Application of the Sea Level Rise Affecting Marsh Model (SLAMM) Using High Resolution Data At Prime Hook National Wildlife Refuge

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Introduction

Prime Hook National Wildlife Refuge, as part of their Comprehensive Conservation Plan (CCP) development, is required to estimate the effects of sea level rise on the Refuge. The United States Fish and Wildlife Service recommends using the Sea Level Affecting Marshes Model (SLAMM) for this application. The Delaware Coastal Programs (DCP) of the Delaware Department of Natural Resources and Environmental Control (DNREC) assisted the Refuge in using the model to predict the land cover changes due to sea level rise. The following is a description of the model, the results of the modeled scenarios, and an explanation of the deviations from a similar modeling effort done for the region by the National Wildlife Federation.

Model Background

The Sea Level Affecting Marshes Model (SLAMM) was developed with EPA funding in the mid 1980's (Park et al. 1986). Since that time, the model has continued to be developed and resulted in the release of SLAMM 5 in April 2007.

Within SLAMM, there are four primary processes that affect wetland fate under different scenarios of sea level rise:

- Inundation: The rise of water levels and the salt boundary is tracked by reducing elevations of each cell as sea levels rises, thus keeping mean tide level (MTL) constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell.

- Erosion: Erosion is triggered based on a threshold of maximum fetch and the proximity of the marsh to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site specific parameters.

- Overwash: Barrier islands of under 500 meter widths are assumed to undergo overwash during each 25 year time-step due to storm events. Beach migration and transport of sediments are calculated.

- Saturation: Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the water table rising with sea level rise close to the coast.

Relative sea level change is computed for each site for each time step; it is the sum of the historic eustatic trend, the site-specific rate of change of elevation due to subsidence and isostatic adjustment, and the accelerated rise depending on the scenario chosen. Sea level rise may be offset by sedimentation and accretion. In the absence of site-specific data, average values are used, depending on the extent of existing marshes (the assumption being that extensive marshes indicate higher accretion rates). Marshes not adjacent to water are assumed to have rates half those adjacent to water. For each time step the fractional conversion from one class to another is computed on the basis of the relative change in elevation divided by the elevational range of the class in that cell. For that reason, marshes that extend across wide tidal ranges are only slowly converted to unvegetated tidal flats.

If a cell is protected by a dike or levee it is not permitted to change until 2 meters of sea level rise is predicted. Developed land can selected to be protected, which assumes a 2 meter levee around all the developed land areas.

In addition to the effects of inundation represented by the simple geometric model described above, second-order effects occur due to changes in the spatial relationships among the coastal elements. In particular, the model computes exposure to wave action; if the fetch (the distance across which wind-driven waves can be formed) is greater than 9 km, the model assumes moderate erosion. If a cell is exposed to open ocean, severe erosion of wetlands is assumed. Wetlands on the lee side of coastal barriers are subject to conversion due to overwash as erosion of backshore and dune areas occurs and as other lowlands are drowned. Erosion of sandy areas to maintain equilibrium with adjacent beaches is modeled, but erosion of other dry lands is ignored. This could seriously underestimate the availability of sediment to replenish wetlands where accelerated bluff erosion could be expected to occur. Coastal swamps and fresh marshes migrate as a response of the water table to rising sea level close to the coast

Comparison to Earlier Modeling Efforts

The Prime Hook National Wildlife Refuge was included in an earlier SLAMM simulation of the Chesapeake Bay Region contracted by the National Wildlife Federation, (NWF, 2008). For that simulation a 30-meter horizontal grid digital elevation model (DEM) and National Wetland Inventory (NWI) datasets were used for the inputs. Due to the course resolution used for the inputs and regional coastal management assumptions, the results provided minimal information containing questionable value for Prime Hook Refuge.

According to the U.S. Climate Change Science Program, Final Report of Synthesis and Assessment Product 4.1 (Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region), any analysis done with the 5 foot contour DEMs could only model sea level change with a 95% confidence interval if the sea level change was 1.82 meters or greater. They further state the minimum increment for reliable modeling using LiDAR data is 0.58 meters, (CCSP 2009). The National Wildlife Federation simulations were done with the 5 foot contour data, while the simulations done by the Delaware Coastal Programs used LiDAR data with a vertical accuracy of better than 15 cm.

To further compound the error, SLAMM primarily determines the land cover based on elevation using mean low water, mean tide level, mean high water, mean high water spring, and 2 classifications that are averages between two tide levels. The other predominant factor for classification is distance inland. If the accuracy of water inundation is only possible at greater than 1.82 meters, or 0.58 meters depending on data source, determining vegetative cover within certain tidal zones introduces an even higher level of uncertainty.

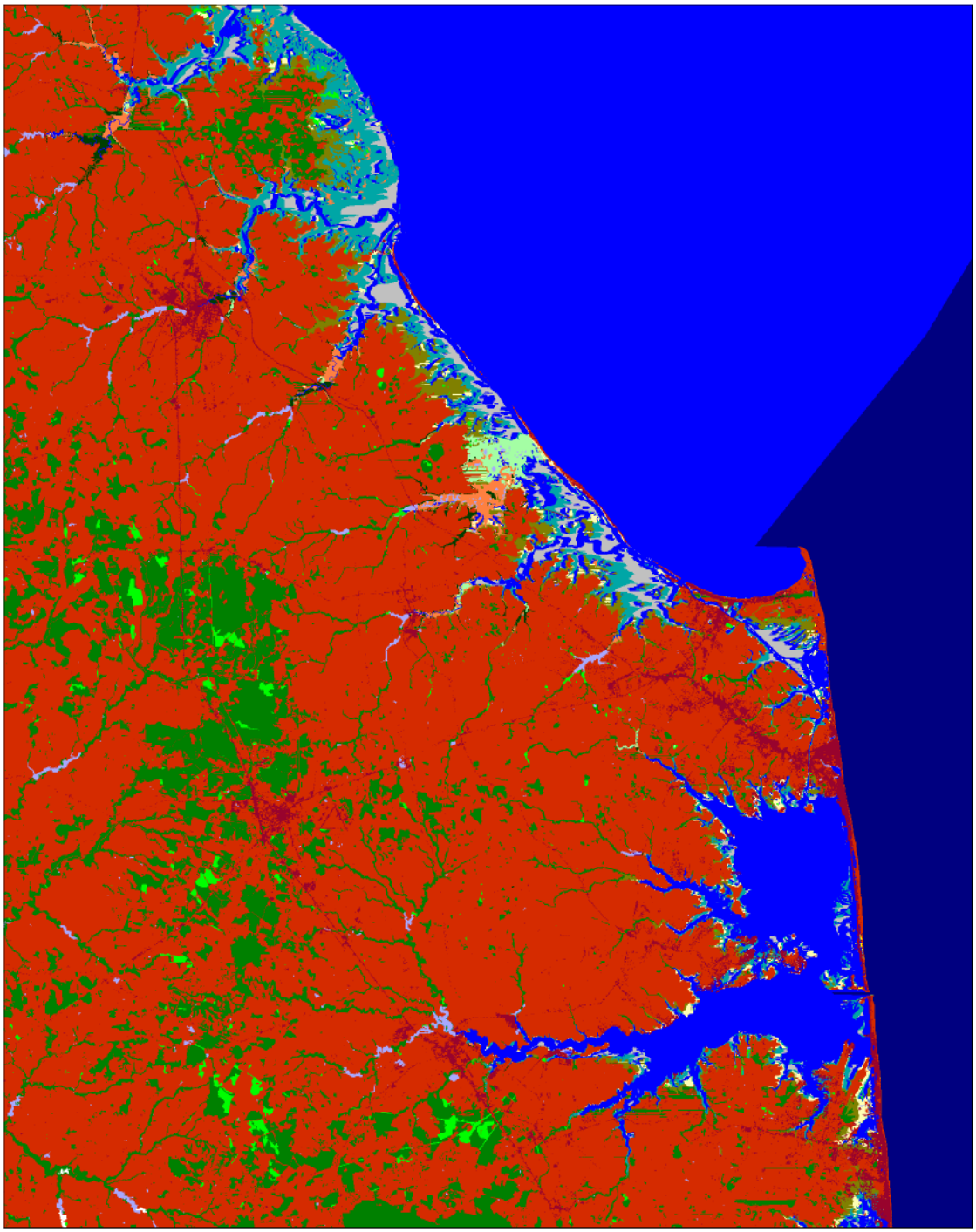
Two approaches were taken by DCP in order to address these elevation issues. The first approach was modeling for statistically significant sea level rise elevations. The A1B scenario adjusted for Delaware results in a 0.50 meter change. While this does not meet the 95% confidence level for typical LiDAR data, validation of the Delaware data has shown higher accuracy than 15 cm. A second scenario with sea level rise of 1 meter was also processed to give additional results without overlapping margins of error, but still within predicted ranges of 100 year sea level rise.

To increase the accuracy of the landcover outputs the classifications were aggregated from 18 local categories into four categories: Upland, Forested Wetland/Scrub Shrub, Marsh, Tidal Mud Flats/Open Water. These would correspond to above inland spring high tide (Upland), inland high water to inland spring high water (Forested Wetland & Scrub Shrub), mean tide level to spring high water or inland high water (Marsh), and below mean tide level (Tidal Mud Flats & Open Water).

Another section in the CCSP report specifically addresses concerns with the SLAMM model:

> *Large scale landscape models, such as the Sea Level Affecting Marshes Model (SLAMM) (Park et al., 1989), simulate general trends over large areas, but typically at a very coarse resolution. These landscape models do not mechanistically simulate the processes that contribute to wetland elevation; the processes are input as forcing functions and are not simulated within the model. Thus, this modeling approach does not account for infrequent events that influence wetland vertical development, such as storms and floods, or for frequent elevation feedback mechanisms affecting processes (for example, elevation change alters flooding patterns that in turn affect sediment deposition, decomposition, and plant production). In addition, these models are not suitable for site-specific research and management problems because scaling down of results to the local level is not feasible. Therefore, although landscape models can simulate wetland sustainability on broad spatial scales, their coarse resolution limits their accuracy and usefulness to the local manager.* (CCSP 2009).

To compensate for the inability of the model to dynamically change input variables, primarily accretion rates, the two reasonable accretion rate extremes were used as inputs. The minimum accretion rate bound was set to be the current rate of sea level rise. This assumes the accretion rate up to this point has kept pace with historic sea level rise; however this is the highest obtainable accretion rate for the area. This value is within documented accretion ranges for the Delaware Bay coast. The upper bound for annual accretion rate was set at 1/100 of the 100 year sea level rise scenario modeled. This value assumed marsh accretion rates would keep pace with sea level rise throughout the next 100 years.



