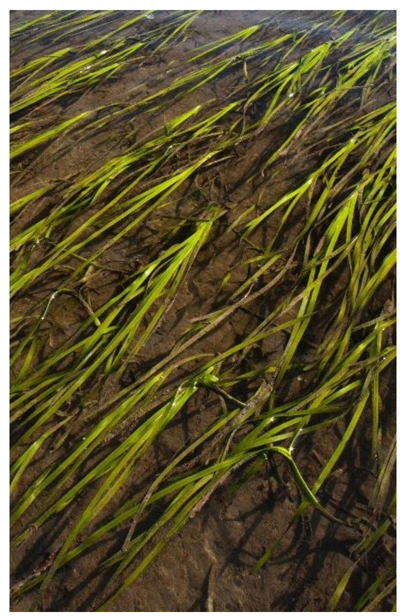
Using Coastal Vulnerability Assessment Results for the Shorelines of Pacific and Grays Harbor Counties

A Practitioner's Guide



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Purpose

Big storms, strong waves, and the erosion and inundation that they bring are the norm for Washington's coastline. In this dynamic environment, coastal habitats play a vital role, anchoring shorelines and protecting coastal residents, their property, and infrastructure from adverse impacts. However, in a changing world where sea levels are rising and habitats are under pressure by human development, coastal communities are at a greater risk to coastal hazards. It is important for coastal communities to understand the vulnerability of their shorelines and the importance of coastal habitats to inform development decisions and increase coastal resilience.

The purpose of this document is to provide clear guidance for Grays Harbor and Pacific County on how to view and interpret outputs of the Natural Capital Project's Integrated Valuation of Environmental Services and Tradeoffs (InVEST) Coastal Vulnerability model. The Nature Conservancy of Washington (the Conservancy) used the model to:

1. Identify coastlines vulnerable to erosion and flooding due to storm surge and waves, and
2. Highlight areas where vulnerability is reduced due to the presence of natural habitats.

Washington's Shoreline Management Act encourages counties to "locate and design [new development] to avoid the need for future shoreline stabilization" and to avoid "no net loss of ecological functions." (WAC 173-26-231). The InVEST Coastal Vulnerability model is one tool that communities can use to generate information in support of achieving these goals. Specifically, the tool will allow communities to view the existing vulnerability of the shoreline, identify where strong buffers are critical to maintaining the shoreline, highlight where to minimize development impacts through mitigation, and choose where to conduct restoration to enhance ecological functions.

The map layers that we have generated from the Coastal Vulnerability model for Grays Harbor and Pacific County are presented here and available online on the Conservancy's Coastal Resilience Web Portal "Regional Planning Application." Additional information can be found on the Conservancy's Coastal Resilience webpage.

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Background

Challenges

Washington's southwest coast is subject to inundation and erosional hazards that pose threats to coastal communities. The sandy beaches and bluffs of Pacific County and Grays Harbor County are particularly vulnerable to erosion due to indirect effects of human activities and natural weather patterns. For example, construction of dams on the Columbia River and jetties at its mouth has altered sediment flow and hydrology of the Columbia River littoral cell. The result is a lack of sediment to replenish beaches as they erode. Erosion of bluffs and shorelines is further intensified during El Niño periods and large storms, when sea levels are higher and wave action is stronger.[1] In southwest Washington, critical erosion sites along the outer coast include Ocean Shores and Westport (Grays Harbor County) and Cape Shoalwater, Leadbetter Point, and North Jetty (Pacific County).

Unlike sandy beaches and bluffs that undergo rapid change, estuaries are a transitional buffer between land and sea. In southwest Washington, the Grays Harbor estuary and Willapa Bay (Pacific County) receive sediment from surrounding rivers and streams. During winter, sediments flow into the estuaries and are trapped in saltmarsh channels.[2] In summer, sediments are released from the channels, but then trapped again, this time by eelgrass meadows on tideflats. However, storm events that bring surge, waves, and high river flow can still lead to inundation and erosion in both the Grays Harbor estuary and Willapa Bay.[3]

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As global climate changes, rising seas on top of storm surges and high tides will intensify flooding and erosion in coastal regions.[4] The National Oceanographic and Atmospheric Administration (NOAA)'s mid-level sea level rise projections for the southwest Washington Coast range from 4-27 cm by 2030, 8-73cm by 2050, and 19-289 cm by 2100 based on a series of future greenhouse gas emission scenarios.[5] An increase in sea level may cause declines in coastal habitats like eelgrass beds that depend on a narrow optimal depth range[6] and saltmarshes that need room to migrate inland.[7] A decline in these protective habitats may further exacerbate the impacts of erosion and flooding.

The outer coast of Washington has thus far avoided many of the negative impacts associated with extensive population growth and urbanization. For existing developments, armoring (e.g. sea walls, jetties, breakwaters, and groins) are used as one solution to control coastal flooding and erosion. While these hard structures may be necessary to prevent damage to existing development, they are costly to the property owners and communities charged with mitigation. For example, the jetty that once guided sand to feed Ocean Shores stopped receiving enough sediments to supply the city's beaches, resulting in severe erosion. In response, property owners had to pay $500,000 to build an 850 ft. seawall to protect their homes from erosion, and then another $100,000 to place sandbags and geotubes around the seawall to prevent further erosion. Today, even with seawalls and geotubes, the area still experiences a high level of erosion and inundation.[8]

Shoreline armoring can also have negative ramifications on ecosystems by degrading surrounding vegetation and ecological functions, as well as altering sediment transport, hydrology, and channel movement (WAC 173-26-231). Additionally, hardened shorelines can prevent the shoreline from retreating inland as sea levels rise, leading to loss of coastal habitats (Figure 1).

Now, more than ever, communities should consider their vulnerability to flooding and erosion, protect or restore important buffering habitats that be cost effective, and reliable solution to hardening a shoreline.

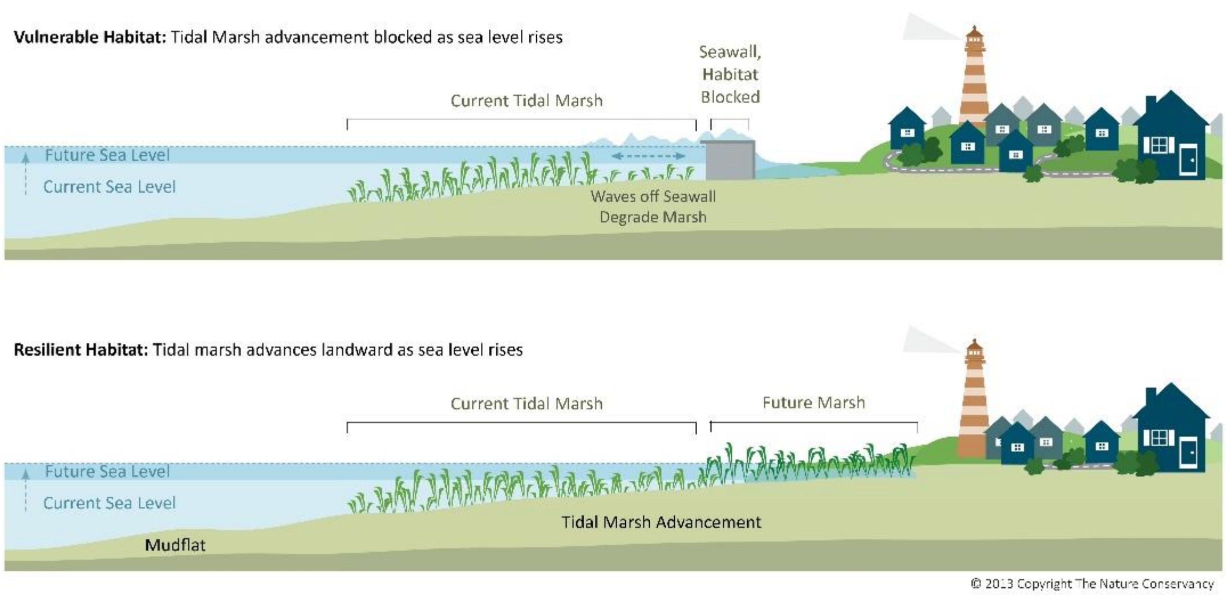

Figure 1. Certain saltwater ecosystems (e.g. wetlands) can move landward as sea levels rise. The ability of a habitat to move landward depends on several factors including the presence of physical obstacles preventing the subtidal or intertidal habitat from migrating.

