels are also shown (Figure 11) and are mostly located in low-lying deltas such as Skagit, Nooksack, and Snohomish deltas. Just under half (42.2%) of the parcels within the database fall within the lowest range of scores (Total Sensitivity between 0 and 1; Figure 12). Generally, as the scores increase the percentage or number of parcels with a range decreased. Parcels within the highest range of scores (Total Sensitivity between 7 and 10) accounted for 1.5% of the data, or 1,702 parcels. Only 4 parcels fell into the highest sensitivity range. These top 500 located in low-lying deltas in Skagit and Snohomish Counties.

Results broken down by county reveal that for each county approximately 25% to 65% of parcels fall into the least sensitive category (Total Sensitivity between 0 and 1; Figure 13). Parcels with the highest sensitivity (Total Sensitivity between 7 and 10) made up a small fraction of parcels by county, all less than 10% of parcels. A few counties stood out as encompassing a greater fraction of highly sensitive parcels – Clallam, Snohomish, Island, and Skagit counties.

The Infrastructure Sensitivity scores (Parcel Infrastructure, Accessibility Reduction, Agricultural Lands) and the Habitat Sensitivity scores, as well as the total Sensitivity scores for the Tulalip Bay area are shown in Appendix A. There we see low to moderate scores for the majority of the parcels with a few higher scoring shoreline parcels.

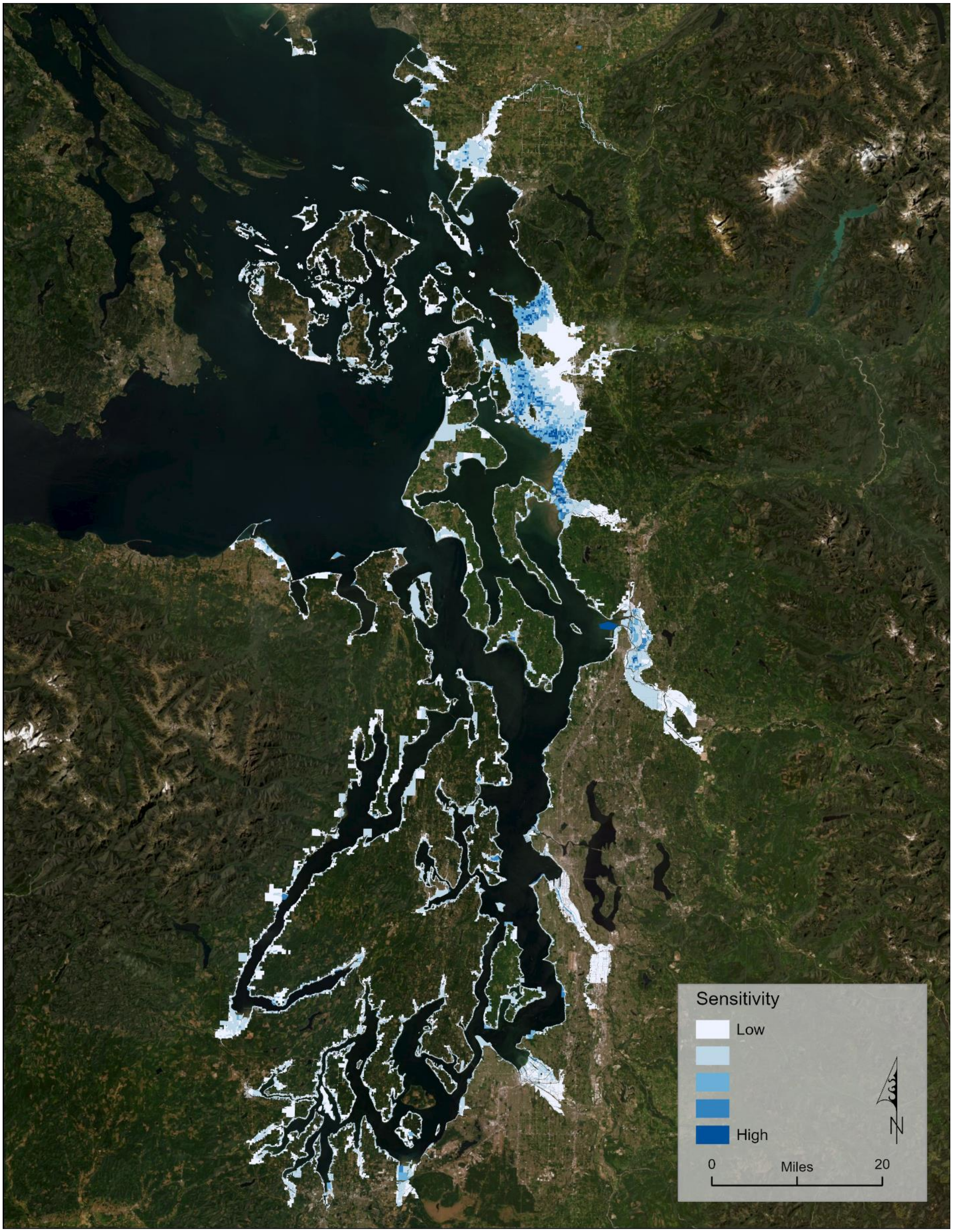

Figure 10. Sensitivity Score results for the entire project area. Darker colors represent increasing sensitivity.