Year 2100 Scenario A1B-Maximum (0.69 meters of global sea-level rise)
Protect Developed Land, Rehoboth Beach & Oceanic Delaware

Figure 1. Diagram from NWF report for Chesapeake Bay Region

Model Inputs for Prime Hook NWR

Elevation and Slope

Elevation input was based on 2007 Light Detection and Ranging (LiDAR) elevation data with a 2-meter horizontal grid spacing and guaranteed 15 cm vertical accuracy with observed 7.5 cm average vertical accuracy. This is compared to the 30 meter DEM which has a vertical accuracy of approximately 50 cm. Using high resolution data uncovered a memory limitation of SLAMM. To include the entire boundary of the Refuge, the model boundaries needed to be 11 kilometers by 12.5 kilometers. At a 2-meter grid spacing this resulted in over 34 million data points per input file, this exceeded the memory capacity of the model. The datasets were resampled to a 5-meter grid resulting in 5.5 million data points, a number within the processing capabilities of SLAMM, a resolution 36 times greater than the NWF simulations using a 30-meter grid. Due to the LiDAR dataset's accuracy and fine detail, numerous tributaries and channels are present in the coverage. Several of these channels have water control structures in them to maintain the freshwater impoundments of the refuge. The elevation DEM was manually modified to include the water control structures at the appropriate locations. Another advantage of the high resolution data is the ability to accurately simulate the levee system of the refuge using the actual elevations. If the levee feature of the model were employed the levees would have been unrealistically set at 2 meter elevation.

All slopes were calculated using the re-sampled 5-meter grid elevation dataset.

Land Cover

The land cover dataset was derived from the 1996 Delaware Statewide Wetland Mapping Project (SWMP) based on 1992 ortho-photograhy. The individual land cover polygons are identified at less than a quarter acre resolution. This data was updated for the model using 2007 aerial digital photography of the area. The updating consisted primarily of reclassifying marsh areas that have subsequently become open water sites.

A unique land cover input issue arose related to anthropogenically manipulated areas similar to Prime Hook NWR. The Refuge has several freshwater impoundments maintained for waterfowl habitat enhancement. These impoundments would most closely represent an inland

freshwater marsh in the SLAMM habitat classification scheme, but salt marsh based on elevation criteria. In addition, the transgression process of the model requires inland freshwater marsh to convert to scrub-shrub through inundation. The northern impoundment of Prime Hook was previously breached, which resulted in the impoundment converting directly to a salt marsh, bypassing the scrub-shrub phase. To properly characterize the long-term transgression of the system the fresh-water impoundments were categorized as salt marsh.

Site Inputs

The site input dataset had several parameters that remained constant throughout all simulations, these included: DEM and land cover dates (2007), offshore direction (east), historic trend (3.1 mm/yr), NAVD correction (0.1785 m), water depth (2 m), tide range ocean (coastal) (1.583 m), MHHW (0.7019 m), marsh erosion (2 m/yr), swamp erosion (1 m/yr), tidal flat (1 m/yr), frequency of large storm overwash (25 yr), and elevation preprocessor use (false).

The marsh erosion rates were set between 1 to 2 meters per year (default values); however, SLAMM with one exception does not allow erosion to take place unless at least 9 km of fetch exists to propagate waves. Because of the high resolution of data used in this simulation and the memory constraints of the software, a 9 km fetch was not possible to include within the model boundaries, therefore erosion was not a factor in the simulations except for tidal flats where erosion takes place under all conditions.

Two sets of input variables were changed depending on the simulation. The first was the inland tide range; currently the inland tide range at the water control structures is approximately 50% of the coastal tide range. This is a value of 0.79 meters, and was used to simulate conditions when the bay-front dune line is maintained. To model conditions if the dunes are breached the inland tide range was set to 1.583 meters, identical to the coastal tide range. The second item was the vertical accretion rates for the various marshes. While accretion rate data exists for various marsh types along the Delaware Bay, the data is highly variable. Research has shown that a healthy marsh will keep pace with sea level rise (Reed, et al., 2008). The current rate of sea level rise, 3.1 mm/yr, falls in the range of the measured accretion rates for the coastal marshes of Delaware, and was used as the minimum rate for the simulations. Since the SLAMM model does not allow for dynamic accretion rates over the simulation period, or a changing accretion

rate corresponding rate of sea level change, a maximum value for yearly accretion rate was input for the other simulations that equaled 1/100 of the 100 year sea level rise.

Sea Level Rise Inputs

The Sea Level Rise Affecting Marsh Model was implemented for the Prime Hook National Wildlife Refuge using two sea level (SLR) rise scenarios. The first was the A1B greenhouse gas emission scenario. This scenario is described in the Special Report on Emissions Scenarios (IPCC, 2000) and in the SLAMM technical report (Clough & Park 2006) as a trend of very rapid economic growth, population growth that peaks in mid-century and declines thereafter, and rapid introduction of alternative sources of energy that includes a balance across all fossil and non-fossil sources. The median of the eustatic sea level rise range for this scenario is 0.387 meters in 100 years. This translates to a total change in sea level for the Prime Hook region of 0.50 meters when local subsidence is considered.

Recent literature (Chen et al., 2006) indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to the dynamic changes in ice flow omitted within the IPCC report's calculations. A recent paper in the journal *Science* (Rahmstorf, 2007) suggests that, taking into account possible model error, a feasible range by 2100 might be 50 to 140 cm. To allow for flexibility when interpreting the results, SLAMM was also run assuming a 1 meter sea-level rise by the year 2100. The A1B maximum scenario was scaled up to produce this rate of change.

Optional Variables

The ability for the model to protect developed land was not enabled. This feature protects areas defined as developed land (residential, commercial properties, etc.) from being inundated up to a sea level rise of 2 meters. In the rural area around Prime Hook NWR it was assumed that a 2 meter dike system would not be constructed to protect developed properties.

The Tall Spartina model was not enabled since the marsh categories were aggregated into broader classifications in the results. The Estuary feature was not used since the small study area did not allow for proper classification of an estuary according to the model guidelines.

Model Outputs for Prime Hook NWR

Results Presentation

Tabular and graphical outputs along with maps of the eight scenarios are included in the Appendices. All scenarios are shown for the years 2007 (current), 2025, 2050, 2075, and 2100. The scenarios represent 2 sea level rise conditions, 2 marsh accretion rates, and 2 inland tide rates. These scenarios would simulate the expected extremes in each category. This includes mean eustatic sea level rise of A1B of 0.39 meters (local of 0.50 meters) to a 1 meter local sea level rise. The two accretion rates simulate the current 3.1 mm/yr being the maximum obtainable, and an either 5 mm/yr or 10.0 mm/yr accretion rate to keep pace with the simulated sea level rise of that particular scenario,. The third variable is inland tide range. The “50% of Coastal Tide” value (0.79 m) is approximately the current tidal range at the water control structures in the refuge and would represent the bay dunes remaining intact. The “100% of Coastal Tide” value (1.58 m) would represent catastrophic dune breach along the bay front allowing free movement of the tidal prism into the impoundment areas.

While SLAMM allows for 18 land use categories for the region, the results have been aggregated into 4 broad categories. This has been done to increase the accuracy of the results by having fewer land use categories to differentiate, for ease of interpretation of the results and to circumvent the inaccuracies of freshwater impoundment succession.

Discussion

It is the Refuge management’s responsibility to interpret the results as they deem appropriate. Possible interpretations could include a combination of the scenarios, for example, maintaining the dunes through 2050 and then converting to the 100% inland tide range to simulate the erosion of the dune line. It must be stressed that the results are only estimates based on limited input factors and historic data. As with any attempt to model natural conditions there is always a high degree of uncertainty.

The results shown are for estimated maximum and minimum expected conditions with the actual conditions probably being somewhere in between. However, certain conditions are apparent under all scenarios and could be a good predictor of the future environment at the

refuge. By the year 2050 at least half of the current upland area of the refuge will be lost, decreasing from 20% (9000 ha) to at most 12% (5000 ha) of the property. Open water and tidal mud flat areas will increase throughout the next 100 years.

Examining the A1B scenario of 0.5 meters local sea level rise over the next 100 years, the land cover percentages have the greatest potential for stability if the accretion rate keeps up with sea level rise. This will allow for a relatively constant marsh area with open water and mud flats going from 15% to 38%. Uplands and fringing wetlands will be the main source of these land cover transformation. The change values are fairly similar with or without the bay dunes remaining intact. The greatest land cover changes based on dune integrity happen outside the current boundaries of the refuge.

If sea level change happens at an accelerated rate of 1 meter in the next 100 years, the impact will be a much greater on the refuge. By the year 2050 open water and mudflats will increase to 26% (10,600 ha) under high accretion rates or possibly up to 58% (23,000 ha) with low accretion rates. By the year 2100 up to 88% (35,000 ha) of the refuge could be open water or tidal mud flats and only 1% (550 ha) of the Refuge would be uplands under the worst case scenario. Similar to the AIB sea level rise scenario, maintenance of the coastal dunes is not a factor because the effects of dune integrity would be seen outside the refuge boundary.

References

CCSP, 2009: *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region*. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [James G. Titus (Coordinating Lead Author), K. Eric Anderson, Donald R. Cahoon, Dean B. Gesch, Stephen K. Gill, Benjamin T. Gutierrez, E. Robert Thieler, and S. Jeffress Williams (Lead Authors)], U.S. Environmental Protection Agency, Washington D.C., USA.

Chen, J. L., Wilson, C. R., Tapley, B. D., 2006 *Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet,* Science 2006 0: 1129007.

Clough, J.S. and R.A. Park, 2007, *Technical Documentation for SLAMM 5.0* January 2007, JonathanS. Clough, Warren Pinnacle Consulting, Inc, Richard A. Park, Eco Modeling.

IPCC, 2001: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

NWF, 2008, *Sea-Level Rise and Coastal Habitats in the Chesapeake Bay Region, Technical Report* [Patty Glick, Jonathan Clough, Brad Nunley], National Wildlife Federation

Rahmstorf, Stefan 2007, *A Semi-Empirical Approach to Projecting Future Sea-Level Rise*, Science 2007 315: 368-370.

Reed, D.J., D.A. Bishara, D.R. Cahoon, J. Donnelly, M. Kearney, A.S. Kolker, L.L. Leonard, R.A. Orson, and J.C. Stevenson. 2008. *Site-Specific Scenarios for Wetlands Accretion as Sea Level Rises in the Mid-Atlantic Region*. Section 2.1 in: *Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1*, J.G. Titus and E.M. Strange (eds.). EPA 430R07004. U.S. EPA, Washington, DC.

