Prioritizing wetlands for carbon and resilience

Delaware coastal vulnerability modeling – Background and methods

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The InVEST coastal vulnerability model (Sharp et al. 2018) calculates the coastal exposure index, a relative index of coastal areas' exposure to flooding and erosion caused by storms, based on a variety of input factors that influence coastal processes leading to flooding and erosion. It has previously been used for analyses from watershed to national scales (Arkema et al. 2013). Coastal habitats are included in the model as a mitigating influence on coastal hazards (the presence of coastal habitats lowers the coastal exposure index), so the model is often used to analyze the protective effects of coastal habitats.

The shoreline in the study area is divided into segments (for this analysis, each segment was 250 meters long); each shoreline segment is ranked from 1 to 5 for each input factor: relief, geomorphology, coastal habitats, wave exposure, wind exposure, sea level rise, and storm surge depth. In each of these factor rankings, a higher number indicates greater exposure to coastal hazards. The final coastal exposure index is calculated as the geometric mean of the factor rankings.

Factor ranking details

Relief

The mean elevation of all land within the elevation averaging radius (see "model parameters") of each shoreline segment is used to assign each segment a relief ranking from 1 (highest mean elevation) to 5 (lowest mean elevation), using quantiles.

Geomorphology

Geomorphology ranks were assigned for each type of shoreline cover or structure present in the Environmental Sensitivity Index database for the state. Initial ranks were based on the ranking provided in the InVEST user's guide and adjusted after conversations with state partners. The final ranks were:

Geomorphology rank	Shoreline type (ESI)
1	Exposed, rocky shores
2	Exposed, solid man-made structures; sheltered, impermeable rocky shores; sheltered, permeable, rocky structures; sheltered, solid, man-made structures; salt and brackish water marshes; freshwater marshes; swamps; scrub and shrub wetlands
3	Scarps and steep slopes; riprap; sheltered scarps; sheltered riprap
4	Exposed, wave-cut platforms; exposed scarps and steep slopes; gravel beaches; vegetated low banks
5	Sand beaches; mixed sand and gravel beaches; exposed tidal flats

Coastal habitats

The protective function of coastal habitats is represented by assigning each habitat a rank (from 1 to 5, where 1 indicates the best protection) and protection range (the maximum distance from the habitat that protection is provided).

Habitat type	Rank	Protection range (meters)
Coastal forest > 100 m wide	1	2000
High dune	2	300
Marsh 100-1000 m wide	2	1000
Marsh 10-100 m wide	3	100
Marsh < 10 m wide	4	100
Low dune	3	300

The protective rank and range of coastal forest and marshes varies by their width, as shown in the table above (Allen et al. 2018, Hanley 2006, Möller et al. 2001, Shepard et al. 2011). The mean width of coastal forest and marsh habitat patches was estimated as

$$w = 4 * \left(\frac{A}{P}\right)$$

where *A* is the area and *P* is the perimeter of the habitat patch.

The InVEST model identifies the habitat types within their protection range of each shoreline segment and calculates a final coastal habitat rank for the shoreline segment as:

$$R_{Hab} = 4.8 - 0.5\sqrt{\left(1.5 \max_{k=1 \text{ to } N}(5 - R_k)\right)^2 + \sum_{k=1}^{N}(5 - R_k)^2 - \max_{k=1 \text{ to } N}(5 - R_k)^2}$$

where R_k is the rank of each individual habitat that is within protective range of the shoreline segment. The habitat type with the lowest protection rank (indicating the best protection) is weighted 1.5 times the other habitat types to ensure that shoreline segments with multiple types of habitat protecting them receive a lower habitat rank (better protection) than shoreline segments with only one type of habitat providing protection.

Storm surge

The InVEST model estimates shorelines' exposure to storm surge based on the distance between the coastline and the edge of the continental shelf. We replaced this relatively simple approximation with inundation estimates from the SLOSH storm surge model. SLOSH maximum-of-maximum storm surge inundation for a category 2 hurricane was used to calculate mean inundation in a 500-meter circle around each shoreline segment. Shoreline segments with no SLOSH inundation within 500 meters (indicating that no inundation from a category 2 storm is expected) were assigned an inundation value of zero. The final storm surge ranking was obtained by classifying shoreline segments from 1 to 5 based on mean inundation, using quantiles.