Solutions

Coastal communities are increasingly interested in using natural habitats and soft stabilization methods to maintain coastal resilience in the face of a changing environment. The National Oceanographic and Atmospheric Administration (NOAA) defines coastal resilience as "building the ability of a community to bounce back after hazardous events such as hurricanes, coastal storms, and flooding- rather than simply reacting to impacts."[9]

A critical piece of resilience is maintaining the steady stream of benefits that healthy coastal habitats provide to communities. For example, estuarine habitats (e.g., eelgrass beds, saltmarshes, oyster reefs) protect coasts and reduce erosion by dissipating wave energy and trapping sediments *while also* purifying water and generating shelter and nursery grounds for economically important fish and shellfish species.[10]

Terrestrial coastal habitats (e.g., vegetation, forests, dunes) also reduce erosion by stabilizing sediments and reducing storm surge *while also* serving as critical habitat for wildlife, space for recreation and tourism, and storing and sequestering carbon.[11] Together, these habitats on land and in the water form a living shoreline that provide benefits both humans and the environment (Figure 2).

Habitat protection and restoration provides economic returns because of the ecosystem services that natural systems provide. In southwest Washington, estimates of the value of services provided by nearshore ecosystems range from $313 million to $3.1 billion per year for Grays Harbor County and $985 million to $4.4 billion for Pacific County.[11,12] In addition, natural habitats are more cost effective solutions than armored shorelines for shoreline protection because natural habitats can grow stronger with time, adapt as sea level rise, and restore themselves after storms.[13]

To learn more about the role that natural habitats play in protecting infrastructure visit [NOAA's Green Infrastructure website].

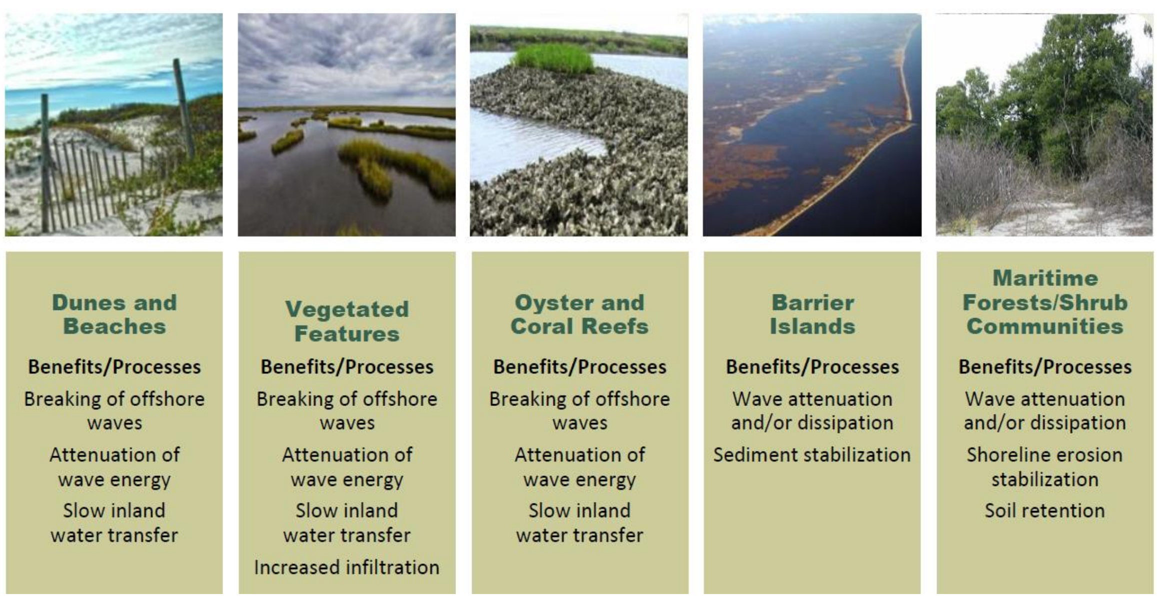

Figure 2. Army Corps of Engineers examples of natural habitats and how they buffer shorelines from storms, preventing inundation and erosion. [14]

The Washington State Department of Ecology (Ecology) encourages counties to avoid shoreline armoring and prevent the loss of shoreline ecological functions. Specifically, Ecology suggests the following practices:

- Prohibit uses [within the shoreline] that are not water dependent or preferred shoreline uses.
- Require that all future shoreline development, including water-dependent and preferred uses, is carried out in a manner that limits further degradation of the shoreline environment.
- Require buffers and setbacks that reduce the impacts of development on the shoreline environment.
- Develop policies and requirements for restoration.
- Require mitigation sequencing to first avoid impacts [to habitat altogether]. [15]

Spatial modeling tools can help communities see risks of coastal hazards both now and in the future. The InVEST Coastal Vulnerability model is one tool that can help communities understand how their shorelines are vulnerable to storms and the role that habitat plays in buffering shorelines from the impacts of erosion and inundation. The mapping results presented here can be used to assist communities adhere to Ecology's shoreline planning guidelines. The results can be used to inform the creation of policies and regulations on buffers for local development plans, educate developers and homeowners on the importance of coastal habitats for shoreline protection, and guide restoration activities.

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Model Description

Approach

The analysis was conducted using the [Natural Capital Project's Integrated Valuation of Environmental Services and Tradeoffs (InVEST) Coastal Vulnerability model]. InVEST is an open-source decision-support tool developed by the Natural Capital Project. The Natural Capital Project**,** an innovative partnership between Stanford University's Woods Institute for the Environment, the University of Minnesota's Institute on the Environment, The Nature Conservancy and the World Wildlife Fund, is working to understand how to value nature and the services it provides so that leaders of countries, companies, and communities can make smarter decisions for both the planet and their bottom lines. The Coastal Vulnerability model – further described below - uses a combination of spatially-explicit information on five characteristics of the shoreline– 1) its *geomorphology*, 2) surrounding coastal *habitats* that may or may not buffer the shoreline, 3) its exposure to *wind* and *waves*, 4) the *surge potential*, 5) and the surrounding *relief* to produce relative maps of vulnerability of shorelines to erosion and inundation.

Study Area

We used the InVEST Coastal Vulnerability model for two regions in Washington: Grays Harbor County and the Willapa Bay estuary and outer coast of Pacific County.