Appendix A

Tabular and Graphical Results from SLAMM Outputs

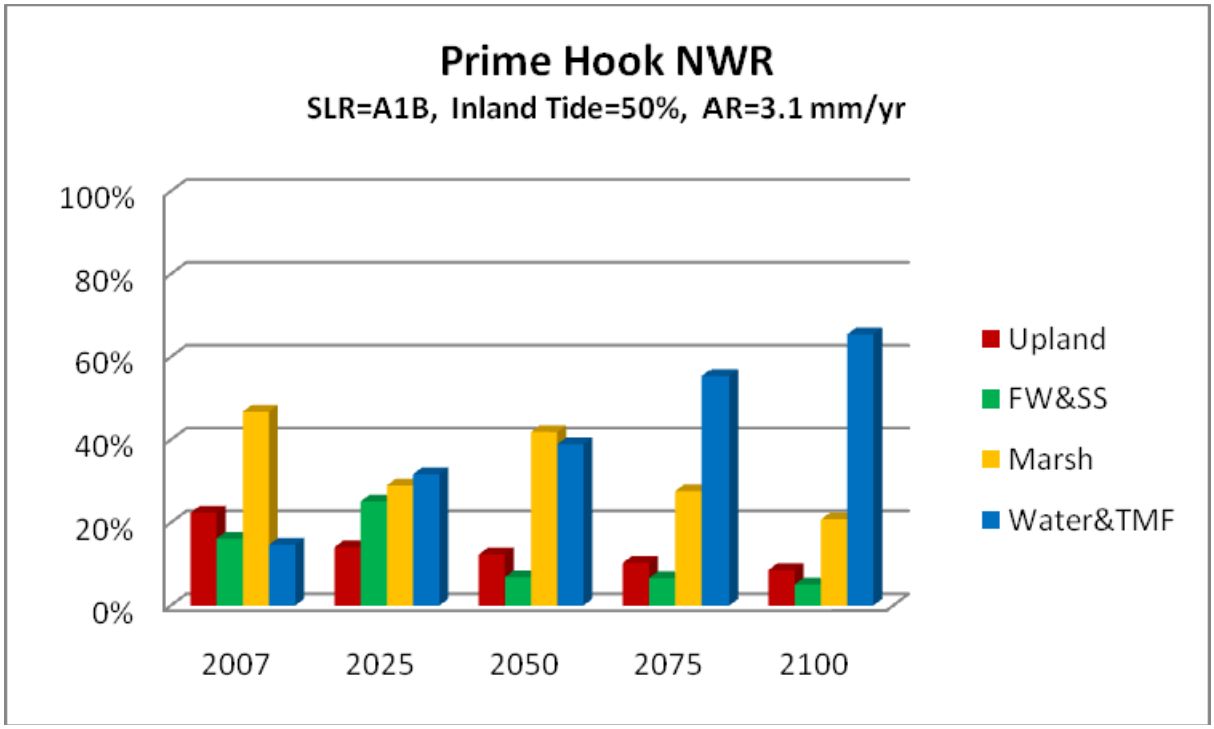
- The following tabular and graphical outputs are for the 8 scenarios modeled.
- The values are for the land area inside the current boundaries of Prime Hook National Wildlife Refuge.
- The following codes are used tables and graphs
    - Upland - Developed and undeveloped dry land
    - FW & SS - Forested wetland, scrub shrub and inland wetlands
    - Marsh - Salt, brackish and tidal fresh marsh lands
    - Water & TMF - Open water and tidal mudflats
    - SLR - Sea level rise
    - AR - Accretion rate
    - Inland Tide - Percentage of coastal tide, measured at water control structures

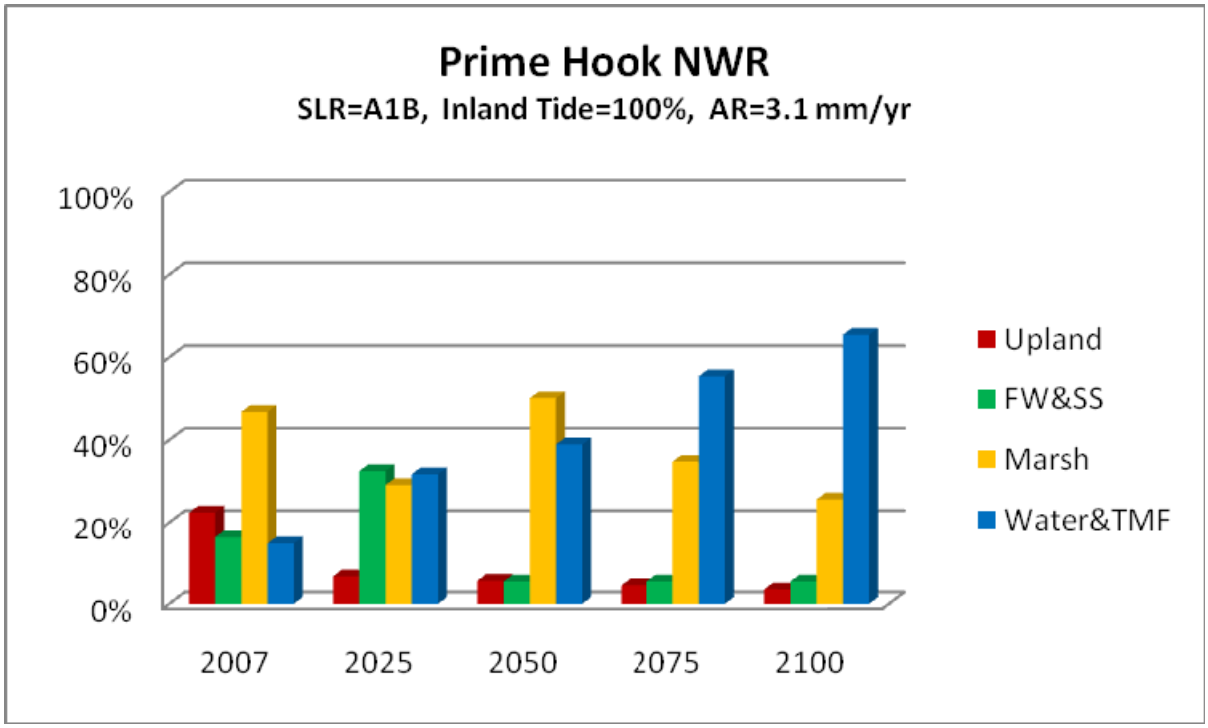
Scenario: A1B SLR, Inland Tide = 50% Coastal Tide, Accretion Rate = 3.1 mm/yr					
Year	Land Cover				
	SLR (meter)	Upland (ha)	FW & SS (ha)	Marsh (ha)	Water & TMF (ha)
2007	0.00	9011	6507	18846	5893
2025	0.07	5675	10129	11679	12773
2050	0.20	4958	2758	16868	15672
2075	0.35	4157	2664	11132	22302
2100	0.50	3462	2060	8380	26354

Scenario: A1B SLR, Inland Tide = 50% Coastal Tide, Accretion Rate = 3.1 mm/yr					
Year	Land Cover				
	SLR (meter)	Upland (%)	FW & SS (%)	Marsh (%)	Water & TMF (%)
2007	0.00	22%	16%	47%	15%
2025	0.07	14%	25%	29%	32%
2050	0.20	12%	7%	42%	39%
2075	0.35	10%	7%	28%	55%
2100	0.50	9%	5%	21%	65%

Scenario: A1B SLR, Inland Tide = 100% Coastal Tide, Accretion Rate = 3.1 mm/yr					
Year	Land Cover				
	SLR (meter)	Upland (ha)	FW & SS (ha)	Marsh (ha)	Water & TMF (ha)
2007	0.00	9011	6507	18846	5893
2025	0.07	2681	13079	11723	12773
2050	0.20	2240	2164	20180	15672
2075	0.35	1803	2164	13987	22302
2100	0.50	1407	2180	10310	26359

Scenario: A1B SLR, Inland Tide = 100% Coastal Tide, Accretion Rate = 3.1 mm/yr					
Year	Land Cover				
	SLR (meter)	Upland (%)	FW & SS (%)	Marsh (%)	Water & TMF (%)
2007	0.00	22%	16%	47%	15%
2025	0.07	7%	32%	29%	32%
2050	0.20	6%	5%	50%	39%
2075	0.35	4%	5%	35%	55%
2100	0.50	3%	5%	26%	65%


Prime Hook NWR
SLR=A1B, Inland Tide=50%, AR=3.1 mm/yr
100%
80%
60%
40%
20%
0%
2007
2025
2050
2075
2100
Upland
FW&SS
Marsh
Water&TMF

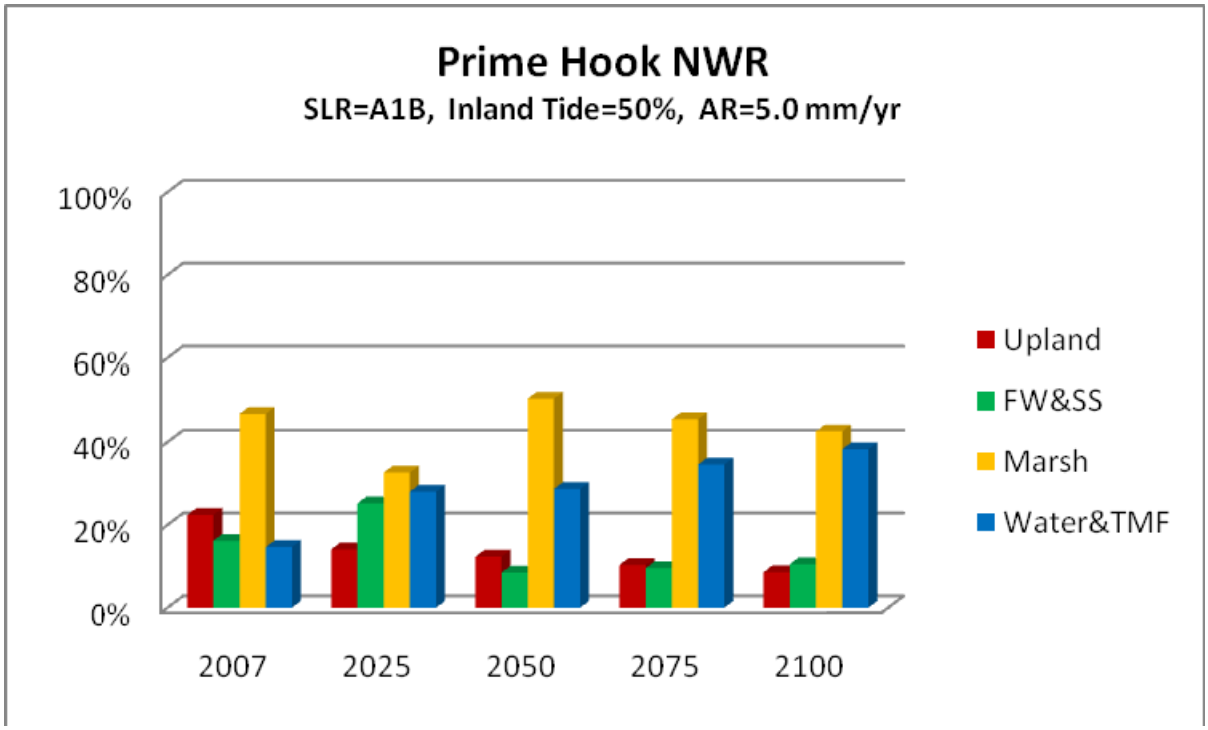

Prime Hook NWR
SLR=A1B, Inland Tide=100%, AR=3.1 mm/yr
100%
80%
60%
40%
20%
0%
2007
2025
2050
2075
2100
Upland
FW&SS
Marsh
Water&TMF