Wind exposure

Wind exposure ranks are based on the Relative Exposure Index of each shoreline segment (Keddy 1982), which is calculated from the highest 10% of historic wind speeds from the WindWatch III database, accounting for the direction and fetch distance that wind blows toward the shoreline segment. The Relative Exposure Index is used to assign wind exposure ranks from 1 (lowest REI) to 5 (highest REI) using quantiles. For more detail on wind exposure calculations, see the InVEST user's guide.

Wave exposure

The InVEST model estimates wave power at each shoreline segment based on historic wind and wave data (WindWatch III), depending on whether the shoreline segment experiences oceanic waves or only locally-generated waves driven by wind. Oceanic waves are estimated based on the highest 10% of wave power values in the WindWatch III database, accounting for the direction from which waves were observed and the percentage of the time waves were observed in that direction. Local, wind-generated wave power is estimated by using the highest 10% of observed wind speed values to calculate the height and period of the locally generated waves. For more detail on wave power calculations, see the InVEST user's guide.

By default, the model ranks shoreline segments' wave exposure from 1 to 5 using quantiles (the same number of shoreline segments in each category). This often results in some sheltered coastlines receiving a rank of 5 despite having much lower estimated wave power than the ocean-facing shoreline. To address this, the intermediate wave power outputs were used to calculate new wave exposure rankings. All shoreline segments with wave power greater than 35 kilowatts/meter (the ocean-facing shorelines) were assigned a rank of 5, and all shoreline segments with wave power less than 35 kilowatts/meter were assigned ranks 1 through 4 using quartiles.

Sea level rise

NOAA sea level rise elevation projections for 2100 under the intermediate (1-m global mean SLR) were used to calculate sea level rise ranks. The InVEST model ranks shoreline segments' SLR from 1 to 5 using quantiles. Because the model interpolates projected sea level rise at each shoreline segment from a few points and there is a small range in the projected sea level rise elevations along the Delaware coast, the 1 through 5 ranking system implies much larger spatial differences in sea level rise than actually exist. To address this, shoreline segments were assigned sea level ranks of 3 through 5 using quantiles.

Model inputs and parameters for Delaware

Input datasets

The following input datasets were used for the model:

Input name	Description	Data source
Land polygon	Geographic shape of the coastline	VIMS Shoreline Inventory (O'Brien et al. 2007, Berman et al. 2008, Berman et al. 2013) & NOAA Global self-consistent, hierarchical, high-resolution shoreline (Wessel and Smith, 2017)
Relief and bathymetry	Elevation (for land area) and depth (for submerged area)	NCEI Continuously Updated Digital Elevation Model (CUDEM) – 1/3 arc-second resolution bathymetric tiles and 1/9 arc-second resolution bathymetric-topographic tiles (NOAA 2014)
Shoreline geomorphology	Shoreline structure, including natural protective features (e.g. rocky cliffs) and manmade protective features (e.g. seawalls)	NOAA Environmental Sensitivity Index (NOAA 2014)
High dunes	Location of dunes >5 m in height	Lidar-derived Beach Morphology for U.S. Sandy Coastlines (Doran et al. 2017)

Low dunes	Location of dunes <5 m in height	Lidar-derived Beach Morphology for U.S. Sandy Coastlines (Doran et al. 2017)
Oysters	Location of oyster beds and reefs	No data found
Seagrass	Location of seagrass beds	No data found
Coastal forests	Location of coastal forests	State of Delaware updated version of NWI (2019, provided by Mark Biddle)
Emergent marsh	Location of emergent marsh	State of Delaware updated version of NWI (2019, provided by Mark Biddle)
Climatic forcing grid	Location of points with wind values representing storm conditions	WindWatch III (provided with InVEST model)
Storm surge depth	Storm surge depth for category 2 hurricane	SLOSH MOM storm surge hazard (Zachry et al. 2015)
Sea level rise	Projected sea level rise in 2100 under the 1-meter global mean SLR, intermediate scenario	NOAA SLR projections (Sweet et al. 2017, Technical Report 83)