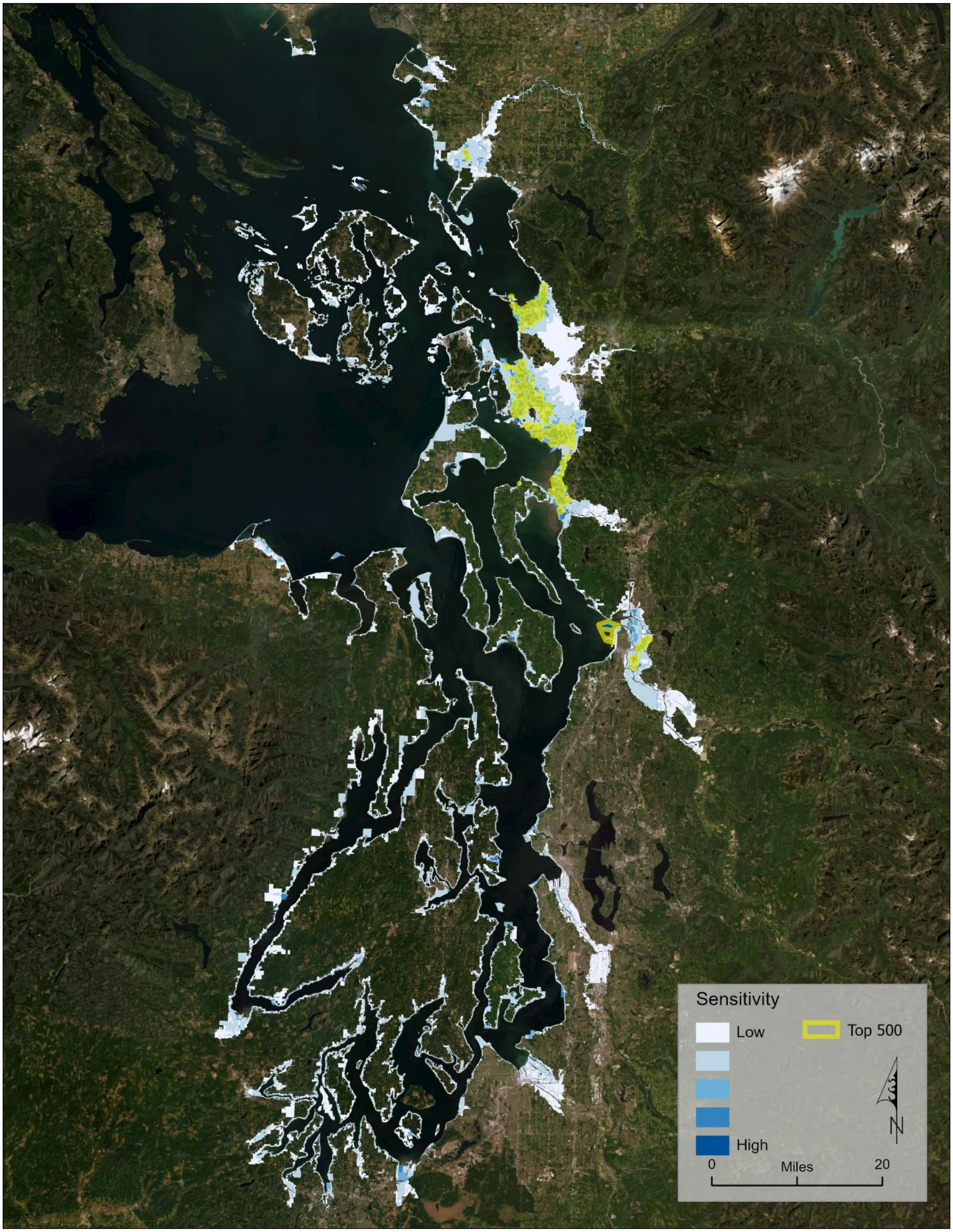

Figure 11. Sensitivity Score results for the entire project area with the top 500 scoring parcels highlighted in yellow.

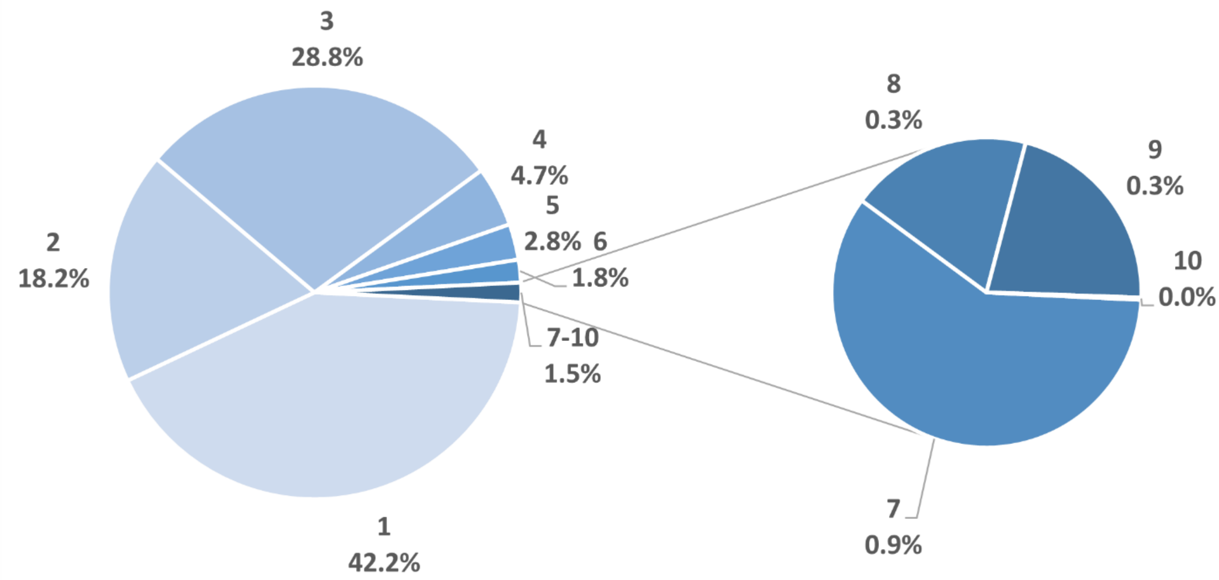

Figure 12. Sensitivity Score results broken down into binned categories.

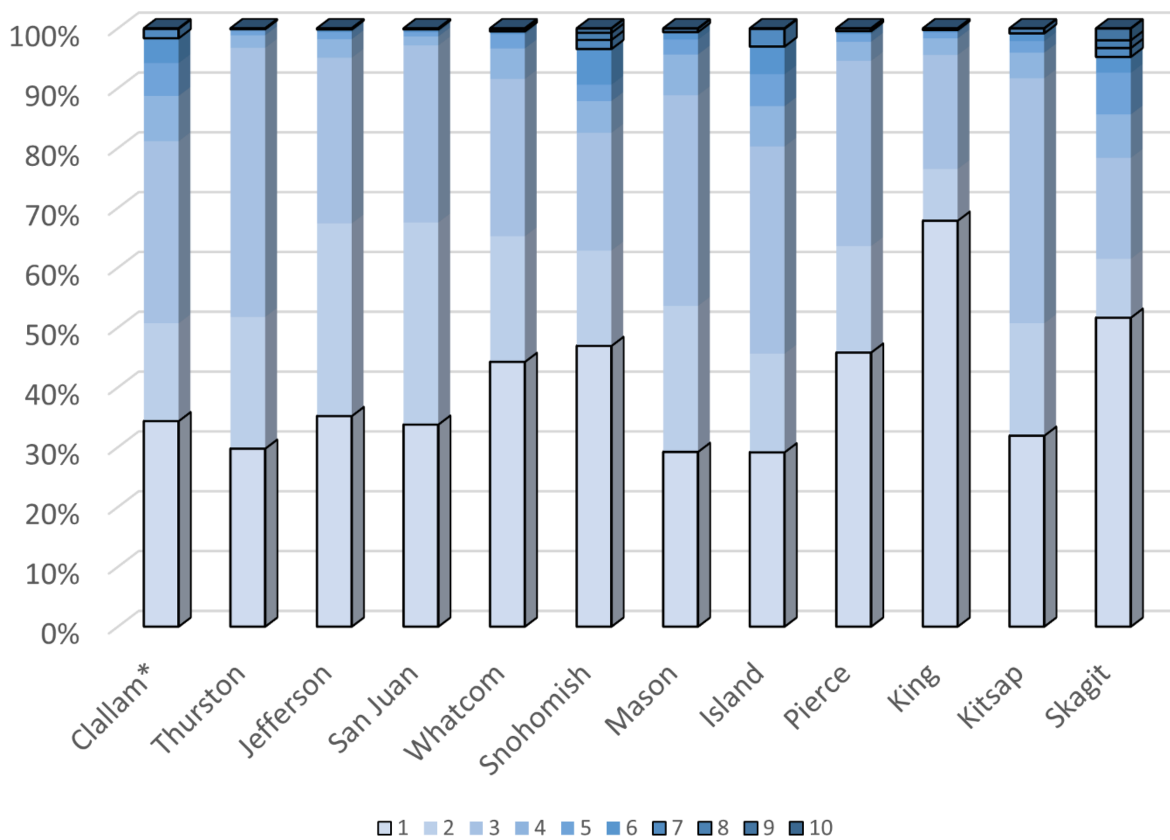

Figure 13. Sensitivity Score results broken down by county, with percent categories within the lowest binned category (0-1) and the upper three (7-10) categories outlined in black. Note that only a small fraction of Clallam County parcels was included in this study.

Physical Vulnerability Assessment

Physical Vulnerability, a function of the Exposure and Sensitivity Scores, for the entire project area is shown in Figure 14. This term is used to differentiate these results from the Socially Modified Vulnerably discussed below.

There are representatives of the highest-scoring 500 parcels for Physical Vulnerability found throughout the study area (Figure 15) but clusters are found in the low-lying large river deltas. One third (33.6%) of the parcels within the database fall within the lowest range of scores (Physical Vulnerability between 0 and 1; Figure 16). Generally, as the scores increase the percentage or number of parcels within a range decreased. Parcels with Physical Vulnerability scores falling between 14 and 20 score accounted for 2.6% of the data, or 2,919 parcels. Only 1 parcel fell into the highest vulnerability range (19-20).