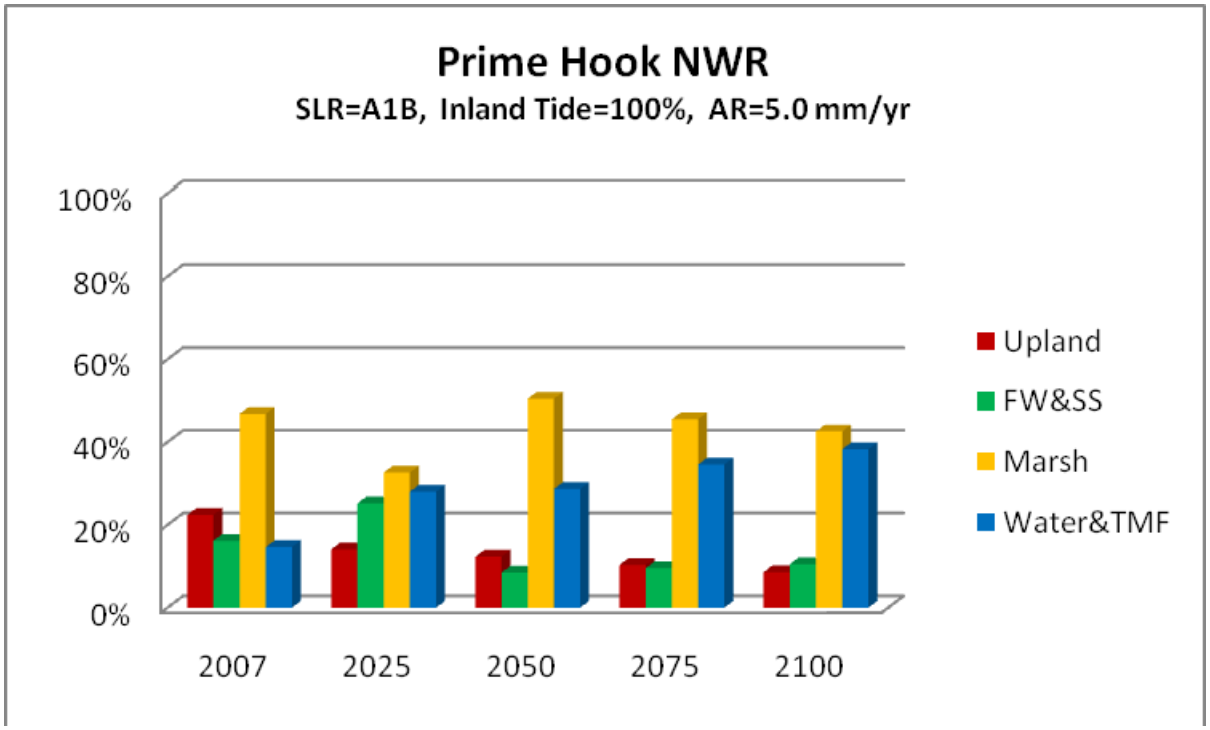
Scenario: A1B SLR, Inland Tide = 50% Coastal Tide, Accretion Rate = 5.0 mm/yr					
Year	Land Cover				
	SLR (meter)	Upland (ha)	FW & SS (ha)	Marsh (ha)	Water & TMF (ha)
2007	0.00	9011	6507	18846	5893
2025	0.07	5677	10144	13145	11290
2050	0.20	4962	3419	20330	11545
2075	0.35	4162	3842	18332	13920
2100	0.50	3466	4239	17143	15408

Scenario: A1B SLR, Inland Tide = 50% Coastal Tide, Accretion Rate = 5.0 mm/yr					
Year	Land Cover				
	SLR (meter)	Upland (%)	FW & SS (%)	Marsh (%)	Water & TMF (%)
2007	0.00	22%	16%	47%	15%
2025	0.07	14%	25%	33%	28%
2050	0.20	12%	8%	51%	29%
2075	0.35	10%	10%	46%	35%
2100	0.50	9%	11%	43%	38%

Scenario: A1B SLR, Inland Tide = 100% Coastal Tide, Accretion Rate = 5.0 mm/yr					
Year	Land Cover				
	SLR (meter)	Upland (ha)	FW & SS (ha)	Marsh (ha)	Water & TMF (ha)
2007	0.00	9011	6507	18846	5893
2025	0.07	2683	13079	13204	11290
2050	0.20	2244	2468	23999	11545
2075	0.35	1807	2725	21803	13920
2100	0.50	1411	2967	20465	15412

Scenario: A1B SLR, Inland Tide = 100% Coastal Tide, Accretion Rate = 5.0 mm/yr					
Year	Land Cover				
	SLR (meter)	Upland (%)	FW & SS (%)	Marsh (%)	Water & TMF (%)
2007	0.00	22%	16%	47%	15%
2025	0.07	7%	32%	33%	28%
2050	0.20	6%	6%	60%	29%
2075	0.35	4%	7%	54%	35%
2100	0.50	4%	7%	51%	38%


Prime Hook NWR
SLR=A1B, Inland Tide=50%, AR=5.0 mm/yr
100%
80%
60%
40%
20%
0%
2007
2025
2050
2075
2100
Upland
FW&SS
Marsh
Water&TMF

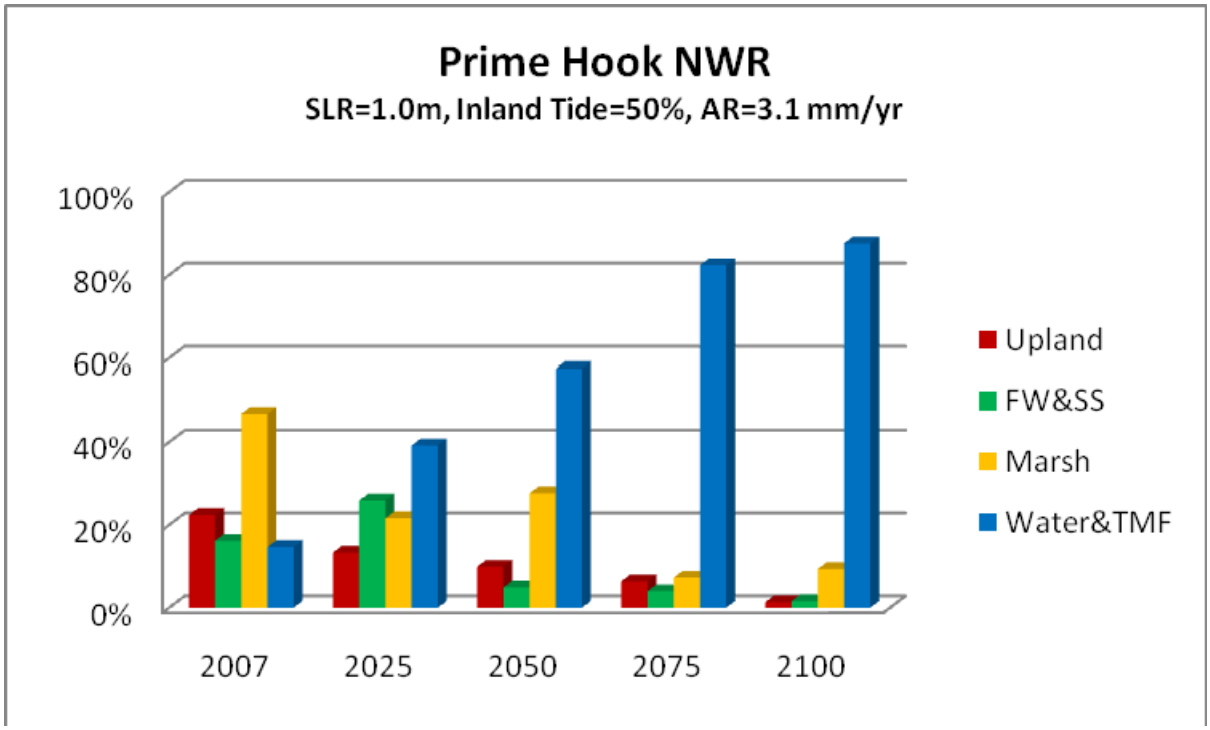

Prime Hook NWR
SLR=A1B, Inland Tide=100%, AR=5.0 mm/yr
100%
80%
60%
40%
20%
0%
2007
2025
2050
2075
2100
Upland
FW&SS
Marsh
Water&TMF

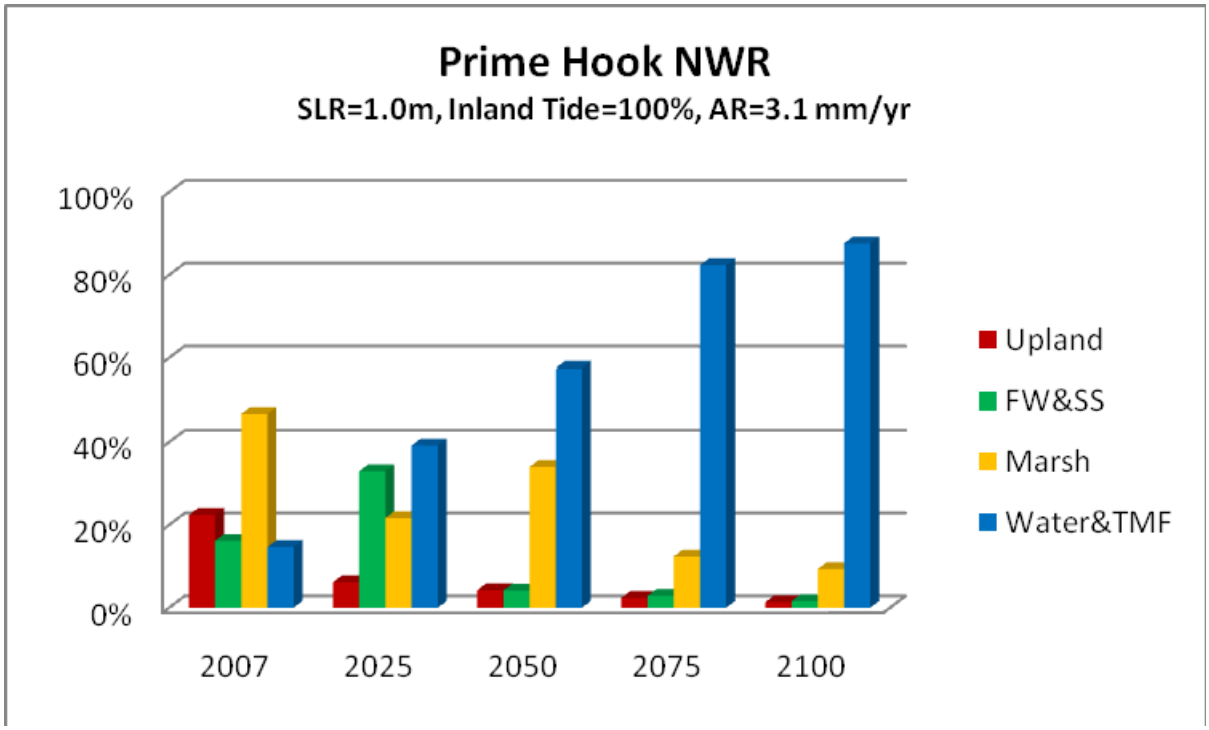
Scenario: 1 meter SLR, Inland Tide = 50% Coastal Tide, Accretion Rate = 3.1 mm/yr					
Year	**Land Cover**				
	SLR (meter)	**Upland (ha)**	**FW & SS (ha)**	**Marsh (ha)**	**Water & TMF (ha)**
2007	0.00	9011	6507	18846	5893
2025	0.12	5360	10424	8695	15777
2050	0.39	3982	1964	11126	23184
2075	0.72	2573	1605	2928	33150
2100	1.06	550	653	3773	35280

Scenario: 1 meter SLR, Inland Tide = 50% Coastal Tide, Accretion Rate = 3.1 mm/yr					
Year	**Land Cover**				
	SLR (meter)	**Upland (%)**	**FW & SS (%)**	**Marsh (%)**	**Water & TMF (%)**
2007	0.00	22%	16%	47%	15%
2025	0.12	13%	26%	22%	39%
2050	0.39	10%	5%	28%	58%
2075	0.72	6%	4%	7%	82%
2100	1.06	1%	2%	9%	88%