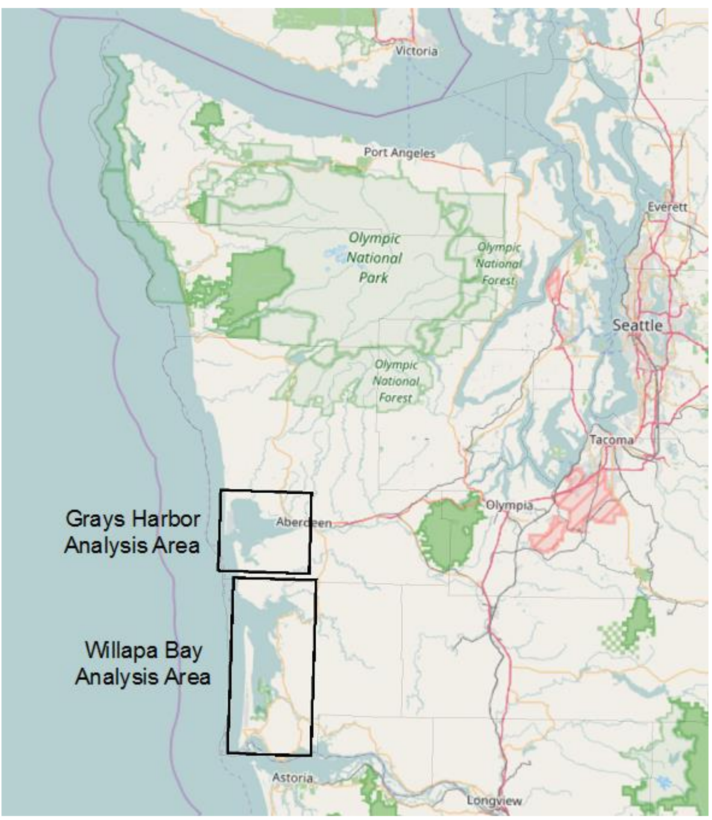


Figure 3. Study areas selected for analysis in Grays Harbor and Pacific County

Habitat Data

The spatial information used in the analysis includes the best available data on distribution of estuarine (seagrass, shellfish reefs, and saltmarsh) and terrestrial (sand dunes, emergent wetlands, grass and agriculture, and forest/shrub) habitats collected by state, federal, and academic institutions. For details about habitat data and references see Appendix A.

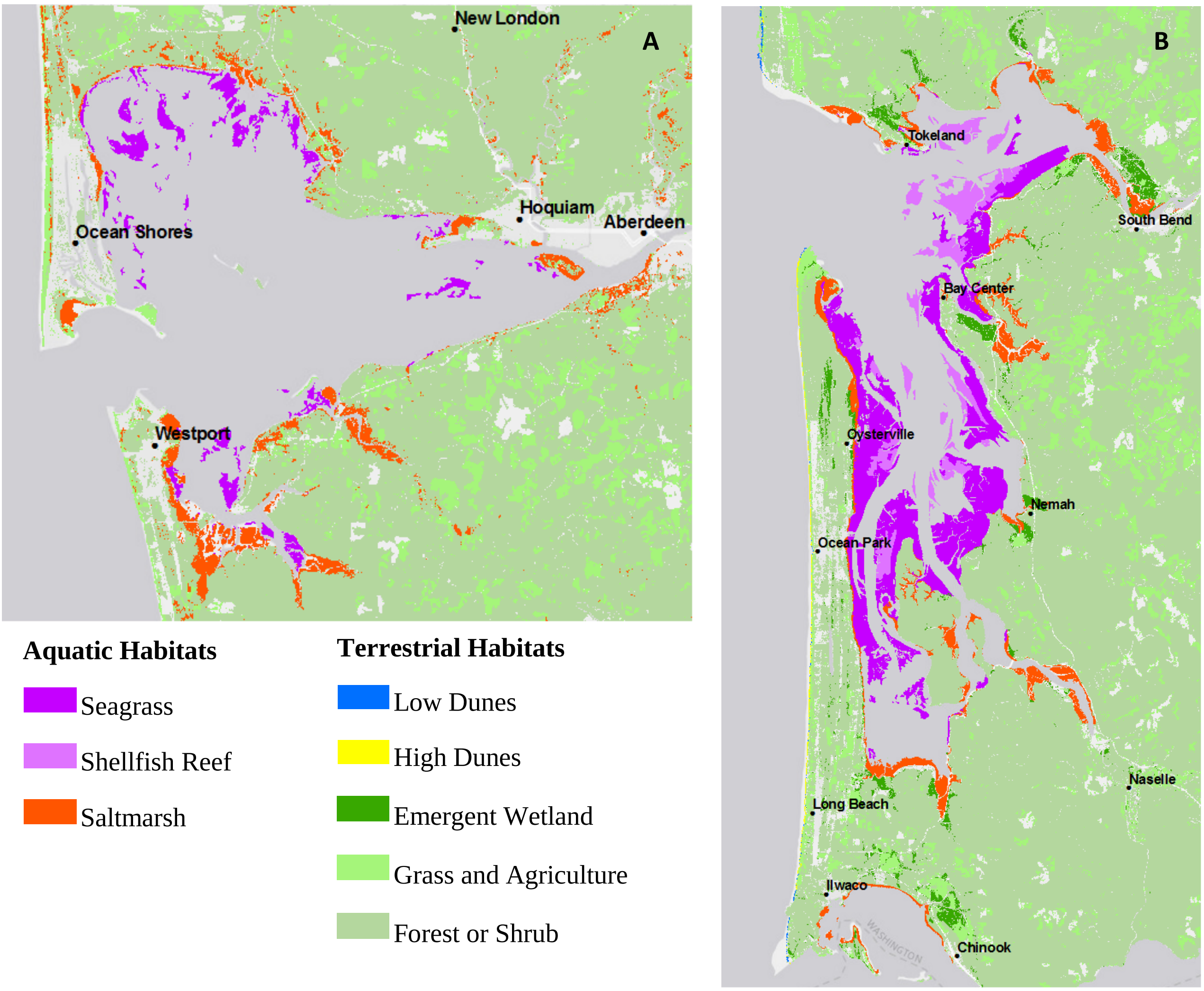


Figure 4: Spatial representation of estuarine and terrestrial habitats included in the InVEST Coastal Vulnerability model for Grays Harbor (A) and Pacific County (B). Note that while Pacific County sand dune data was included in the model, it does not appear on this map due to scale. Additionally, the Grays Harbor County analysis only contains data categorized as “seagrass, marsh, grass/agriculture, and forest/shrub” due to data availability.

Description of Model Results

The InVEST Coastal Vulnerability model results presented here help to answer the questions: What shorelines are vulnerable to inundation and erosion with and without current habitats? What role do all current habitats play in reducing vulnerability of shorelines? Furthermore, what are the specific roles of terrestrial and estuarine habitats in reducing vulnerability?

Interpreting the Map Legend

Vulnerability: LOW ● ● ● ● ● ● ● ● HIGH

We show the mapping results for coastal vulnerability on a color scale from cool to warm, where low vulnerability is blue, moderate vulnerability yellow, and high vulnerability orange and red. The color scale corresponds a relative scale of vulnerability from 1.1 to 5, where 5 is a highly vulnerable coastline (i.e., red). Model outputs are relative, not absolute, within the areas of analysis, so a score of 5 in Grays Harbor may not equate to a 5 in Willapa Bay in terms of actual vulnerability. Rather, each of those fives describes where the highest possible vulnerability occurs within those analysis areas.