Generally, between 15% to 50% of parcels in each county fell into the least vulnerable category (Physical Vulnerability between 0 and 1; Figure 17). The highest Physical Vulnerability, between 14 and 20, made up a small fraction of parcels by county, mostly less than 10% of parcels. The largest fraction of highly vulnerable parcels was found in Eastern Clallam, Snohomish, Island, and Skagit counties.

The Physical Vulnerability scores and all the subcomponents' scores for the Tulalip Bay area are shown in Appendix A. There we see low to moderate scores for the majority of the parcels with a few higher scoring shoreline parcels in the same areas as the higher scores for exposure and sensitivity. Maps showing the Physical Vulnerability scores separately for each county are also in Appendix A.

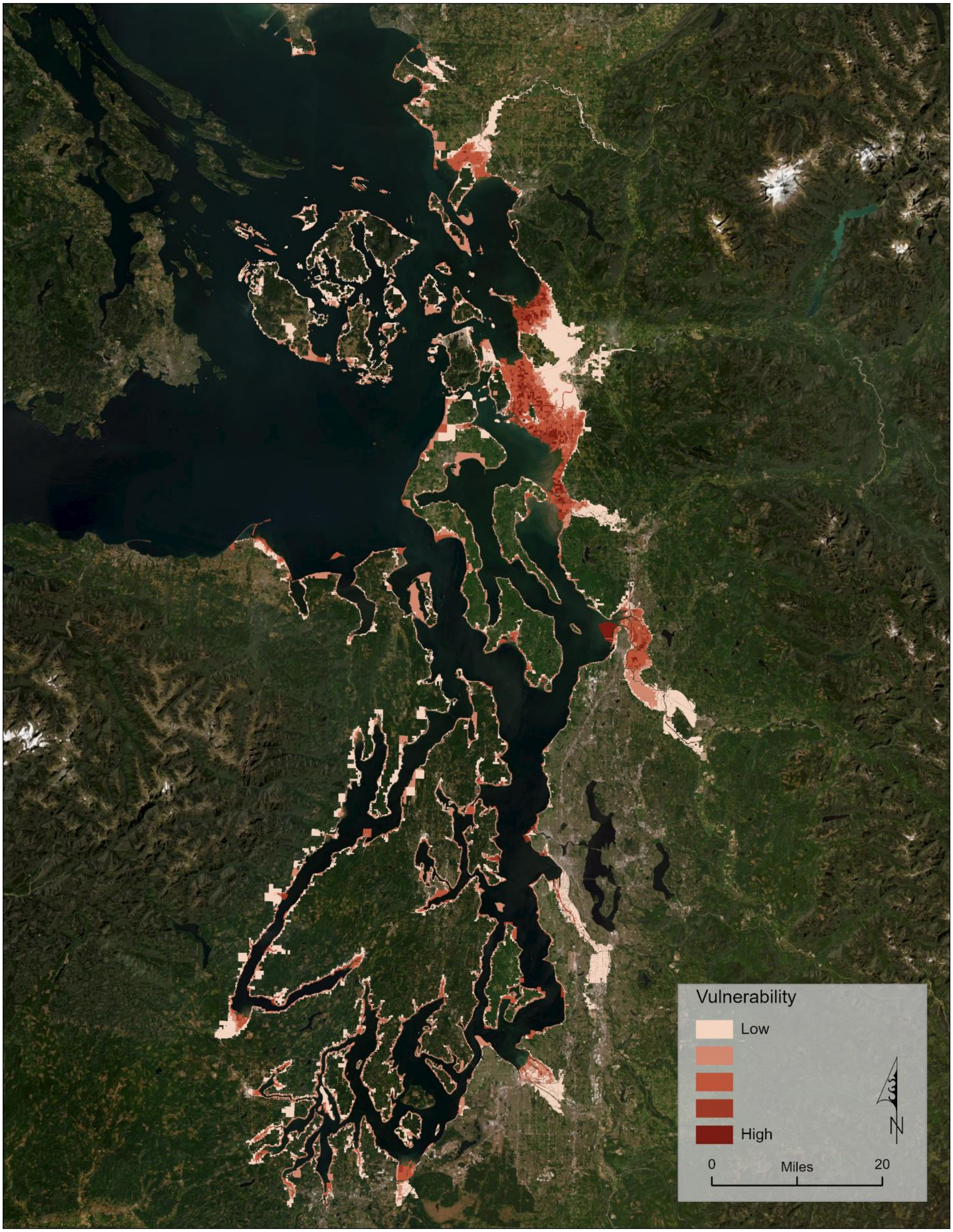

Figure 14. Physical Vulnerability Score results for the entire project area. Darker colors represent increasing vulnerability.

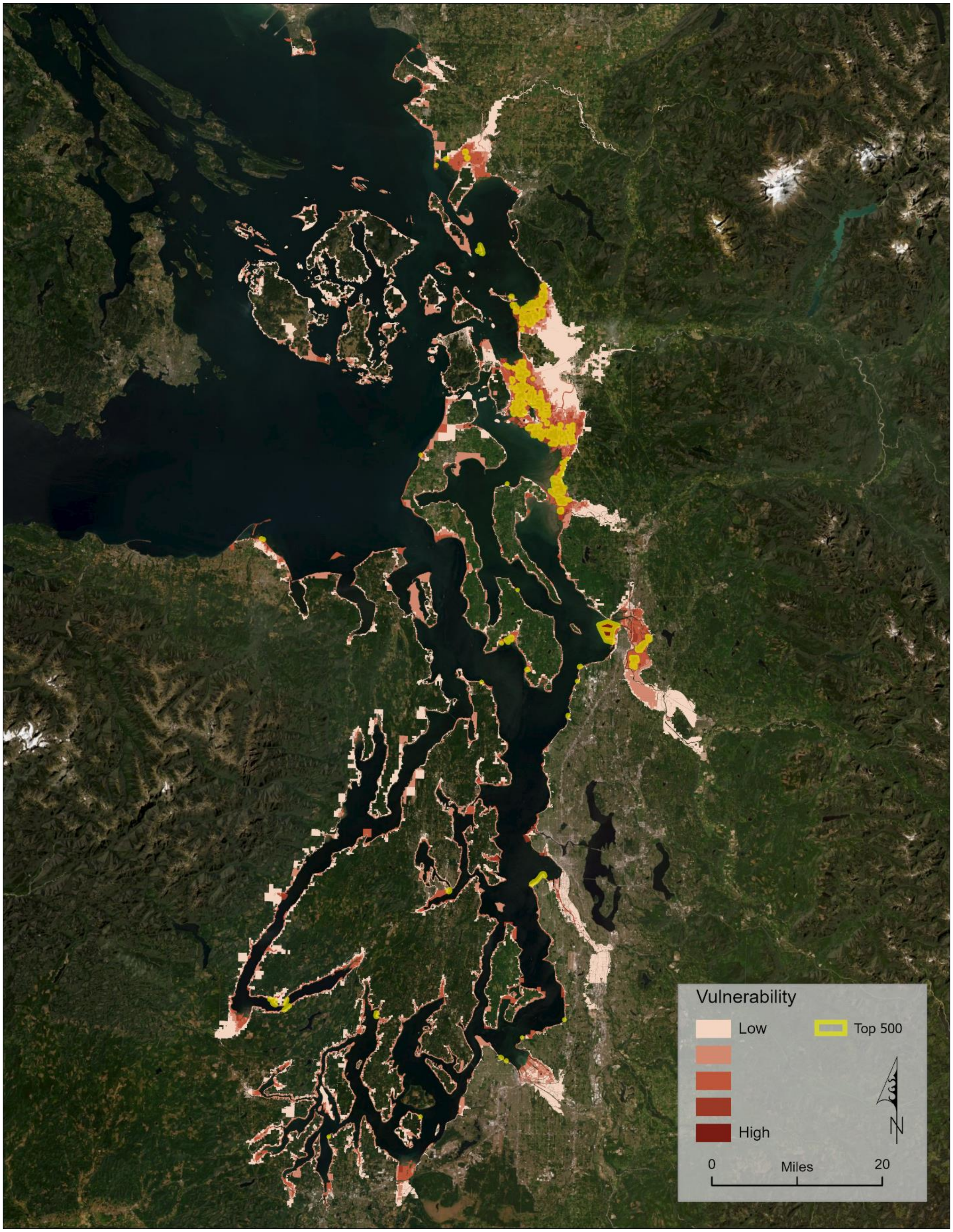

Figure 15. Physical Vulnerability Score results for the entire project area with the top 500 scoring parcels highlighted in yellow.