Scenario: 1 meter SLR, Inland Tide = 100% Coastal Tide, Accretion Rate = 3.1 mm/yr					
Year	**Land Cover**				
	SLR (meter)	**Upland (ha)**	**FW & SS (ha)**	**Marsh (ha)**	**Water & TMF (ha)**
2007	0.00	9011	6507	18846	5893
2025	0.12	2483	13274	8722	15777
2050	0.39	1704	1675	13693	23184
2075	0.72	955	1163	4986	33152
2100	1.06	550	653	3773	35280

Scenario: 1 meter SLR, Inland Tide = 100% Coastal Tide, Accretion Rate = 3.1 mm/yr					
Year	**Land Cover**				
	SLR (meter)	**Upland (%)**	**FW & SS (%)**	**Marsh (%)**	**Water & TMF (%)**
2007	0.00	22%	16%	47%	15%
2025	0.12	6%	33%	22%	39%
2050	0.39	4%	4%	34%	58%
2075	0.72	2%	3%	12%	82%
2100	1.06	1%	2%	9%	88%


Prime Hook NWR
SLR=1.0m, Inland Tide=50%, AR=3.1 mm/yr
100%
80%
60%
40%
20%
0%
2007
2025
2050
2075
2100
Upland
FW&SS
Marsh
Water&TMF

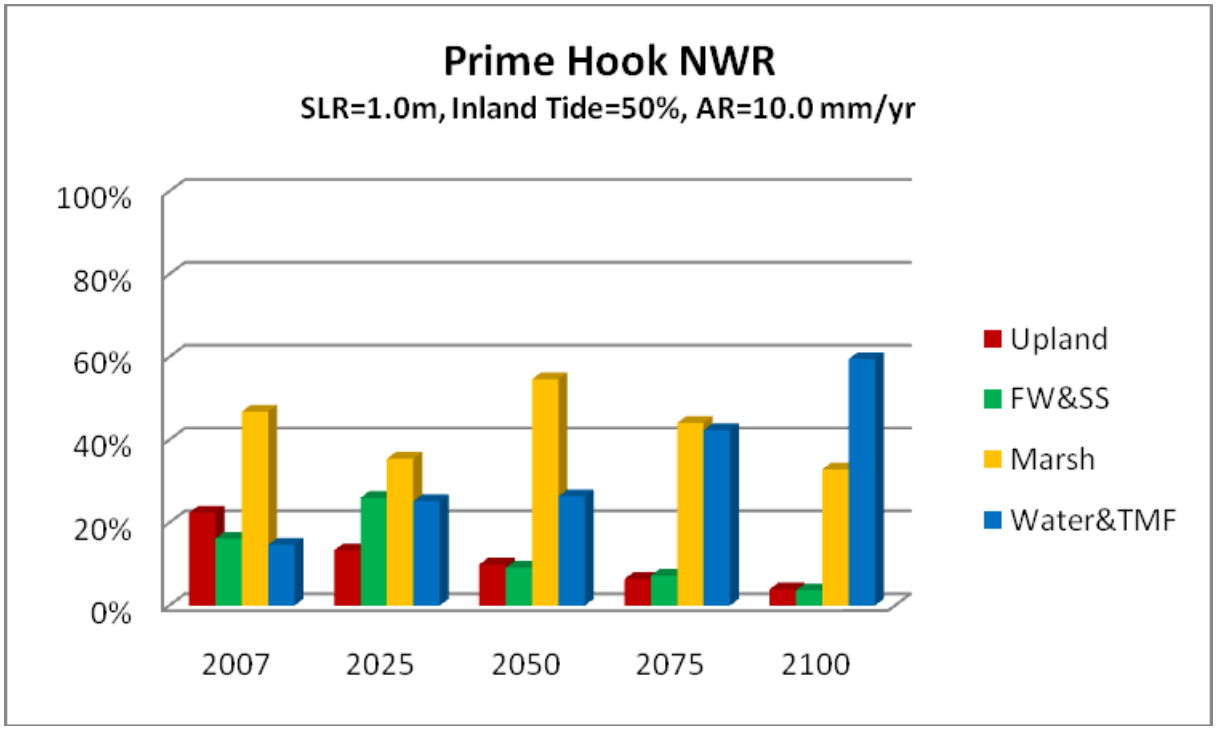

Prime Hook NWR
SLR=1.0m, Inland Tide=100%, AR=3.1 mm/yr
100%
80%
60%
40%
20%
0%
2007
2025
2050
2075
2100
Upland
FW&SS
Marsh
Water&TMF

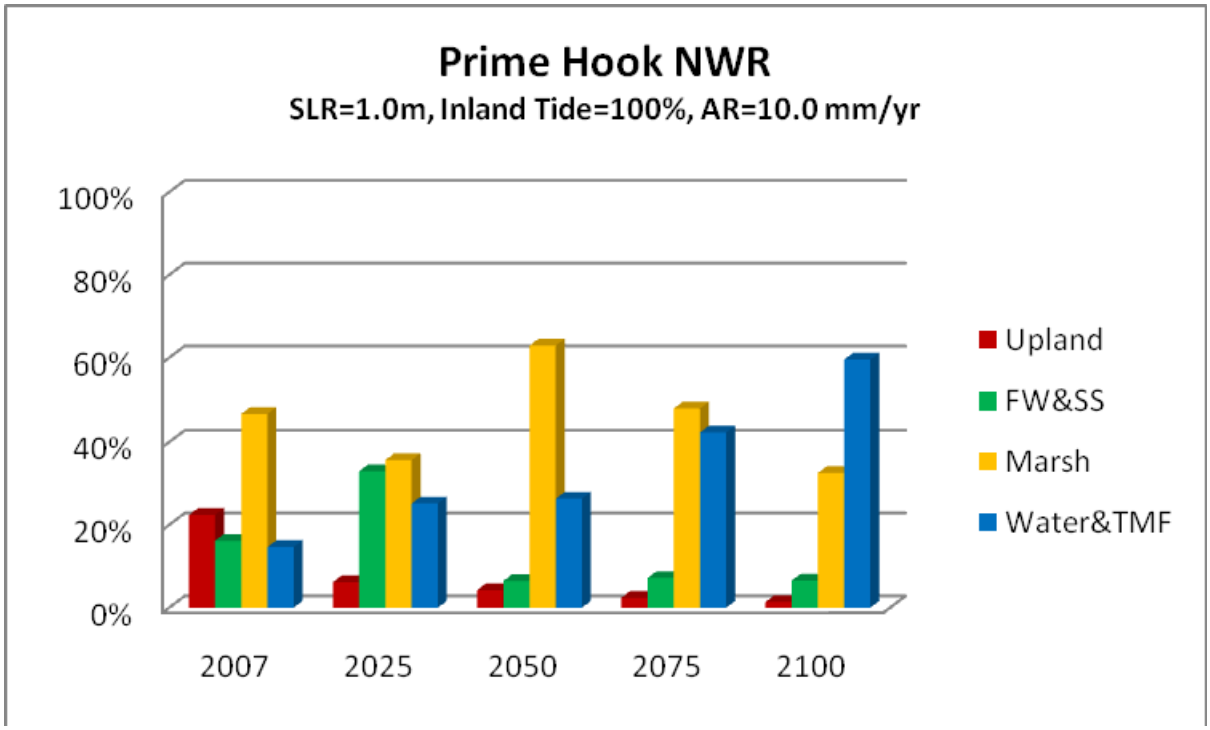
Scenario: 1 meter SLR, Inland Tide = 50% Coastal Tide, Accretion Rate = 10.0 mm/yr					
Year	Land Cover				
	SLR (meter)	Upland (ha)	FW & SS (ha)	Marsh (ha)	Water & TMF (ha)
2007	0.00	9011	6507	18846	5893
2025	0.12	5365	10478	14279	10133
2050	0.39	3990	3672	21993	10600
2075	0.72	2579	2895	17747	17035
2100	1.06	1576	1483	13238	23959

Scenario: 1 meter SLR, Inland Tide = 50% Coastal Tide, Accretion Rate = 10.0 mm/yr					
Year	Land Cover				
	SLR (meter)	Upland (%)	FW & SS (%)	Marsh (%)	Water & TMF (%)
2007	0.00	22%	16%	47%	15%
2025	0.12	13%	26%	35%	25%
2050	0.39	10%	9%	55%	26%
2075	0.72	6%	7%	44%	42%
2100	1.06	4%	4%	33%	60%

Scenario: 1 meter SLR, Inland Tide = 100% Coastal Tide, Accretion Rate = 10.0 mm/yr					
Year	Land Cover				
	SLR (meter)	Upland (ha)	FW & SS (ha)	Marsh (ha)	Water & TMF (ha)
2007	0.00	9011	6507	18846	5893
2025	0.12	2489	13275	14359	10133
2050	0.39	1712	2600	25343	10600
2075	0.72	962	2890	19368	17037
2100	1.06	555	2635	13101	23964

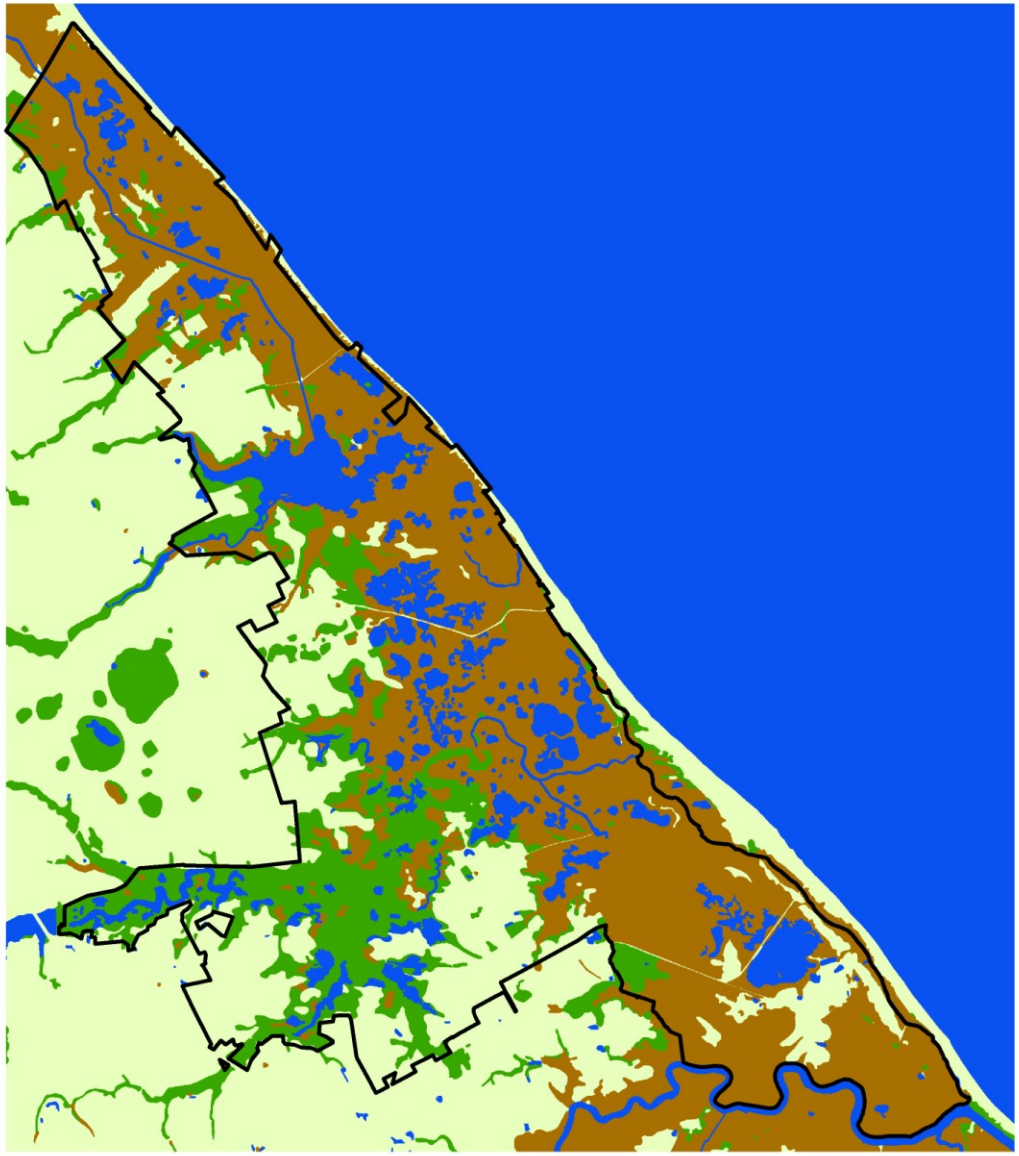
Scenario: 1 meter SLR, Inland Tide = 100% Coastal Tide, Accretion Rate = 10.0 mm/yr					
Year	Land Cover				
	SLR (meter)	Upland (%)	FW & SS (%)	Marsh (%)	Water & TMF (%)
2007	0.00	22%	16%	47%	15%
2025	0.12	6%	33%	36%	25%
2050	0.39	4%	6%	63%	26%
2075	0.72	2%	7%	48%	42%
2100	1.06	1%	7%	33%	60%