Four Scenarios

The model results show which shorelines in Pacific County and Grays Harbor are relatively more vulnerable to erosion and inundation from storm surge and waves. Here, we have explored how vulnerability of shorelines varies under four scenarios:

> **Scenario 1 (S1):** *Vulnerability with All Habitats.* This scenario reflects current conditions, where all terrestrial and estuarine habitats are included.
>
> **Scenario 2 (S2):** *Vulnerability with No Habitats*. In this scenario, all terrestrial and estuarine habitats are excluded from the model run. In other words, this is a model of vulnerability of the shoreline if all habitats were lost or degraded. The map highlights where habitat is related to vulnerability.
>
> **Scenario 3 (S3):** *Vulnerability with only Estuarine Habitats*. Here, results show how vulnerable shorelines would be if only estuarine habitats are present, but without any terrestrial habitats. In other words, this is a model of vulnerability if terrestrial habitats are lost or degraded.
>
> **Scenario 4 (S4):** *Vulnerability with only Terrestrial Habitats*. This scenario is the complement to Scenario 3, where the results show shoreline vulnerability in the absence of estuarine habitats, but with intact terrestrial habitats. In other words, this is a model of vulnerability if estuarine habitats were lost or degraded.

We recognize that a system devoid of all natural habitat, or even just terrestrial or estuarine habitats in isolation, is an extreme and is unlikely to occur. The purpose of these scenarios is to bookend the range of vulnerability that could exist and indicate how vulnerability varies from one location to another.

By the Numbers

We compared vulnerability scores between Scenarios 1 and 2 (with and without habitats, respectively) by calculating percent change across categories of vulnerability. To do so, we calculated the percent of scores in each of five categories (low, low-medium, medium, medium-high, and high vulnerability), where categories were equally sized bins based on ranges of scores returned by the model.

Highlighting the Role of Natural Habitat

A key use of the model is to understand the role that natural habitats – both those on land and those in the water – have in buffering the shoreline from erosion and inundation. We created a set of maps from results for Scenarios 1, 3, and 4, to explicit highlight the protective role of habitat in reducing coastal vulnerability. In the maps, we show the roles that all habitat (Scenario 1), just estuarine (Scenario 3), and just terrestrial (Scenario 4) play in reducing vulnerability.

Interpreting the Map Legend

Protective role of habitat: LOW ● ● ● HIGH

As with the overall vulnerability maps, those reflecting the role of habitat are displayed spatially on a relative scale using three color categories. High protective role of habitat is dark teal, moderate is mid- teal, and low is light teal. Specific protective role indices are located in the legends of each "role of habitat" map. Please note that the high, moderate, and low values for each map scenarios are based on a different range of indices produced by the model results.

Three Scenarios

The model results show where habitat provides a role in shoreline protection in Pacific County and Grays Harbor. Here, we have explored the protective role of habitat in three scenarios:

> **Scenario 1 (S1):** *Protective Role of All Habitats.* This scenario reflects the current role that both estuarine and terrestrial habitats play in reducing coastal vulnerability.
>
> **Scenario 3 (S3):** *Protective Role of Just Estuarine Habitats*. This scenario highlights where along the shoreline, estuarine habitats play a role in reducing coastal vulnerability.
>
> **Scenario 4 (S4):** *Protective Role Just Terrestrial Habitats.* This scenario displays where along the shoreline, terrestrial habitats play a role in reducing coastal vulnerability.

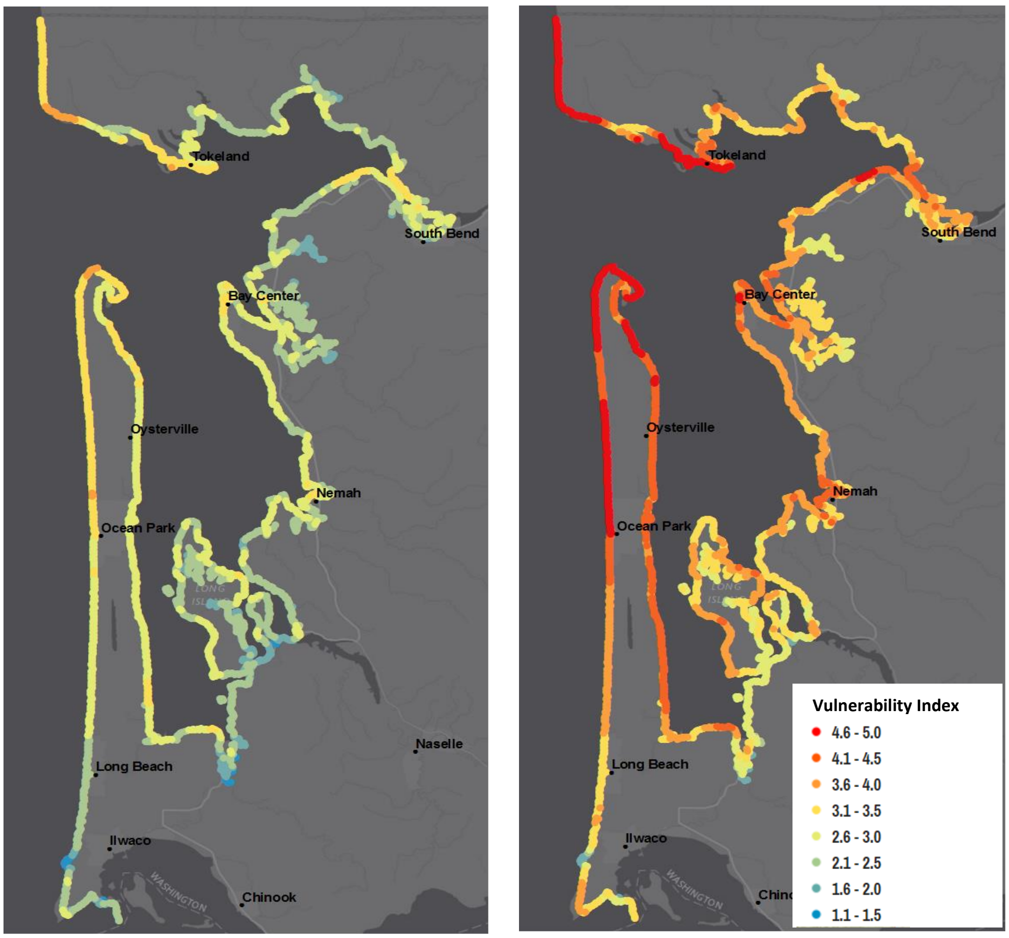
Results

Pacific County

The maps below help to answer the question, what coastlines in Pacific County are vulnerable to inundation and erosion with and without current habitats?

Scenario 1 (S1):
Vulnerability with All Habitats

Scenario 2 (S2):
Vulnerability with No Habitats



The maps above depict the vulnerability of shorelines from low to high with current estuarine and terrestrial habitats present (S1) and then removed (S2). When the coastal habitats are removed, the vulnerability of Pacific County shorelines increases (indicated by a greater cover of red/orange shorelines in S2). Specifically, the model indicates that there is high shoreline vulnerability (red/orange) when habitat is removed at North Cove, Tokeland, South Bend, Bay Center, Nemah, and the Long Beach Peninsula.

By the numbers

Vulnerability scores for Pacific County ranged from 1.2 to 5. The table below depicts the percentage of the shoreline in each vulnerability category from low to high when all current habitats are present (Scenario 1 - Coastline Vulnerable with Current Habitat (%)) and then when they are removed (Scenario 2 - Coastline Vulnerable without Current Habitat (%)). The "Coastal Change" column shows the change for each category when habitats are removed (i.e., Shoreline Change = Scenario 1 – Scenario 2). A negative "Coastal Change" indicates a reduction in a "Vulnerability Category". A positive "Coastal Change" reflects an increase in a "Vulnerability Category".