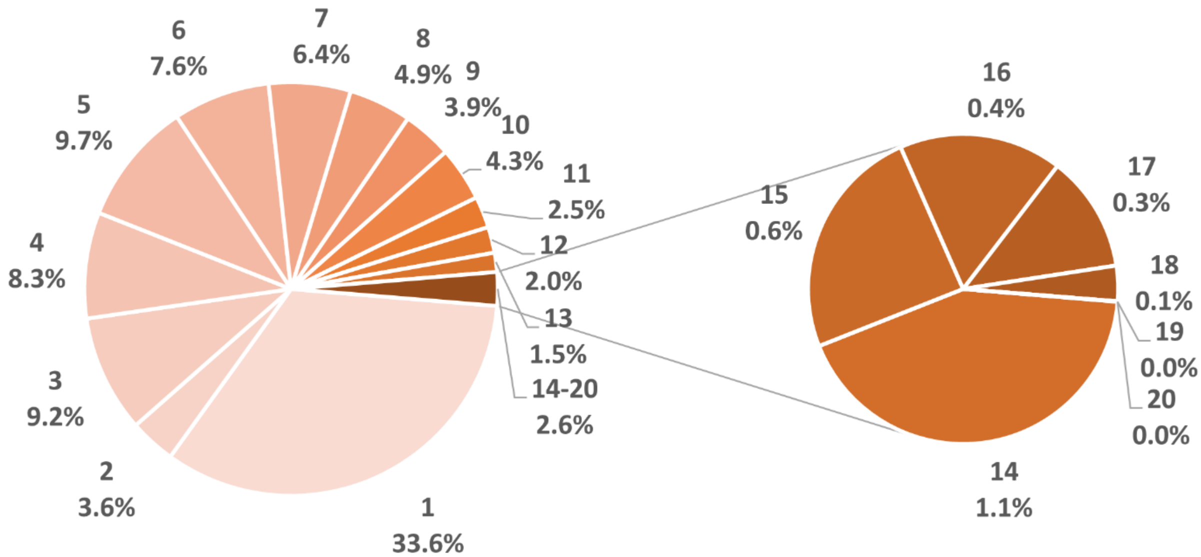

Figure 16. Physical Vulnerability Score results broken down into binned categories.

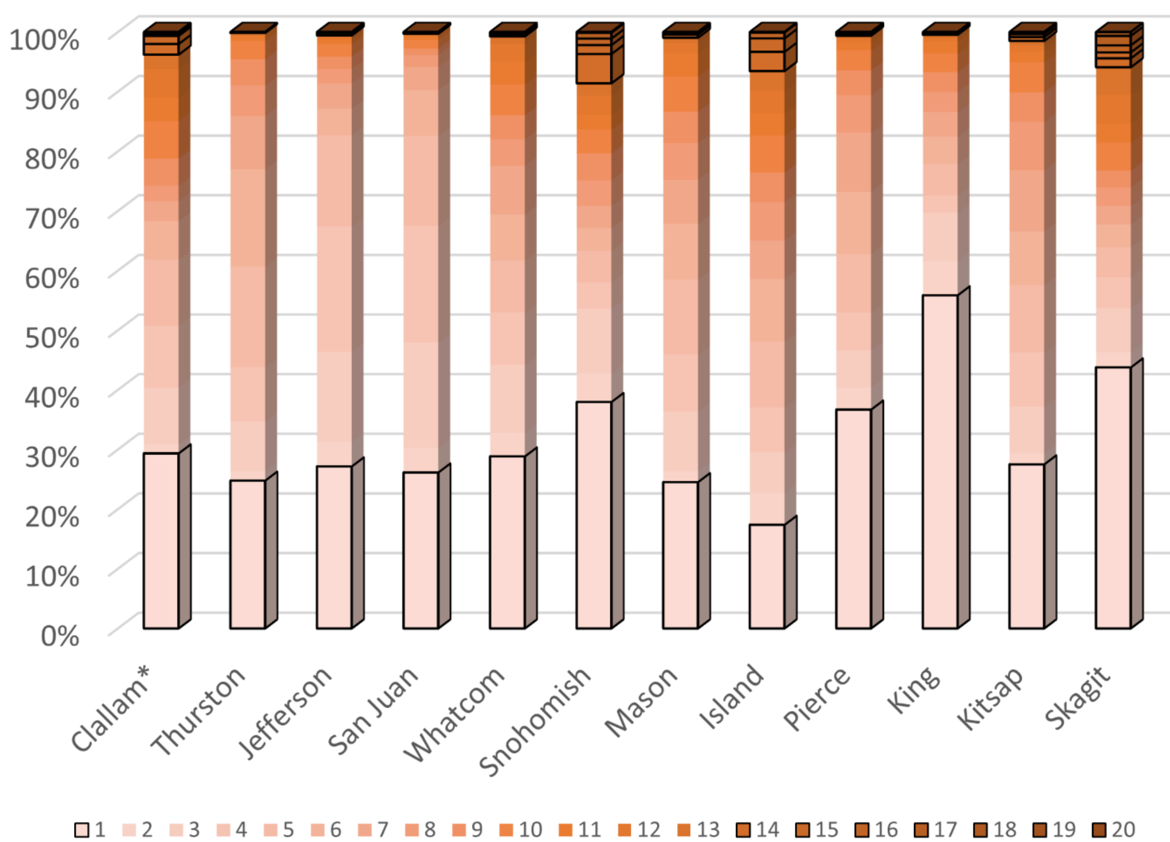

Figure 17. Physical Vulnerability Score results broken down by county, with percent categories within the lowest binned category (0-1) and the upper three (7-10) categories outlined in black. Note that only a small fraction of Clallam County parcels was included in this study.

Socially Modified Vulnerability

Socially Modified Vulnerability is a function of this project's Exposure and Sensitivity scores (Physical vulnerability), modified by the community social vulnerability index developed for Puget Sound (Fleming and Regan, 2022). Puget Sound wide data are shown in Figure 18. The top 500 scoring parcels are spread out across the study area but are mostly located in the low-lying deltas in the north and central study area and spread out within the southern area in more populated areas (Figure 19).

Less than 1% of the parcels within the database fall within the lowest range of scores (Socially-Modified Vulnerability between 0 and 1; Figure 16). Generally, the largest number of parcels in the study area fall in the low to mid-level range of scores (Socially Modified Vulnerability between 5 and 12). Relatively few parcels fall within the range of very high Socially-Modified Vulnerability scores. Parcels with Socially-Modified Vulnerability scores between 14 and 30 accounted for 11.8 % of the data, or 13,136 parcels. Only 0.4% of parcels fell into the highest third of the Socially-Modified Vulnerability score range (20-30).

Generally, less than 1% of parcels in each county are given a Socially-Modified Vulnerability score that falls in the lowest range (between 0 and 1; Figure 17). Reflecting the same pattern of variation identified for the entire study area, relatively few parcels (generally less than 25%) also fell into the upper half of the Socially-Modified Vulnerability score range (Socially-Modified scores between 14 and 30). A few counties stood out as encompassing a greater fraction of highly vulnerable parcels where vulnerable is evaluated using our Socially-Modified Vulnerability score – Eastern Clallam, Snohomish, and Skagit counties. San Juan County has very few parcels that are highly vulnerable when accounting for social vulnerability.