Prime Hook NWR
SLR=1.0m, Inland Tide=50%, AR=10.0 mm/yr
100%
80%
60%
40%
20%
0%
2007
2025
2050
2075
2100
Upland
FW&SS
Marsh
Water&TMF


Prime Hook NWR
SLR=1.0m, Inland Tide=100%, AR=10.0 mm/yr
100%
80%
60%
40%
20%
0%
2007
2025
2050
2075
2100
Upland
FW&SS
Marsh
Water&TMF

Appendix B

Land Cover Maps from SLAMM Outputs



Prime Hook NWR SLAMM Output

Year = 2007
SLR Scenario = A1B
Sea Level Rise = 0.00 meter

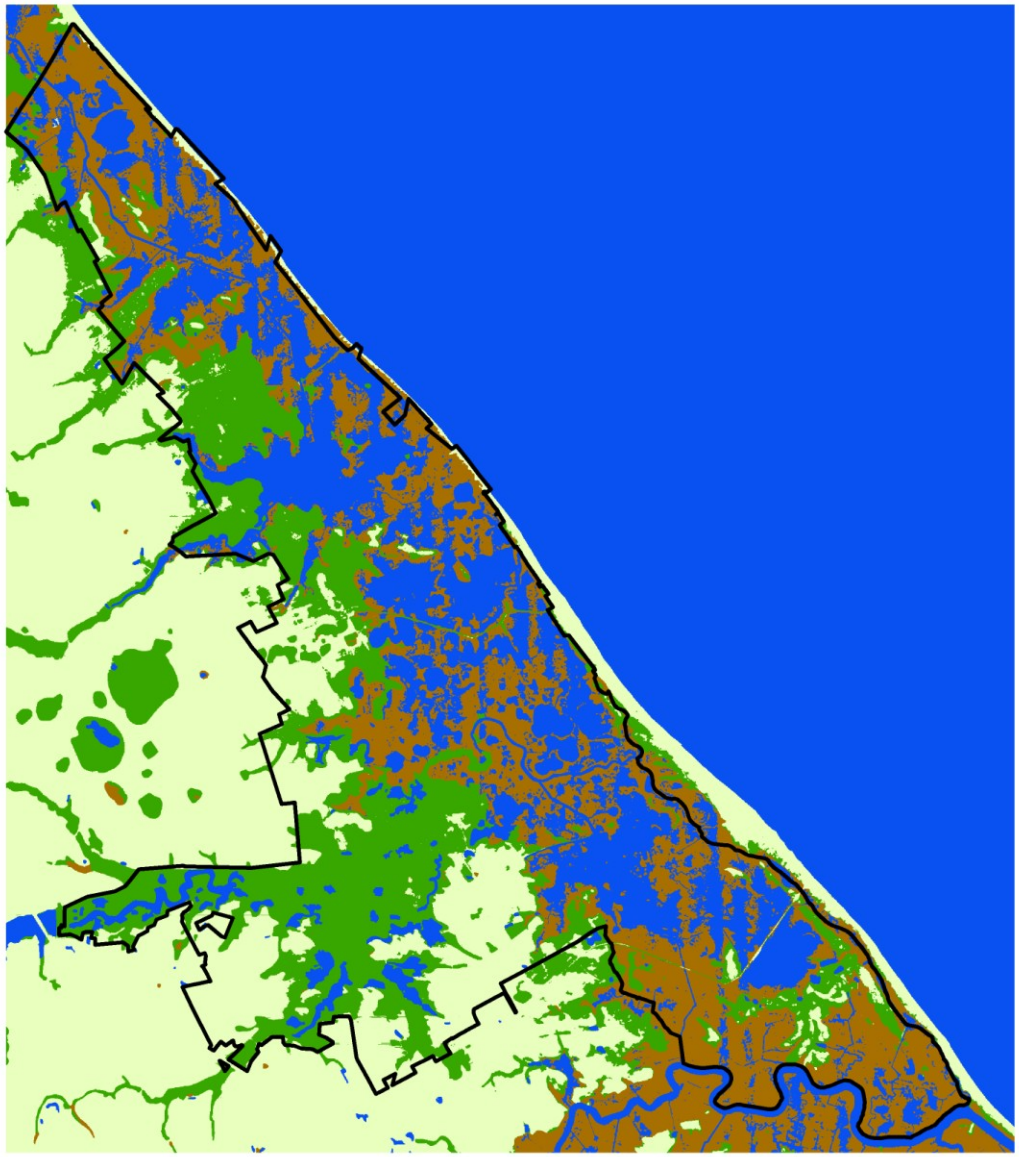
Accretion Rate = 3.1 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2025
SLR Scenario = A1B
Sea Level Rise = 0.07 meter

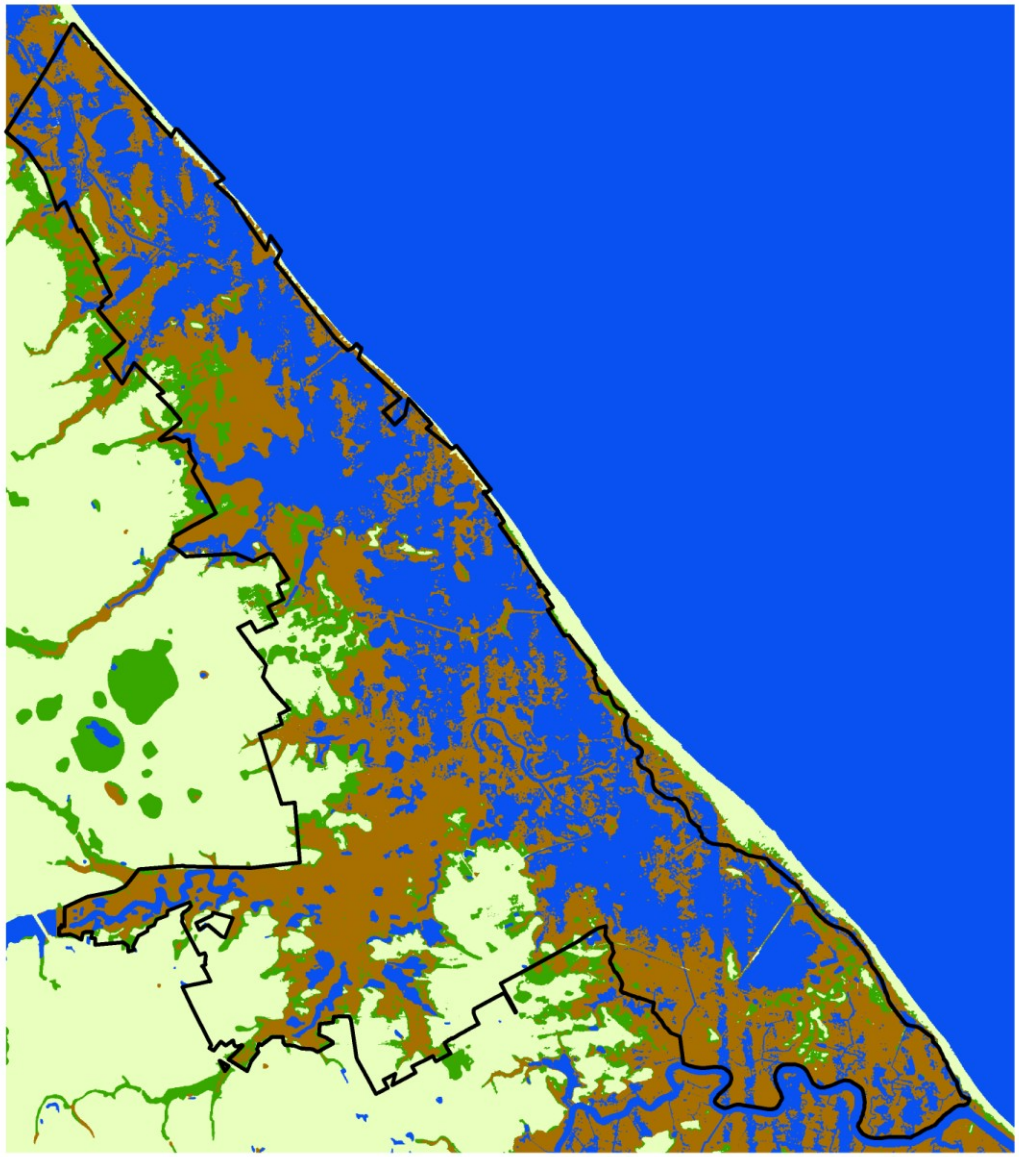
Accretion Rate = 3.1 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2050
SLR Scenario = A1B
Sea Level Rise = 0.20 meter