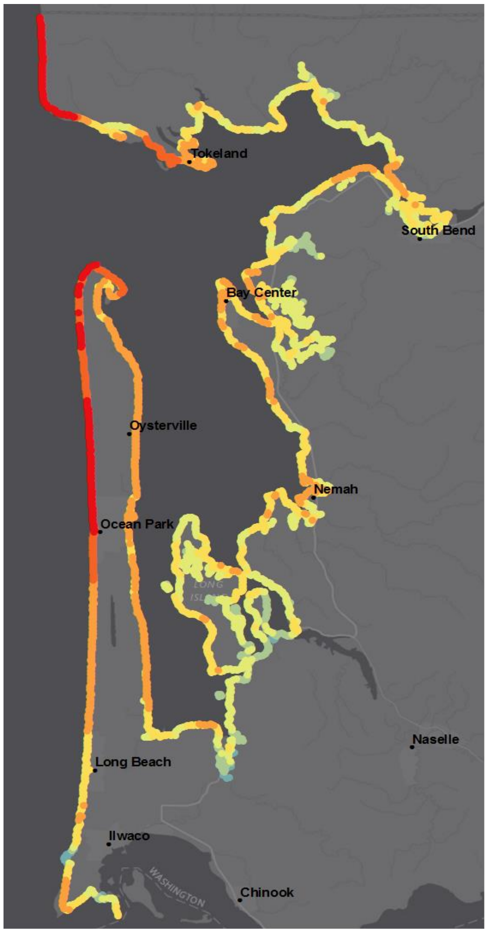
Vulnerability Range	**Vulnerability Category**	**Coastline Vulnerable *with* Current Habitat (%)**	**Coastline Vulnerable *without* Current Habitat (%)**	**Coastal Change**
1.20-1.96	Low	**8%**	0%	-8%
1.96-2.72	Low- Medium	**61%**	7%	-54%
2.72-3.48	Medium	30%	**42%**	+12%
3.48- 4.24	Medium- High	1%	**33%**	+32%
4.24-5.0	High	0%	**18%**	+18%

With current habitats present, a majority of shorelines range from low to low-medium in vulnerability (69%). If all current habitats are removed from the analysis, there is a decrease in the percent of shorelines with low to low-medium vulnerability and an increase in shorelines with a medium to high vulnerability. The shoreline change for low to low-medium categories decreases, while the shoreline change for medium to high categories increases. Thus, a reduction in habitat leads to more vulnerable coastlines.

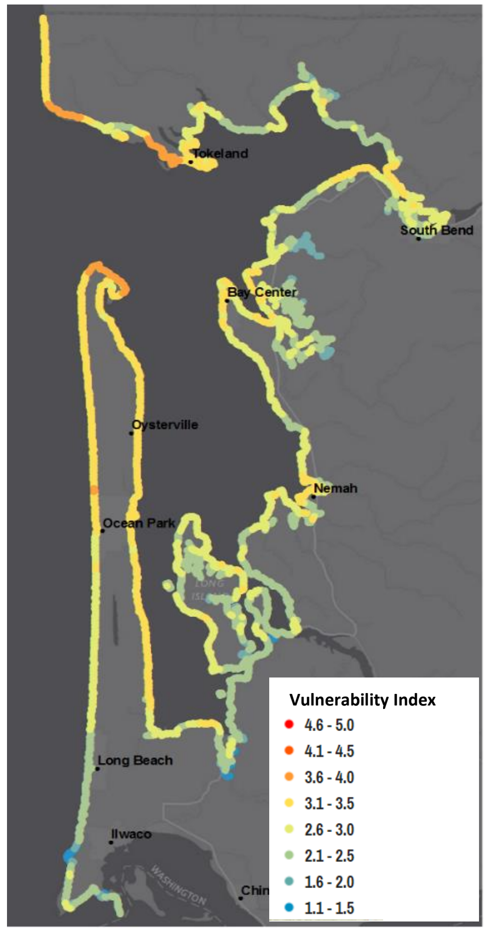
Vulnerability with only Estuarine and Terrestrial Habitats

The maps below help to answer the question, what shorelines in Pacific County are vulnerable to inundation and erosion without terrestrial or estuarine habitats?

Scenario 3 (S3):
Vulnerability with only Estuarine Habitats



Scenario 4 (S4):
Vulnerability with only Terrestrial Habitats

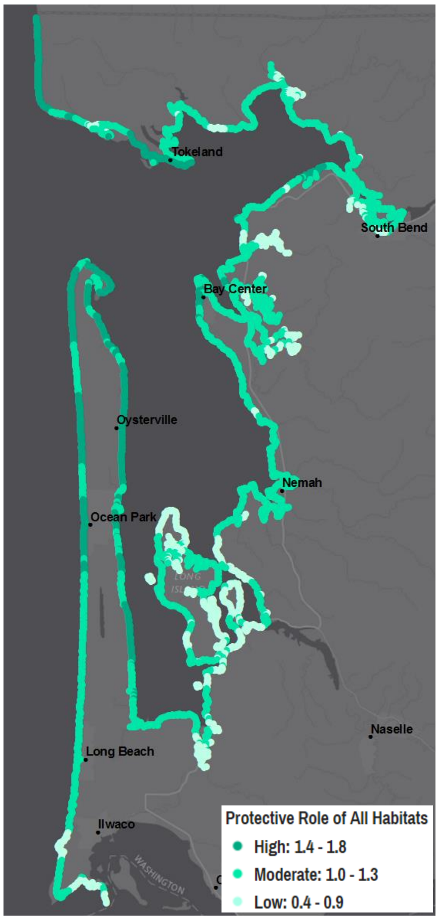


The maps above depict the vulnerability of shorelines from low to high in two scenarios: (S3) when only estuarine habitats present and (S4) when only terrestrial habitats present. In comparing S3 and S4, the model indicates that terrestrial habitats are relatively more important in reducing vulnerability overall (due to a higher cover of red and orange shorelines). This is especially the case along the Long Beach Peninsula, North Cove, as well as sections near Bay Center, South Bend, and Nemah.

Protective Role of Habitat

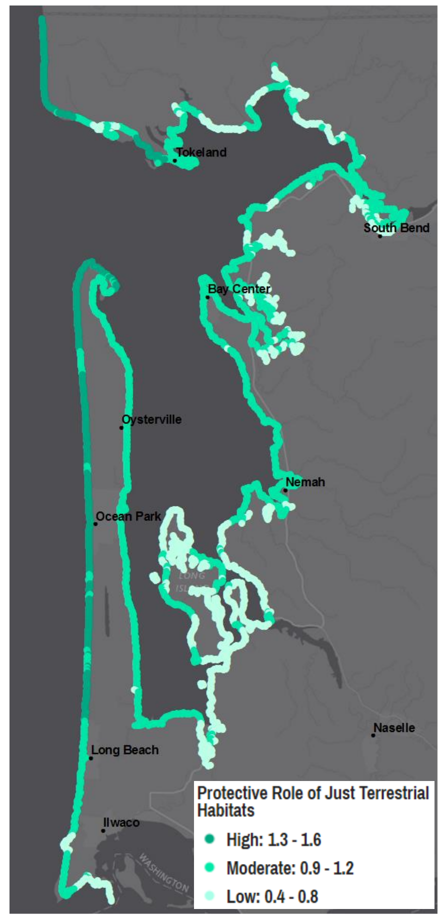
The maps below help to answer the question, what role do all current habitats play in reducing the vulnerability of Pacific County shorelines? Furthermore, what are the specific roles of terrestrial and estuarine habitats in reducing the vulnerability?