Integration of the Socially Modified Vulnerability led to increasing the scores of approximately 107k parcels, decreasing approximately 4k parcels, and keeping a handful the same relative to our original Physical Vulnerability score. Comparing the top 500 highest Socially-Modified Vulnerability scores (Figure 19) to the top 500 Physical Vulnerable parcels (Figure 15), we see that incorporating social vulnerability has the effect of increasing the scores in the greater South Puget Sound region (e.g., Duwamish, Tacoma, South Hood Canal), where there are more populous areas.

The Socially Modified Vulnerability scores and all the subcomponents' scores for the Tulalip Bay area are shown in Appendix A. There we see low to moderate scores for the majority of the parcels with a few higher scoring shoreline parcels in the same areas as the higher scores for exposure and sensitivity. Maps showing the Socially Modified Vulnerability scores for each county are also in Appendix A.

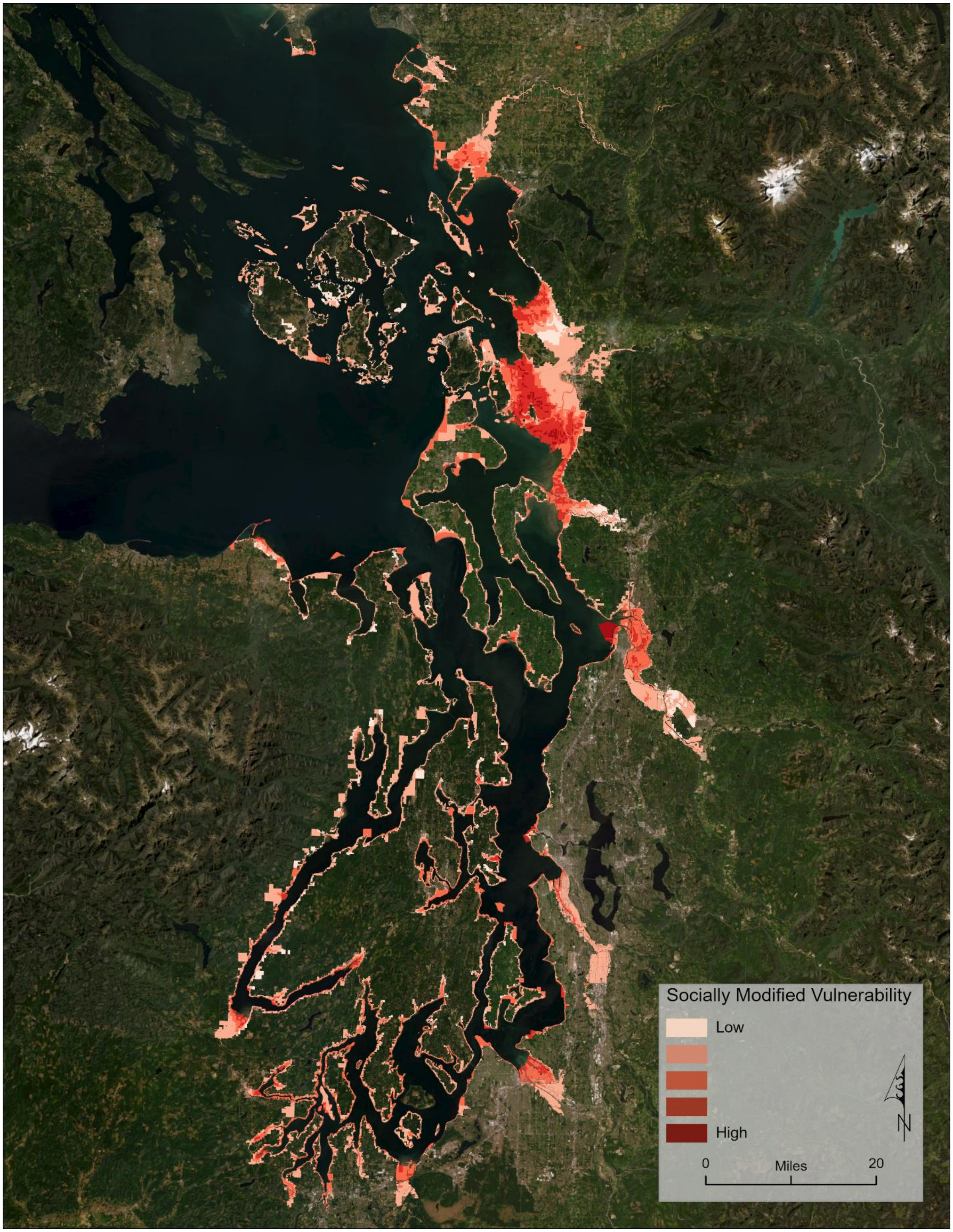

Figure 18. Socially Modified Vulnerability Score results for the entire project area. Darker colors represent increasing vulnerability.

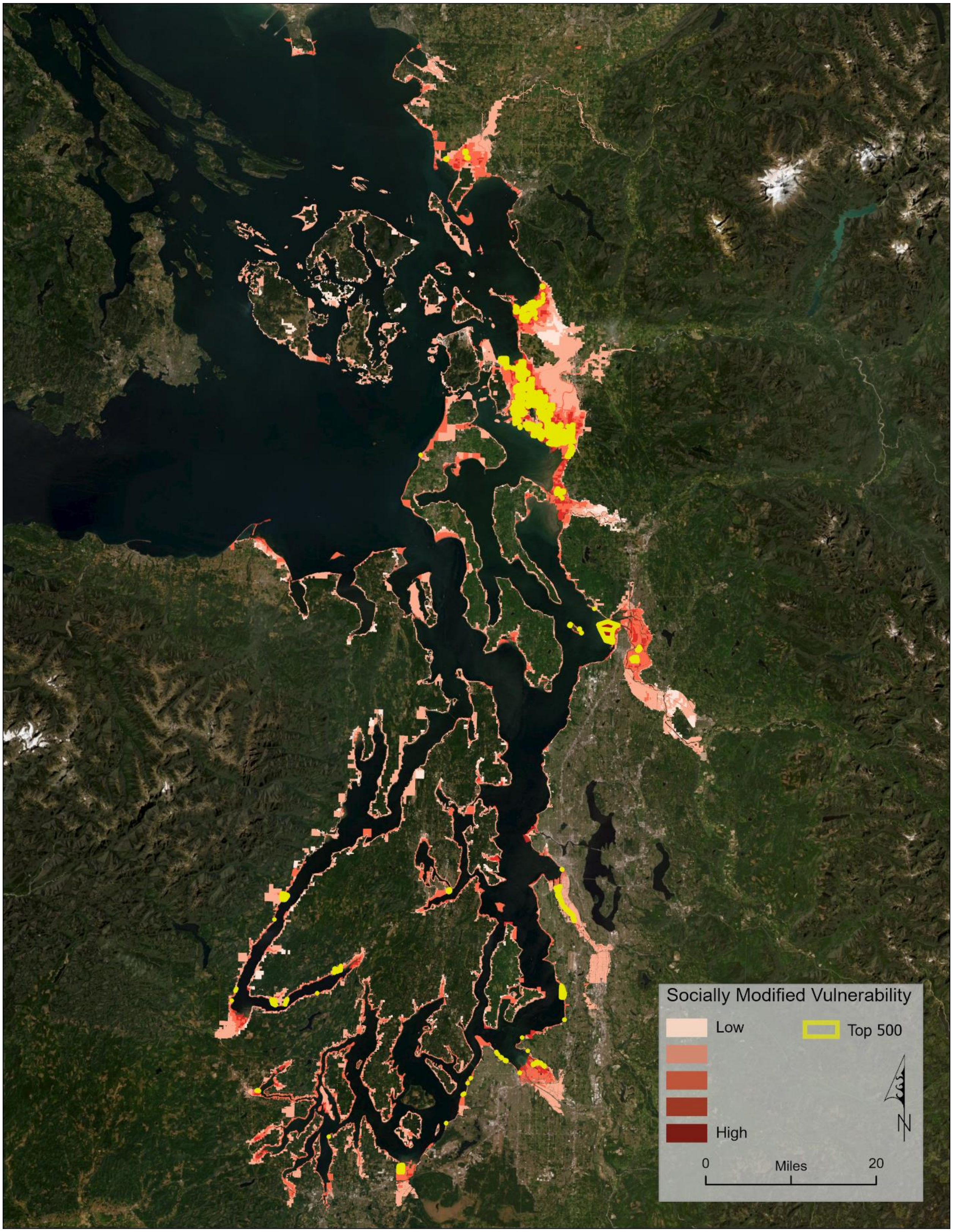

Figure 19. Socially Modified Vulnerability Score results for the entire project area with the top 500 scoring parcels highlighted in yellow.