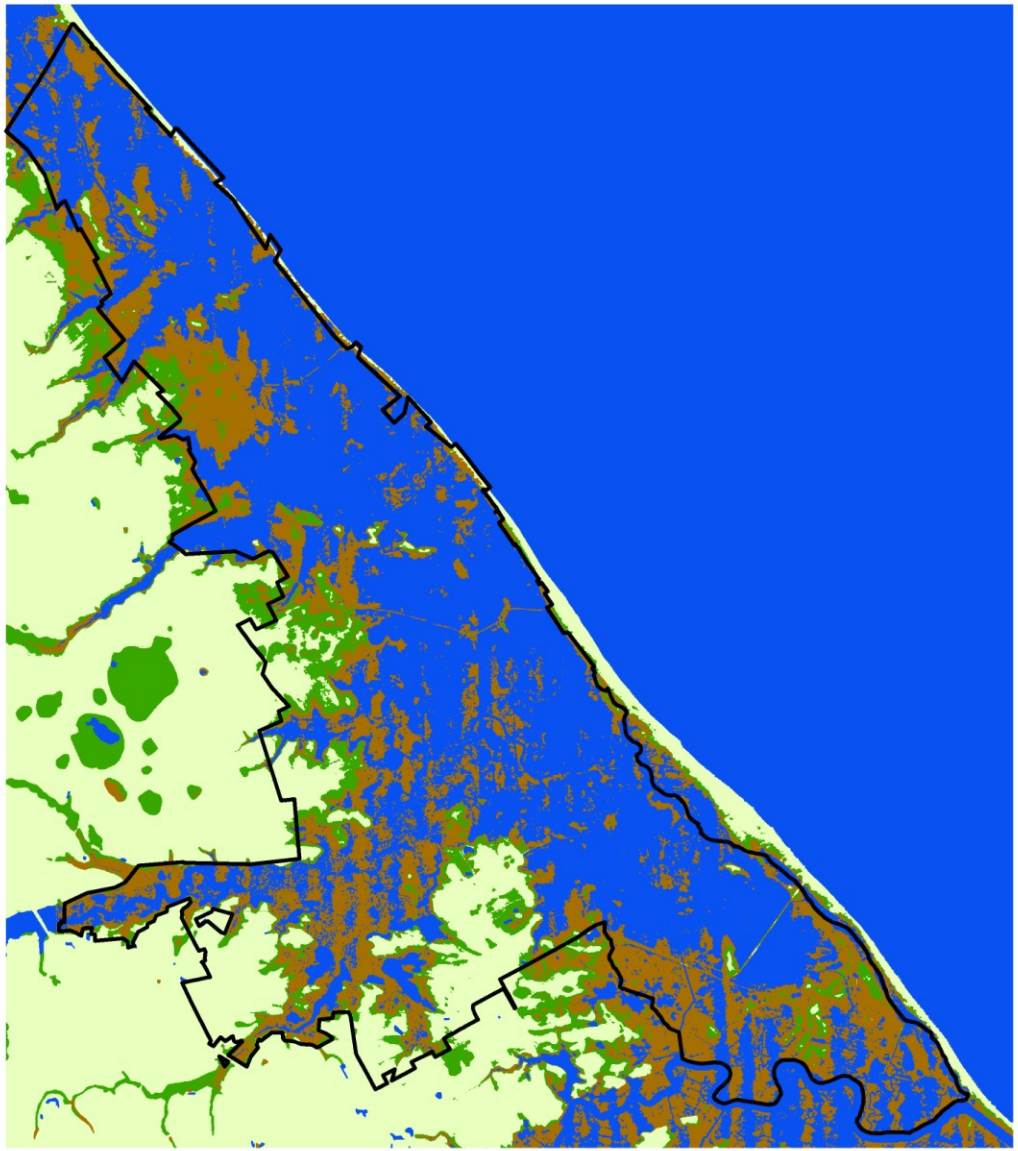
Accretion Rate = 3.1 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2075
SLR Scenario = A1B
Sea Level Rise = 0.35 meter

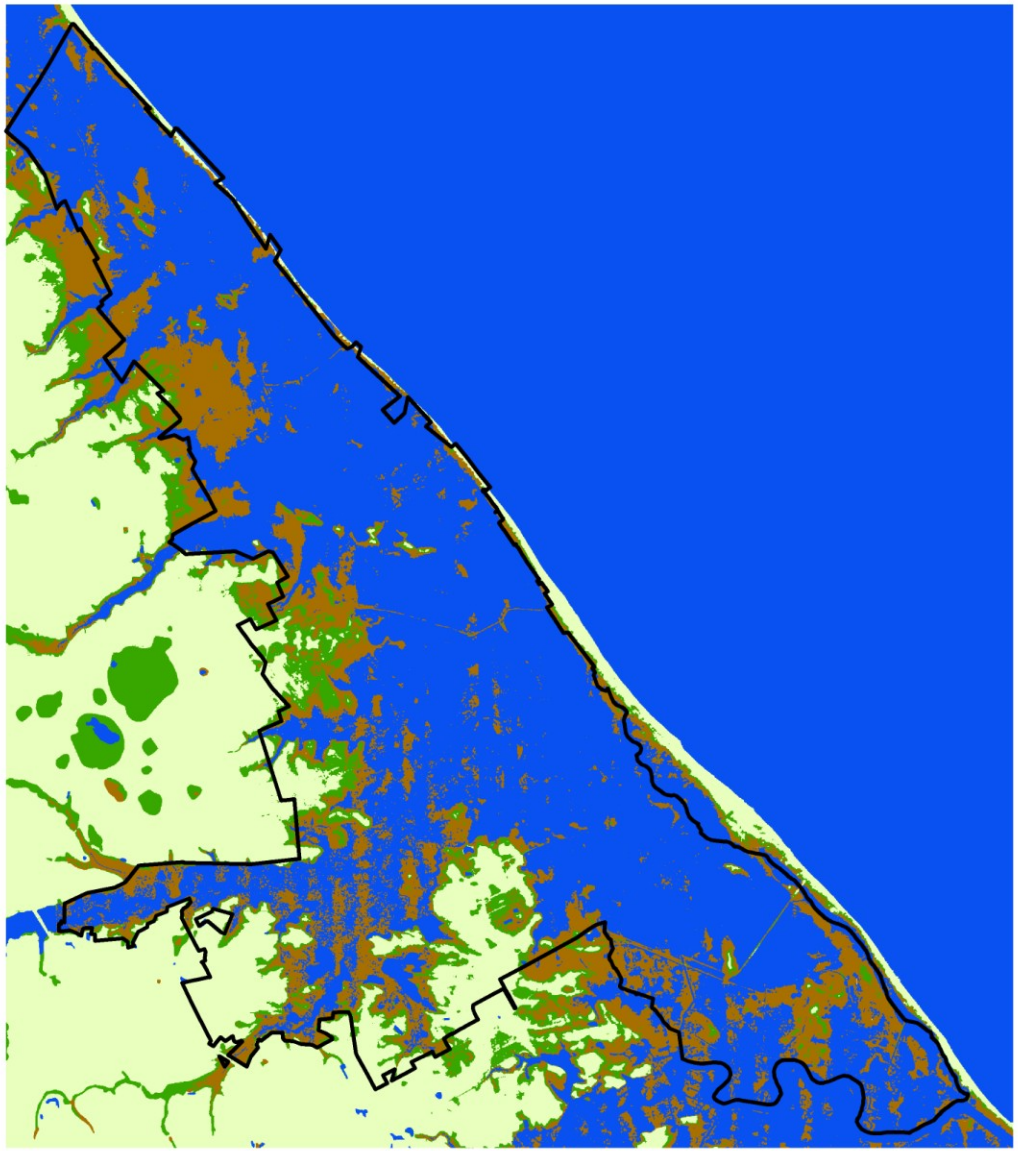
Accretion Rate = 3.1 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2100
SLR Scenario = A1B
Sea Level Rise = 0.50 meter

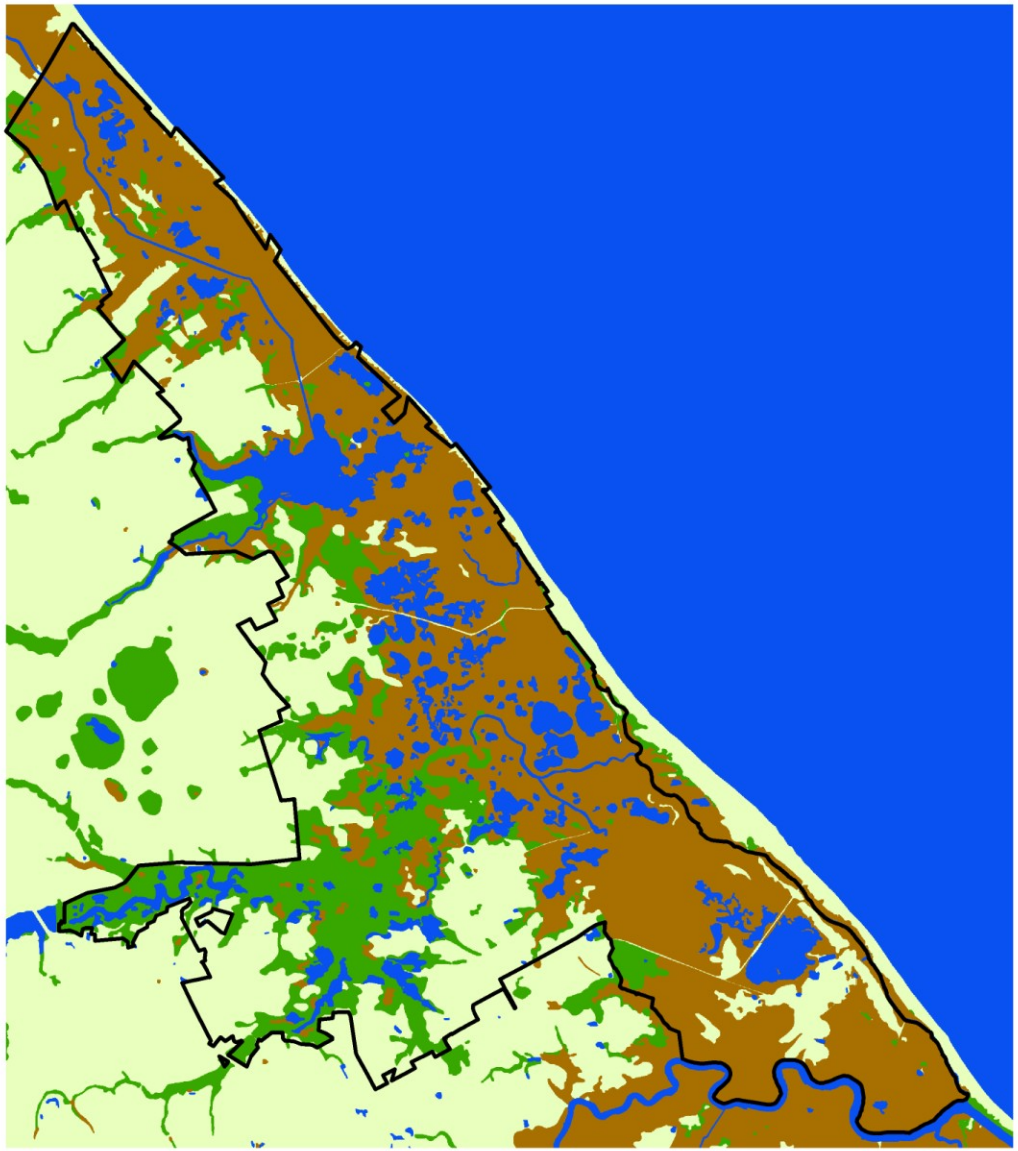
Accretion Rate = 3.1 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2007
SLR Scenario = A1B
Sea Level Rise = 0.00 meter