Scenario 1 (S1): *Protective Role of All Habitats*



Scenario 3 (S3): *Protective Role of Just Estuarine Habitats*

Scenario 4 (S4): *Protective Role of Just Terrestrial Habitats*

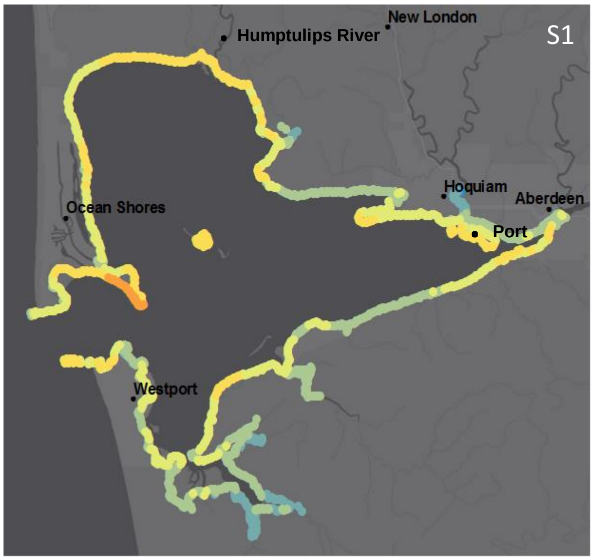


On page 12, terrestrial habitats were found to have a higher potential to reduce shoreline vulnerability than estuarine habitats. Here, "the protective role of habitat" maps depict the relative role that each habitat type (all (S1), estuarine (S3), and terrestrial (S4)) plays in shoreline protection. The protective role of terrestrial habitat is higher than estuarine habitats (see legend scales). However, while the role of estuarine habitats is lower overall (see S3 legend), S3 indicates where estuarine habitats play a relatively high role in shoreline protection. Estuarine habitat role is the highest (dark teal) on the estuary side of the Long Beach Peninsula, Long Island, near Nemah, Bay Center, South Bend, and near Tokeland.

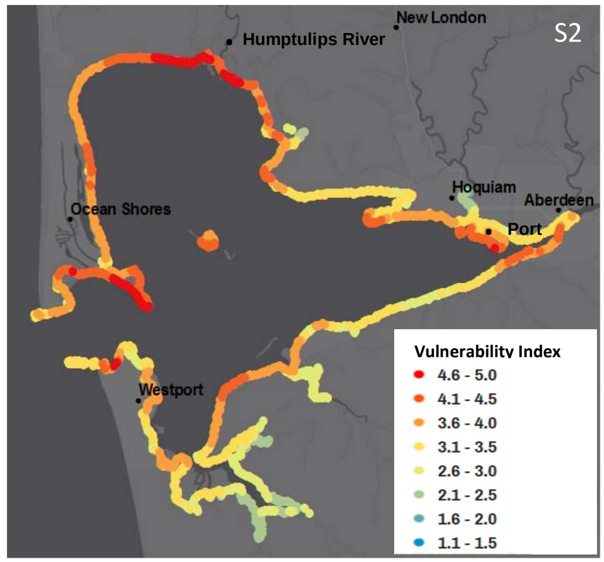
Grays Harbor

The maps below help to answer the question, what shorelines in Grays Harbor are vulnerable to inundation and erosion with and without current habitats?

Scenario 1 (S1):
Vulnerability with All Habitats



Scenario 2 (S2):
Vulnerability with No Habitats



The maps above depicts the vulnerability of shorelines from low to high with current estuarine and terrestrial habitats present (S1) and then removed (S2). When habitats are removed, the vulnerability of Grays Harbor shorelines increases (indicted by a greater cover of red/orange shorelines in S2). Shorelines particularly vulnerable (outlined in red) include the north shore near the mouth of the Humptulips River, Ocean Shores, and the Port.

By the numbers

The vulnerability indices for Grays Harbor ranged from 1.47- 4.57 overall. The table below depicts the percentage of shorelines in each vulnerability category from low to high when all current habitats are present (Coastline Vulnerable with Current Habitat (%)) and then when they are removed (Coastline Vulnerable without Current Habitat (%)). The "Coastal Change" column shows the change in shoreline vulnerability for each category when habitats are removed. A negative "Coastal Change" reflects a reduction in a "Vulnerability Category." A positive "Coastal Change" reflects an increase in a "Vulnerability Category."

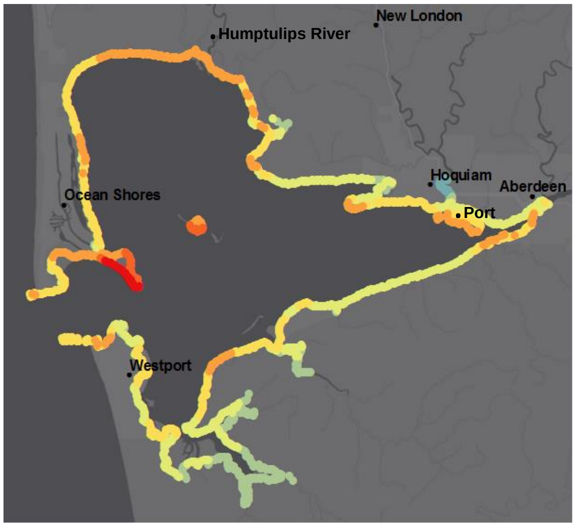
Vulnerability Range	**Vulnerability Category**	**Coastline Vulnerable *with* Current Habitat (%)**	**Coastline Vulnerable *without* Current Habitat (%)**	**Coastal Change**
1.47-2.09	Low	**17%**	0%	-17%
2.09- 2.71	Low-Medium	**43%**	9%	-34%
2.71- 3.33	Medium	34%	**36%**	+2%
3.33-3.95	Medium- High	6%	**35%**	+29%
3.95-4.57	High	0%	**20%**	+20%

With current habitats present, a majority of shorelines range from low to low-medium vulnerability (60%). If all current habitats are removed from the analysis, there is a decrease in the percent of shorelines with low to low-medium vulnerability and an increase in shorelines with a medium to high vulnerability. The shoreline change for low to low-medium categories decreases, while the shoreline change for medium to high categories increases. Thus, a reduction in habitat leads to an increase in coastal vulnerability.

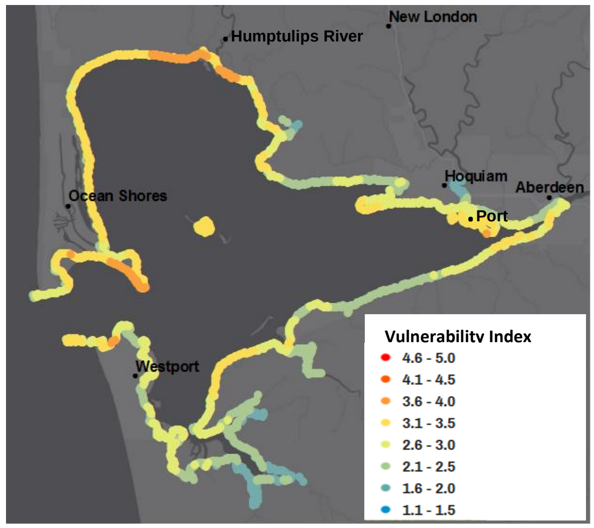
Vulnerability with only Estuarine and Terrestrial Habitats

The maps below help to answer the question, what shorelines in Grays Harbor are vulnerable to inundation and erosion without terrestrial or estuarine habitats?