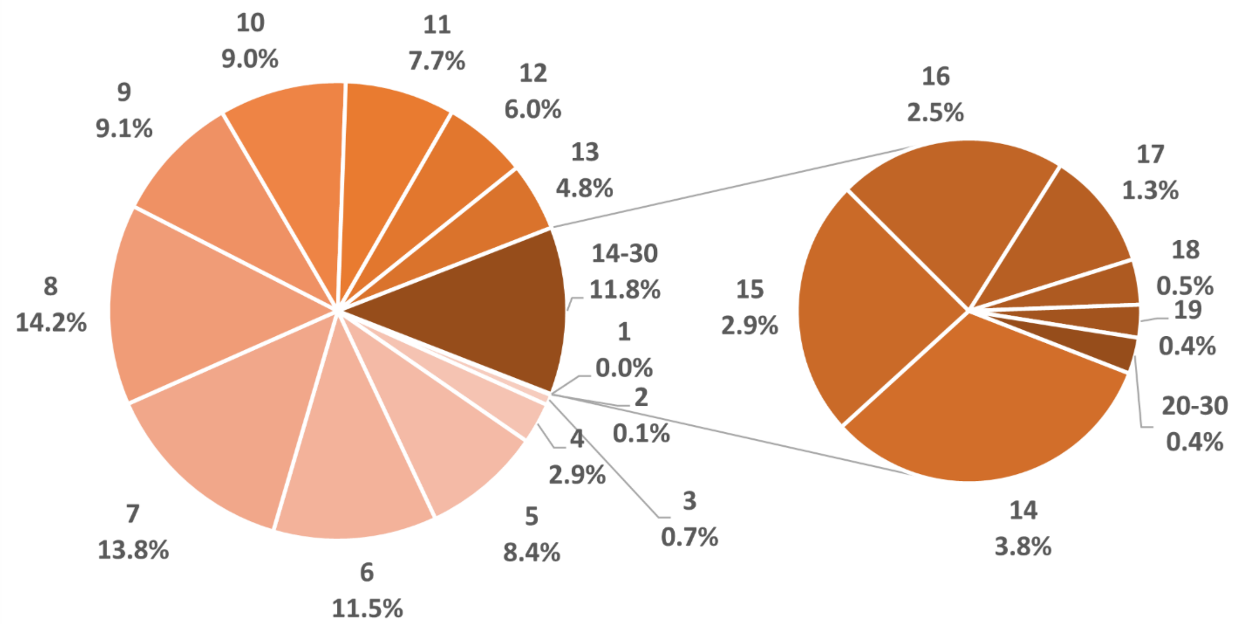

Figure 20. Socially Modified Vulnerability Score results broken down into binned categories.

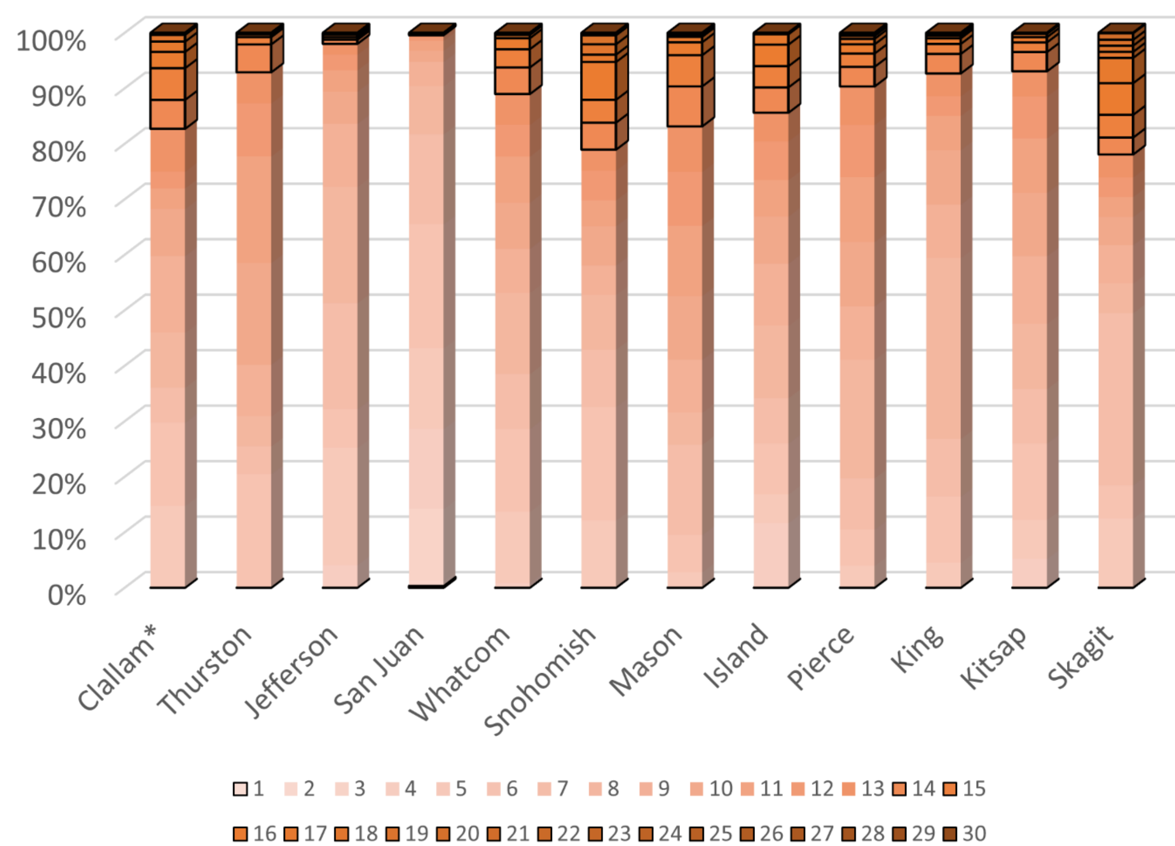

Figure 21. Socially Modified Vulnerability Score results broken down by county, with percent categories within the lowest binned group (0-1) and the upper three (14-30) categories outlined in black. Note that only a small fraction of Clallam County parcels was included in this study.

Discussion

A primary objective of this analysis is to better understand the vulnerability of Puget Sound coastal parcels to sea level rise. Results identified several areas and specific parcels of high vulnerability based on several factors incorporated into the exposure and sensitivity assessments. Future users of these data should be informed of the full context of the data, limitations, potential policy implications, and ways in which the data could be expanded upon in the future; these are described in further detail below.