Model parameters

The model was initially run using default parameters, adjusted based on the project team's judgment and with feedback from the state team. The final parameters are:

Parameter	**Description**	**Value**
Model Resolution	Distance between shoreline points. 250 meters is the highest recommended resolution for this model.	250 meters
Elevation Averaging Radius	Radius of the circle around each shoreline point for which the elevation is averaged; the mean elevation is used to generate the relief ranks.	5000 meters
Maximum Fetch Distance	Maximum straight-line distance that the model will use when creating fetch rays as part of wind and wave calculations. The major effect of this distance is in determining which shore points are affected by ocean waves, and which only by locally generated waves. If at least one fetch ray from a shore point does not intersect land within the maximum fetch distance, the shore point is considered to be affected by ocean waves.	25000 meters

Model runs and outputs

Model outputs include the individual factor rankings as well as the coastal exposure index for each shoreline segment. The coastal exposure index was recalculated using the modified storm surge and wave power rankings in place of the storm surge and wave power rankings generated by the model, as described above.

To identify areas where coastal habitats are playing a large role in coastal protection, the coastal exposure index was also calculated with all coastal habitats removed, so that their protective influence was not included. The difference between the original coastal exposure index and the coastal exposure index calculated without habitats gives an indication of where the habitats are providing protection.

Model limitations and caveats

The InVEST coastal vulnerability model is a highly simplified summary of complex processes related to coastal hazards. It does not represent potential impacts of specific coastal storms, but a generalized overview of an area's exposure to coastal hazards, based on the individual factors described above. No interactions between these factors are included in the model. There are additional specific limitations related to individual factors, and some significant coastal processes are not represented in the model.

Limitations of factors included in the model

Wind and wave exposure: Wind and wave exposure is calculated from a subset (top 10%) of historic wind and wave measurements in the WaveWatch III database, rather than the full dataset. This means that the model does not consider the full range of wind and wave conditions observed in the study area. In addition, oceanic wave exposure for shoreline segments is estimated from the nearest three WaveWatch III measurements and does not take into account nearshore wave processes that determine specific wave power at the shoreline.

Coastal habitats: The model does not account for the amount and quality of coastal habitats, both of which influence habitats' protective capacity. This limitation was partially addressed through the marsh and coastal forest width classes, as described above. In addition, the dunes data source does not include back-barrier dunes, so the coastal exposure index for the back of barrier islands with dunes is likely overestimated. Because dunes are so dynamic, the dunes data also does not capture recent dune loss (e.g., due to storms) and beach renourishment, which is essential for maintaining dunes in certain areas.

Sea level rise: Sea level rise is interpolated for each shoreline segment from the few locations (usually tidal gauges) at which sea level rise projections are available. This approach does not account for local factors, such as vertical land movement, that influence local sea level rise. This limitation was partially addressed by decreasing the range of sea level rise ranks in the model, effectively lowering the weight of the sea level rise factor.

Storm surge: The SLOSH MOM storm surge inundation projections are the worst-case scenario for a category 2 storm, representing the maximum inundation at each point from a large number of modeled hypothetical storms approaching at different angles. Storm direction is a key factor in determining the extent and depth of storm surge inundation, and this dataset does not take into account the probability of storms approaching from particular directions. Therefore, certain areas with high MOM inundation may result from extremely unlikely storms, while other areas may have lower MOM inundation, but are much more likely to be affected by storm surge due to higher likelihood of storms influencing those areas.

Coastal processes not represented in the model

Sediment transport: Sediment transport plays a significant role in determining the spatial distribution of erosion effects; for example, sediment eroded from one coastal area is often redeposited elsewhere. The model does not represent sediment transport.

Other impacts on erosion: Bulkheads can cause higher erosion rates at either end of the bulkhead and directly in front of the bulkhead, due to wave reflection. Shipping channel traffic also causes erosion. Neither of these effects is included in the model.

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