Scenario 3 (S3):
Vulnerability with only Estuarine Habitats



Scenario 4 (S4):
Vulnerability with only Terrestrial Habitats

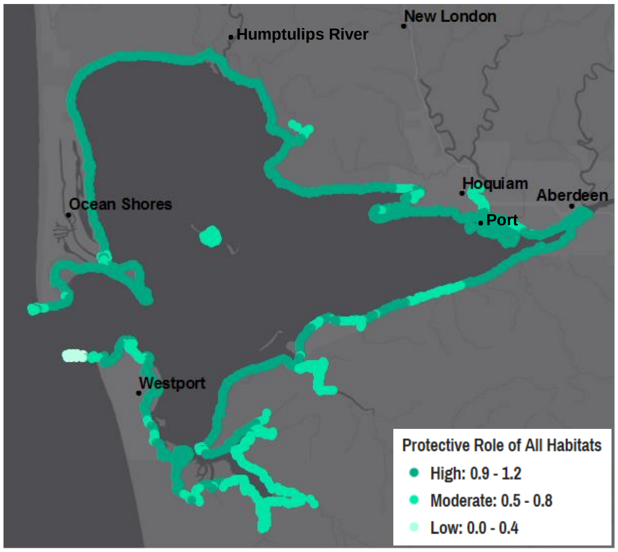


The maps above depict the vulnerability of shorelines from low to high in two scenarios: (S3) when only estuarine habitat are present and (S4) when only terrestrial habitats present. In comparing S3 and S4, the model indicates once again that terrestrial habitats are slightly more important in reducing vulnerability overall (with a higher cover of red and orange shorelines). This is especially the case near Ocean Shores and the Port (indicated by red and dark orange shorelines). It appears that both estuarine and terrestrial habitats reduce vulnerability on the north side of Grays Harbor near the mouth of the Humptulips River.

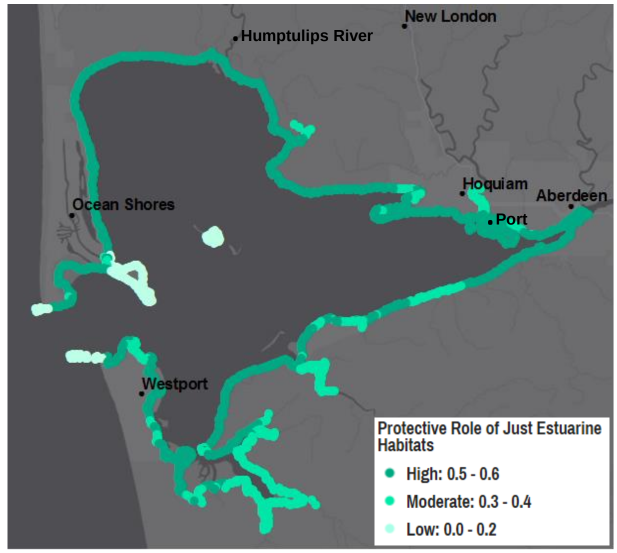
Protective Role of Habitat

The maps below help to answer the question, what role do all current habitats play in reducing the vulnerability of Grays Harbor shorelines? Furthermore, what are the specific roles of terrestrial and estuarine habitats in reducing the vulnerability?

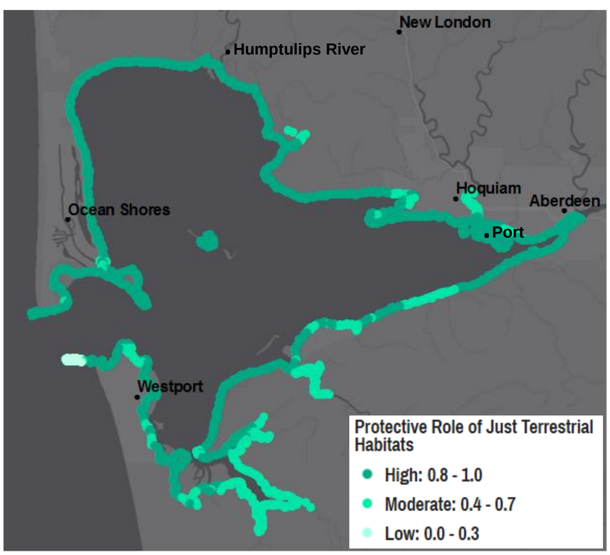
Scenario 1 (S1): *Protective Role of All Habitats*



Scenario 3 (S3): *Protective Role of Just Estuarine Habitats*



Scenario 4 (S4): *Protective Role of Just Terrestrial Habitats*



On page 16, terrestrial habitats were found to have a slightly higher potential to reduce shoreline vulnerability than estuarine habitats. Here, the protective role of terrestrial habitat is slightly higher than estuarine habitats (see legend scales). However, S3 and S4 show the relative role of each habitat type along the shoreline of Grays Harbor County. For estuarine and terrestrial habitats present in Grays Harbor, each provides a relatively high (dark teal and mid-teal) role in shoreline protection.

How the Model Can Be Used

Shoreline Planning Committees

Shoreline planning committees can use model results to support policies and regulations in Shoreline Master Programs and Critical Areas Ordinances for vegetation conservation, critical areas buffers, and environmental designation buffers and setbacks. The committee may consider requiring additional habitat conservation measures (such as stronger buffers) in areas that are highlighted as vulnerable (red/orange) when habitat is removed.

County Planners

County planners can use the model, in conjunction with geotechnical reports, FEMA flood maps, and sea level rise projections, when discussing risks with developers for proposed developments.

Restoration Practitioners

Restoration practitioners can use model results as a guide for prioritizing where to conduct restoration projects, depending on their objectives. For example, in areas on the map where the shoreline is highly vulnerable and habitat is no longer intact, restoration could be done to enhance coastal habitats to protect the shoreline. Also, when designing and implementing restoration projects, results can provide information to help understand how certain habitats may need to shift in the future to maintain their ecological function, resulting in development of a more robust project. There are several funding streams available to support these types of restoration projects, including Floodplains by Design (FbD) and Washington Coast Restoration Initiative (WCRI).

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Discussion

To integrate natural solutions into coastal planning, communities need the capacity to access and use relevant science and management tools.[16] The InVEST Coastal Vulnerability model is one tool that planners and citizens of Pacific and Grays Harbor Counties can easily access to inform policies in the Shoreline Master Program (SMPs), Critical Areas Ordinances, Growth Management plans, as well as the location of restoration projects.

Spatial results from the model serve as an education piece to help communities understand the role of coastal habitats in southwest Washington. From this analysis, we learned that when habitats are lost or degraded, shorelines become increasingly vulnerable to erosion and inundation. In Willapa Bay, terrestrial habitats (e.g., agricultural land, emergent wetlands, and forests) appear to have a relatively greater role in shoreline protection than estuarine habitats (e.g., eelgrass beds, shellfish reefs, and saltmarshes). In these regions – like the Long Beach Peninsula, North Cove, and near Bay Center, South Bend, Nemah – communities could encourage resiliency by requiring enhanced development standards to avoid shoreline vegetation loss. Intact terrestrial habitats are also essential to keep estuarine habitats healthy and functioning property. Systems such as eelgrass beds and saltmarshes are sensitive to activities upland that produce sediments, nutrients, and polluted runoff.[17] The loss or degradation of terrestrial habitats not only increases vulnerability, but also has cascading effects on habitats downstream.