Assumptions

Several assumptions were made during the development of this analysis that are important to assess and consider, especially where the results may be considered in planning and decision-making processes. Many of these assumptions were considered and discussed by the project Advisory Group well as senior professionals in the fields of coastal geology, mapping and spatial analysis, and coastal hazards within the project teams. They include:

- Sea level rise scenarios associated with a high emissions scenario (RCP 8.5) were the basis for modeling inundation for this analysis, as they provide a more conservative assessment of possible future conditions and represents the current emissions trajectory. However, it is important to note that the overall results are likely relatively insensitive to the choice of emissions scenario, or sea level rise scenarios. Selecting sea level projections for RCP4.5, or another lower emissions scenario would not substantially change the relative trends that are the primary output of this project.
- Modeled wave height provides a more directly applicable metric to evaluate coastal erosion potential from fetch, which was used in the *Beach Strategies* project. Only recently have modeled wave heights been made available for Puget Sound in a regionally consistent manner. It is important to note, though, that incorporating modeled wave heights into this analysis represents an advance, however, coastal erosion rates are not perfectly correlated to wave height. Better erosion models, and historic erosion rates, would improve analyses like this one, but are not currently available for Puget Sound.
- This analysis assumes that coastal features have a more or less fixed geomorphic shoretype that are subject to have a generally unchanging wave exposure and erosion potential. This means that although shoreforms and wave heights may change with sea level rise, the Coastal Erosion Potential score approach does not predict or incorporate this type of change. How the complex shoretypes and localized wave heights may change is not well understood or modeled for the region. Boarder sediment dynamics and their implications to erosion, especially with sea level rise, is not well understood Sound-wide and is therefore not included in the erosion potential. It is feasible that increased erosion expected with SLR could increase sediment to coastal landforms such as spits, allowing them to be dynamically more resilient to SLR.
- For the purpose of this analysis the presence of shore armor and development was treated as a barrier to habitat migration. This may not always be the case, and the particular type and configuration of armoring may lead to variable habitat migration responses.
- Bluff shoreforms without armor or development will provide a greater amount of room for habitats to migrate into with sea level rise, over what is modeled by the NOAA Marsh Migration

data, due to future bluff recession. This is an assumption, though and parcels that are currently undeveloped may be developed and/or armored in the future.

- If water is blocked via the topobathymetric elevation model, habitat will not be able to migrate into these areas with those specific SLR scenarios. We assume that topographic features within the DEM such as roads, banks, high levees, or hills that inhibit sea level rise inundation, will also inhibit habitats from migrating into these areas in the future.

Limitations and Possible Additional Work

Our approach evaluates the admittedly abstract concept of sea level rise vulnerability solely as a function of the components of exposure and sensitivity that we have included in this assessment. We recognize that other physical and societal factors impact vulnerability within the study area and that these results only provide a limited assessment of the true scope of vulnerability on individual parcels in the Puget Sound region.

While we sought to include the best available data that fit our data acceptance criteria, it is important to recognize that the project results are limited by the type and quality of input data. A discussion of some of the data limitations follow.

Sea Level Rise

Previous assessments of the vulnerability to sea level rise have typically been based on a limited number of indices with several physical variables (slope, geomorphology, etc.) and different rates or increments of sea level rise (Gornitz, 1991). In contrast, this assessment utilized sea level rise projections from localized probabilistic projections of relative sea level rise (Miller et al., 2018) and high resolution elevation data (Tyler et al., 2020) to create inundation models for the study area. This allowed the quantification of physical conditions and effects on Puget Sound shorelines using the best available science.

The projections utilized in this assessment include central and high probability sea level estimates for a single emissions scenario (RCP 8.5), which was selected by the project team and Advisory Group. However, the incorporation of other probabilities, emissions scenarios, and timeframes into a similar analysis would produce different exposure and sensitivity scores. Additionally, the sea level rise projections from Miller et al., 2018 will undoubtedly be updated as new science becomes available. The overall ranking of exposure, sensitivity, and vulnerability scores, though, is likely not very sensitive to the choice of sea level projections, or emissions scenario (as also discussed above).

Surface Model

As the assessment was reliant on the inundation layers, built using the USGS's topobathymetric model of the Puget Sound region, any issues with this surface model propagate through the analysis and the scores. Low-lying areas within the study are especially sensitive to misrepresentations of physical surface conditions, such as levees or seawalls, as even small gaps in elevation can allow huge areas to be modeled as inundated. The shallow subtidal portions of the DEM are particularly subject to inaccuracy due to limited basic data in the gap between upland topography and deeper water hydrographic data. While interpreting the results, it is especially important to consider how the topography and inundation are modeled compared to known conditions if possible. The analysis was also spatially-limited to the area covered by the USGS topobathymetric model at the time we conducted the analysis. As a result, only the eastern portion of Clallam County was included.

Parcel Data

The parcels included in this analysis were derived from the Washington Statewide Parcel Database (Rogers and Cooke, 2012) in order to make this project compatible with *Beach Strategies*. These data vary in places from more recently updated parcel databases from the state[10], which we infer to mean that either changes in real parcel boundaries and/or parcel mapping refinements have occurred since the data were published. At the start of this project, we investigated the possibility of using a newer parcel database, however it became clear that this update would make compatibility with *Beach Strategies* far more difficult and was not selected for that reason. Future projects may benefit from utilizing updated parcel data.

Parcels in this database included all *Beach Strategies* parcels and additional adjacent lowland parcels. Some of the parcels within the *Beach Strategies* database largely encompassed tidelands, for example near Everett and Seattle. Based on our approach, these parcels tended to score very high due to flooding of the parcel which effects the relative scoring off all parcels in the database. Future steps may include eliminating these tideland parcels completely. There are also many parcels that include an upland area, and extend into the tidelands, affecting scoring. These parcels tended to score higher than parcels with relatively similar conditions that do not include tidelands. This is especially true for bluff backed parcels with tidelands. Cutting the parcel boundaries at a water line, such as MHHW or OHWM, could help limit this bias in the results.

We also note that using one score per parcel cannot capture all physical complexities, which is especially true for larger parcels within the database. Many parcels have more than one shoretype mapped and a small number of parcels have up to six different shoretypes mapped and can have a wide variety of exposure. Larger parcels, especially those that extend far inland, are also more difficult to fully flood under present and future conditions, which may represent an exposure bias in our analysis.

Building Data

After reviewing the available building datasets for Washington State, the Microsoft building footprint dataset was selected for this analysis. This layer was created by leveraging AI technology to identify building footprints using aerial imagery. Through this analysis we found that this dataset was generally accurate, however, several areas were discovered where buildings were either mispresented in their shape, were missing, or existed where no building currently exists.

While working on the Parcel Infrastructure Score analysis, we also noticed that many building footprints did not fit completely inside parcel boundaries. This led us to clip building footprints at the parcel boundary and remove any building "slivers" that were < 200 SF. The influence on the overall results isn't clear, but is likely small. However, when analyzing the results for a specific parcel or area, it may be important to consider the quality of input data to real world conditions.

[10] https://geo.wa.gov/datasets/wa-geoservices::current-parcels/about

Habitat Sensitivity Analysis

The approach for quantifying habitat sensitivity was to calculate the change in area of habitats on a parcel with rising seas. The approach was intended to recognize the value of coastal habitats in Puget Sound as an asset and help to identify those parcels where coastal habitats are most likely to have the best chance of persisting through time. This approach, though, does not capture the change in the whole habitat area. For example, it is possible that a parcel loses habitat area, giving it a high sensitivity score, while it may be feasible for the habitat to move landward into adjacent low-lying areas with a similar or even larger habitat area.

Larger parcels may also be more likely to have a lower habitat sensitivity score, simply because their larger area would make it more likely that suitable topography for habitat migration is present. While this assessment is limited to analyzing the physical properties within a given parcel, other assessments could develop an approach to better identify the relative ease of a habitat to migrate at other scales. Additionally, the source data is effectively 30m grid cell data (data are in 10m cells based on elevation data, but the underlying method uses 30m land cover data from C-CAP data from NOAA), which may not be the appropriate scale for smaller parcels.