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In Grays Harbor, terrestrial habitats play a slightly larger role in shoreline protection in our analysis. However, both terrestrial and estuarine habitats appear to play a strong role along a majority of the shoreline. To allow both habitat types to remain functional over time, the county could look to sea level rise projections to consider increased buffers that would allow estuarine habitats to migrate inland as inundation occurs. In doing so, both estuarine and terrestrial habitats may remain intact and continue to provide protective services to the coastline. Without taking this into consideration, the coast could experience coastal squeeze where "habitats are lost due to a high water mark being fixed by a structure and the low water mark migrating landwards in response to sea level rise." [17]

Around the United States, about 14 percent of our shorelines have been hardened since 1990 at a rate of 200 km/yr.[18] If this trend continues, almost one-third of our shorelines will be hardened by 2100 as populations grow along coastlines.[19] Washington State has taken measures to reduce the expansion of hardening structures by requiring counties to think ahead about the importance of coastal habitats in shoreline development planning. Washington State's Shoreline Master Program (SMP) and Critical Areas Ordinance (CAO) guidelines require communities to consider the multiple benefits that ecosystems provide and to avoid "no net loss" of shoreline ecological functions. New development is also required to be located and designed to avoid the need for future shoreline stabilization to the extent feasible"(WAC 173-26-221). As a state, we are well equipped to plan for resilience in our coastal areas.

This is important because coastal habitats can also help cut the costs of storm damage and mitigation for property owners. For example, coastal wetlands have been estimated to have a value of $8,240 ha^{-1} yr^{-1}, on average, in storm protection services alone.[19] Protection services and their co-benefits can make using, restoring, or enhancing coastal habitats more cost effective than building hardening structures. In North Carolina, the Division of Coastal Management compared the costs of restoring marshes versus installing hardening structures and found that, on average, it costs $850/meter to place a network of bulkheads and rip rap, while a marsh planting only cost $70/meter.[20] Hardening structures also need maintenance, while natural habitats grow stronger over time.[20]

The communities of Pacific County and Grays Harbor have the opportunity to think ahead to prevent the need for hardening structures by using cost effective natural habitats for shoreline protection. By using the InVEST Coastal Vulnerability model, in conjunction with other science tools on sea level rise, southwest Washington can become more resilient in the face of a changing coastline.

Appendix A: Methods and Data

The Model
The InVEST Coastal Vulnerability model produces estimates of how vulnerable different areas of the shoreline are to erosion and inundation during coastal storms.[21,22] Shorelines considered highly vulnerable are those that are most likely to experience erosion and inundation. That vulnerability is a based on five characteristics of the shoreline – 1) its *geomorphology*, 2) surrounding coastal *habitats* that may or may not buffer the shoreline, 3) its vulnerability to *wind* and *waves*, 4) the *surge potential*, 5) and the surrounding *relief*. Each of these characteristics are ranked for the shoreline segment and those ranks are then combined and rescaled to produce an index of vulnerability (called exposure) from low to high. We are using the following data, as ArcGIS shapefiles, in the model to characterize shorelines of Pacific County and the Grays Harbor estuary.

Geomorphology of shoreline segments is derived the Shorezone dataset[23] (DNR Nearshore Habitat Program 2001). The input is in the form of a polyline, where each line segment represents a different type of geomorphology (e.g., rocky cliff, sandy beach). Shorezone shoreline classifications were viewed at a fine scale (~1:2,000) overlaid on Esri's imagery and each segment ranked from 1 to 5. The rankings reflect relative degree of susceptibility to erosion and inundation; for example, rocky cliffs are given a rank of '1', meaning that they are less susceptible than sandy beaches (rank=5). Note – Shorezone was also used to define the boundary of the coastline, with one adjustment made at Toke Point.

Coastal habitats in the Grays Harbor estuary were gathered from the 2011 National Land Cover Database.[24]

Pacific County coastal habitat data for the Willapa Bay estuary and on land are included as polygons and are from the following sources. The model ranks the natural habitat adjacent to each shoreline segment based on these habitat layers. Habitat layers are shown in Figure 4.

Estuarine habitats: *Eelgrass beds, saltmarsh, emergent wetlands,* and *shellfish reefs* are included as unique layers, and were all derived from the National Wetland Inventory (NWI).[25] The NWI for this region is based on imagery from 2011. For eelgrass beds, there is no distinction in the mapped beds between native (*Zostera marina*) and non-native (*Zostera japonica*). Within the NWI's classification scheme, eelgrass beds are considered aquatic beds within the intertidal zone; saltmarsh are emergent vegetation within the intertidal; emergent wetlands classified as freshwater emergent wetland; and shellfish reefs as reefs.

Terrestrial habitats: *Dunes* are classified as low or high depending on if foredune areas are projected to be overtopped by storm surges in the year 2050. Low dunes are those that are overtopped, and high dune are those not projected to be overtopped. Input data were derived from cross-dune LiDAR transects. Methods and data from Mull and Ruggiero (2014)[26] and Serafin and Ruggiero (2014)[27] were used in 2015 by Reuben Biel of Oregon State University to process the data. We then performed further analyses to create polygons representing high and low dunes using the points as inputs to the ArcGIS Euclidean Allocation tool and clipping that output to only include areas between the dune toe and dune heel.

Forests are characterized from two sources. The primary source is NOAA's Coastal Change Analysis Program (C-CAP) 2010 land cover data at 30m resolution.[28] Classes include: 'Deciduous Forest', 'Evergreen Forest', 'Estuarine Forested Wetland', 'Mixed Forest', 'Palustrine Forested Wetland', 'Palustrine

Scrub/Shrub Wetland', 'Scrub/Shrub', 'Estuarine Scrub/Shrub Wetland'. We also added the coastal forest class from the NWI.

Grass or Agriculture is also from C-CAP.[14] Classes include: 'Cultivated', 'Pasture/Hay', 'Grassland'.

Wind and wave exposure is determined from Wave Watch III data[29] provided by NOAA and included as a default data set in the InVEST software suite. The point shapefile contains values of observed storm wind speed and wave power across an area of interest (i.e., Pacific County and its offshore waters).

Surge potential is generated within the model by measuring the distance from the shoreline segment to the edge of the continental shelf. In general, the longer the distance between the coastline and the edge of the continental shelf at a given area during a given storm, the higher the storm surge.

Relief is represented by a 30m resolution topography-bathymetry dataset derived from NOAA's 'Southwest Washington' dataset.[30]

Invasive Species Habitat layers used in the InVEST Coastal Vulnerability model currently include both native and non-native species. Some of the non-natives species are invasive and while some of them may contribute to shoreline protection, they can be detrimental to other ecosystem services. It is not the intention of this analysis to encourage Pacific County to prevent the removal of these invasive species. Shoreline protection is just one function of coastal habitats and the impact of invasive species on renewable resources, ecological services, and biodiversity should also be considered when making management and restoration decisions. The negative effects of some of these invasive species (e.g. *Ammophila* spp., *Zostera japonica*, and *Spartina alterniflora*) are discussed in the 2015 Pacific County Shoreline Inventory and Analysis Report.

Model limitations While we believe the results are informative, we recognize that the model does not provide a quantitative estimate of the absolute amount of erosion or inundation for a shoreline segment. Rather, it is built to aggregate several complex processes into one metric. Further limitations are listed on the InVEST documentation webpage.

For More Information

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