Potential Beneficial Data

Several additional datasets should be developed to support future assessments of sea level rise vulnerability of Puget Sound. These include:

- **An explicit erosion model for Puget Sound.** Having the ability to project rates and magnitudes of erosion along the shoreline would alter our assessment of exposure and, in particular, sensitivity of a given parcel. Our parcel infrastructure score was based solely on the inundated area of building footprints, so lower-lying buildings are assigned a higher sensitivity. Structures at the top of eroding bluffs, though, are likely also sensitive to sea level rise. While our analysis captures this sensitivity indirectly, via the larger exposure scores assigned to parcels on bluffs with large erosion potential, being able to intersect building location relative to an eroding bluff would add more specificity and accuracy to the evaluation of both exposure and sensitivity of infrastructure.
- **Comprehensive mapping of bluff crests.** Bluff crest mapping would allow projected bluff recession rates (which could also be more accurately determine using a more complex methodology, such as that envisioned in the CosMoS project by USGS) to be applied. This could be used to inform potential threats to structures associated with sea level rise as well as armor removal feasibility. This was identified in *Beach Strategies 2* as a data gap (Coastal Geologic Services et al., 2020).
- **Comprehensive mapping of levees.** Mapping, including the location and elevation of shore armor and levees would allow more accurate modeling of future conditions with sea level rise, especially on low lying delta areas that are especially vulnerable to sea level rise.
- **Comprehensive mapping of shore armor.** Existing armor mapping is incomplete or out of date in many Puget Sound counties and typically does not map actual locations (instead uses the ShoreZone shoreline) or elevations of armor.
- **Evaluation of impacts of SLR and precipitation events on bluff erosion and landslides.** Long term collection of historic and current erosion rates to relate to changing conditions

(precipitation events, SLR). This evaluation would be helpful in establishing appropriate regulations such as structure setbacks and nearshore vegetation retention.

- **Structure setback distances.** Bluff crest mapping would aid in measuring setback distances in conjunction with bluff crest mapping to assess the vulnerability of a structure to erosion and sea level rise. This was also identified in *Beach Strategies 2* as a data gap (Coastal Geologic Services et al., 2020).
- **Monitoring and analysis of shore and habitat change.** Collecting data to evaluate shoreline and habitat change for the greater Puget Sound with SLR and climate change would inform appropriate policy and management response and restoration efforts.

Policy Implications

The intended utility of this assessment was to take steps towards understanding the relative vulnerability of parcels within the Puget Sound region to sea level rise by creating an additional tool that coastal managers, restoration practitioners, regulators, and decisions-makers have available to them to manage the coastal lands and resources of the region. Specifically, this data could inform coastal hazards analysis, aid prioritization planning, and focus restoration or other feasibility assessments. Identifying and evaluating the top 100 most vulnerable parcels within a county is an example of how resource managers and restoration practitioners could utilize these data to begin to investigate the feasibility of restoration or potential acquisition of parcels.

The parcel scale was chosen as the most applicable spatial scale of analysis because it is the most relevant scale for decision-makers, permitting, and management. Concerns were initially brought up by Advisory Group members and others about showing the results of this analysis at the parcel scale. Results from the Policy Implications memo (Miller, 2020) detailing specific feedback and concerns, similar tools, and relevant literature found that this scale of analysis is unlikely to have significant negative policy implications.

A summary of the conclusions from the Policy Implications memo for this project are as follows:

- The interpretation of any quantitative GIS-based assessment should be done carefully, with the quality of inputs, and the weighting applied to those inputs, in mind.
- This physical parameters in this study are a snapshot in time, however there are many factors that may influence how communities and nature adapt to rising sea levels. Therefore, the results of this study tell us what could happen, and which parcel are the most vulnerable if we do not change our behaviors and or policy.
- Analyses like this DO NOT replace guidance or analyses that are defined by law. For example, GIS-based flood exposure rankings developed for this project will not replace federal flood standards or regulations.
- Quantitative GIS-based analyses should not be viewed as stand-alone decision-making tools; rather, they should be viewed as one input in a decision-making or planning context.
- The interpretation of any quantitative GIS-based product should be made with input from a variety of people coming ideally from a variety of sectors.
- The communication of results in a public forum can be “rolled up” geographically in order to avoid any possible negative outcomes associated with communicating results at the scale of individual parcels. In addition to avoiding sensitivity about publishing parcel scale data, such an approach can aid with the interpretation of results at regional or state-wide scales.

Lastly, we want to emphasize that this analysis is strictly a sea level rise vulnerability assessment and does not incorporate the assessment of other vulnerabilities due to climate change such as increased precipitation, freshwater flooding, extreme temperature, fire etc. These are important conditions to take into consideration but were not part of the scope of this project.

Conclusions

The goal of this project was to construct, calculate, and map a SLR vulnerability index for the greater Puget Sound shore that includes both coastal infrastructure and habitat sensitivity at the parcel scale. Our assessment was based on a quantitative vulnerability framework, which defines vulnerability as a function of exposure and sensitivity. The exposure index, which incorporates coastal flooding and erosion, was coupled with a sensitivity index, which integrates infrastructure and coastal habitats, into a physical vulnerability index.

This report presents the methods and results of the assessment, intended to inform local hazard planning and habitat restoration efforts. This project includes a vulnerability assessment of 111,249 parcels within the Puget Sound coastal study area using SLR projections out to 2100. These results are also coupled with a concurrently developed social vulnerability index, which provides additional insight about people and places that may be predisposed to adverse impacts from SLR-related risks.

Over fourteen existing datasets were incorporated, along with the creation of five new Puget Sound wide inundation layers. The main project deliverable is a geodatabase including all input data, inundation layers, intermediate analysis layers, and a parcel layer with 12 scores associated with vulnerability, including two social vulnerability scores (Social Vulnerability Index and Socially Modified Vulnerability scores) derived from our NCCOS partners.

The results showed that high energy locations in the north Sound, on west Whidbey Island, and the Strait of Juan de Fuca are the most exposed, while large delta areas stood out as being highly sensitive. For the final Physical and Socially Modified Vulnerability assessments, large low-lying delta areas stood out as having some of the highest vulnerability to sea level rise within the study area, but vulnerable parcels are distributed throughout the Puget Sound region. We also found that a small portion of the parcels within the study area (less than 2,000 parcels) scored between 15-20. This suggests that we can significantly decrease Puget Sound’s collective vulnerability by directing our efforts to a relatively small number of parcels region-wide. Lastly, when integrating social vulnerability, we believe we get a realistic transfer of the highest vulnerability into different areas than when we consider physical vulnerability on its own, for example into urban estuaries in southern Puget Sound.

Despite the limitations in project capacity and datasets (discussed above), this project developed the Puget Sound region’s first approach to quantify sea level rise vulnerability at the parcel scale, which:

- Incorporated present and future marine flooding conditions using the newest sea level rise projections and elevation data
- Updated and expanded a coastal erosion potential metric
- Assessed the sensitivity of infrastructure on and related to a parcel
- Quantified the change in habitat area on a parcel with rising seas

As the results of this assessment provided the first approach of this kind for the Puget Sound region, we hope that it provides a foundation for which additional refinement and assessment can be conducted.

Greater understanding of relative sea level rise vulnerability in the Puget Sound region can inform better management through more focused feasibility assessments and efforts. Adaptive actions can be prioritized using these results alongside other more site-specific data and objectives. This can improve conditions for nearshore habitats, processes, and the resilience of coastal communities.

This assessment could be built from or revised in several ways. This includes the expansion of the project area west along the western Strait of Juan de Fuca as additional high resolution topobathymetric data from the USGS was released during the course of the project. Other input data would need to be evaluated to see if they encompass an expanded study area. Additionally, the removal of tideland areas within a parcel could be investigated to reduce some of the very high scores for tideland parcels. Lastly, if the appropriate data became available, such as those identified in the *Data Gaps* section, an erosion model, levee data, or building setbacks could be incorporated into a future assessment.

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Appendices

Appendix A. Map Folio of results for Tulalip Bay and each county within the study area

Appendix B. Geodatabase User Guide

Appendix C. Reviewer Comments and Responses