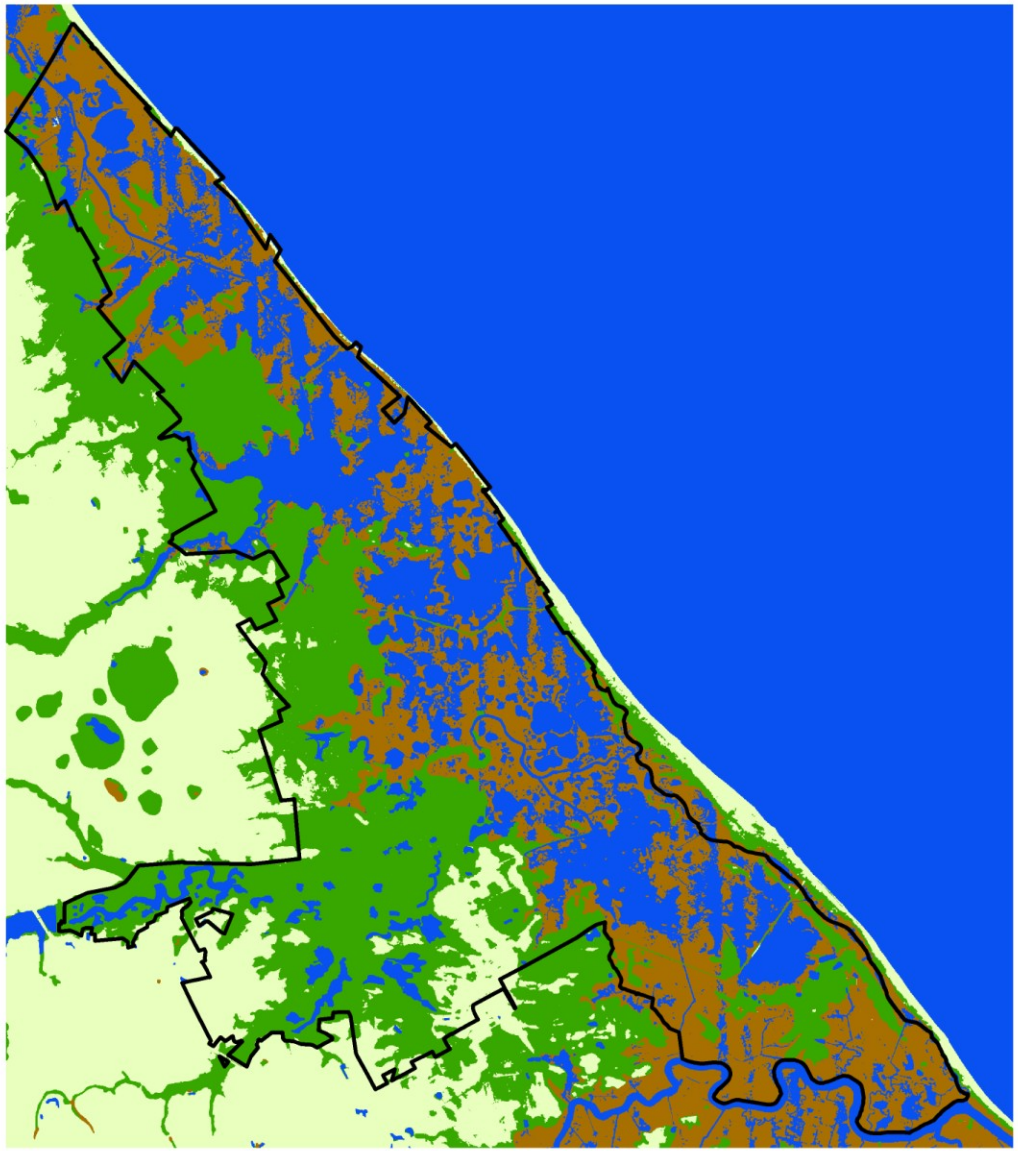
Accretion Rate = 3.1 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2025
SLR Scenario = A1B
Sea Level Rise = 0.07 meter

Accretion Rate = 3.1 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
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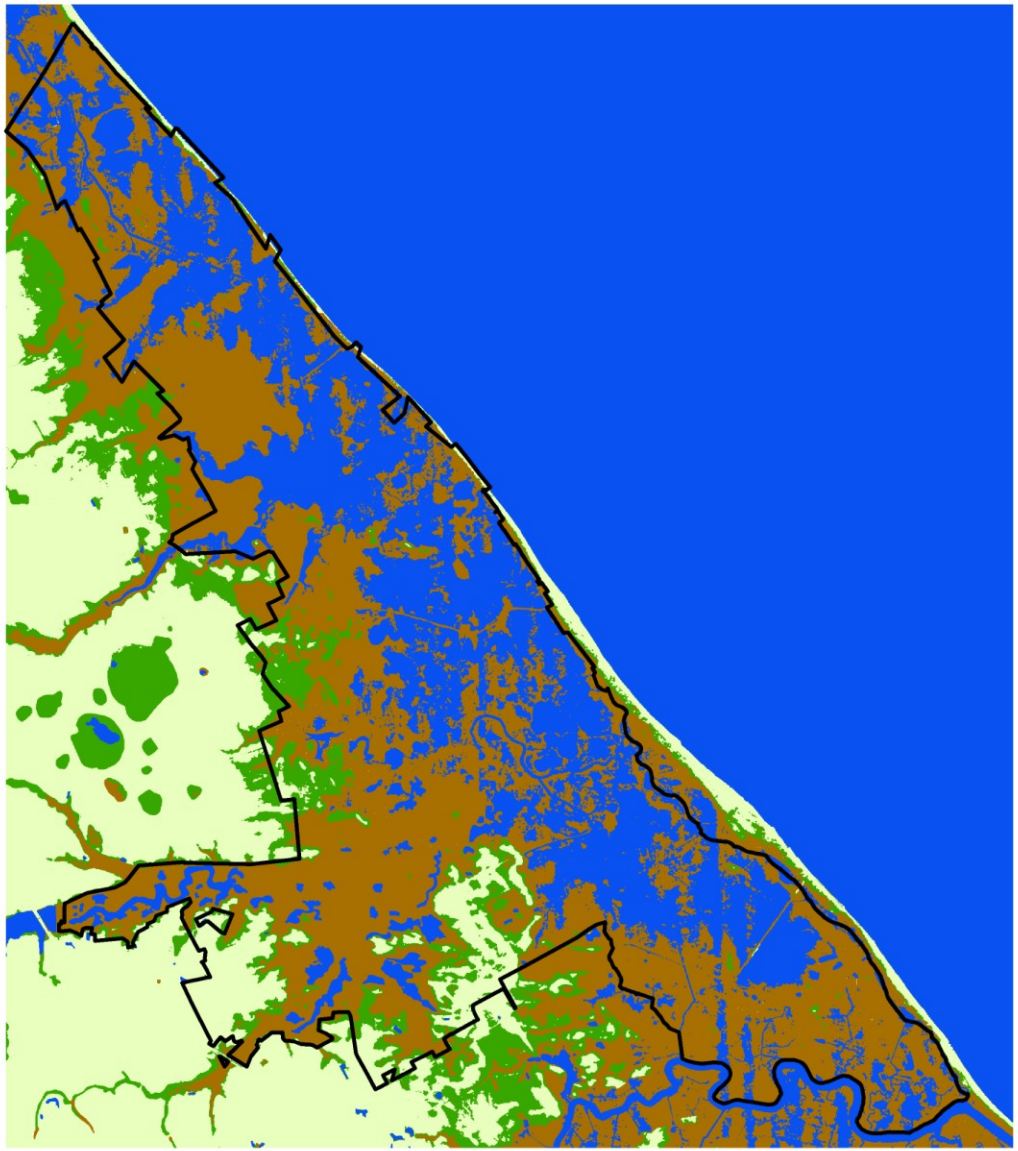
S

0 0.5 1 2 3
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2050
SLR Scenario = A1B
Sea Level Rise = 0.20 meter

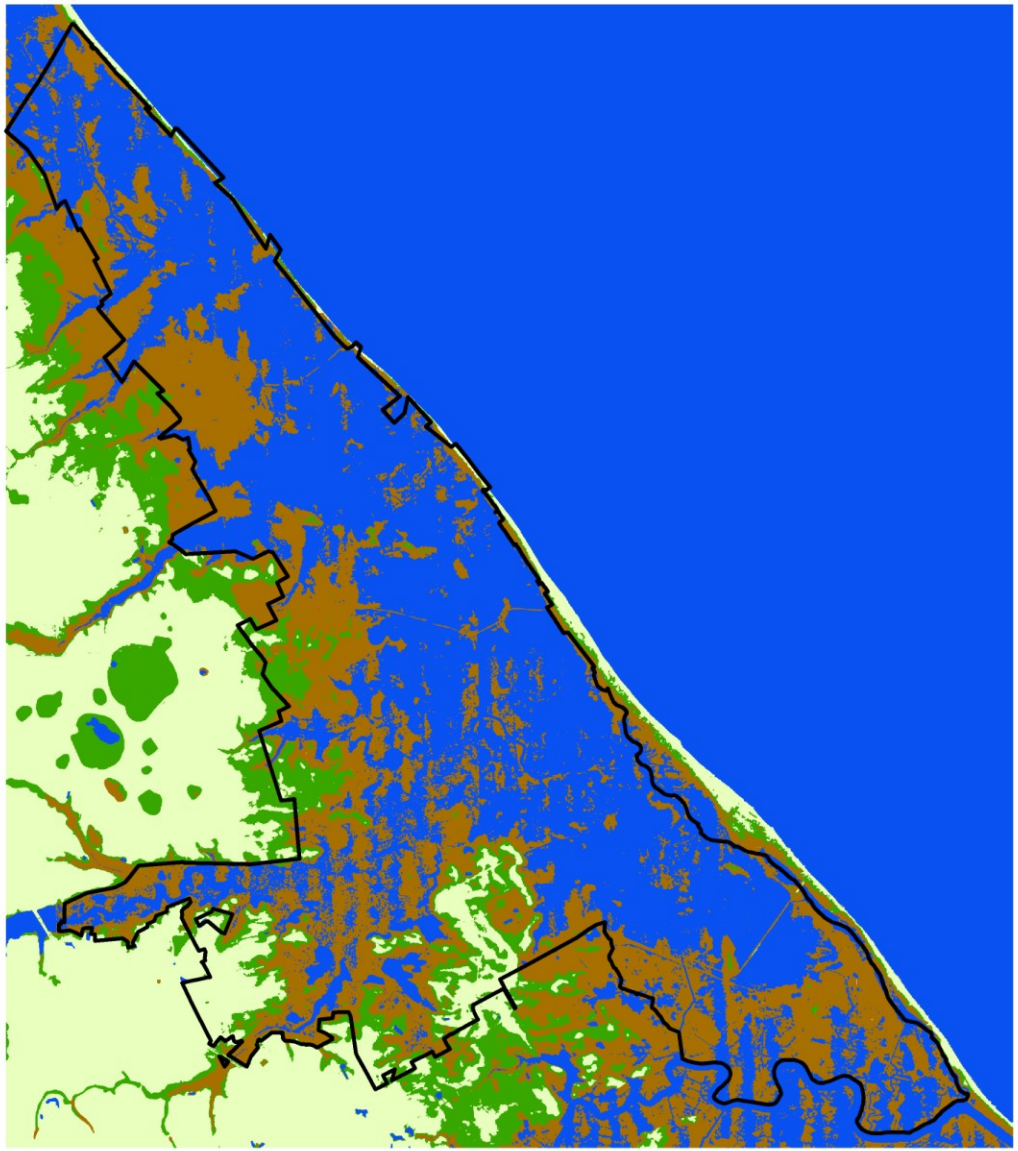
Accretion Rate = 3.1 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2075
SLR Scenario = A1B
Sea Level Rise = 0.35 meter

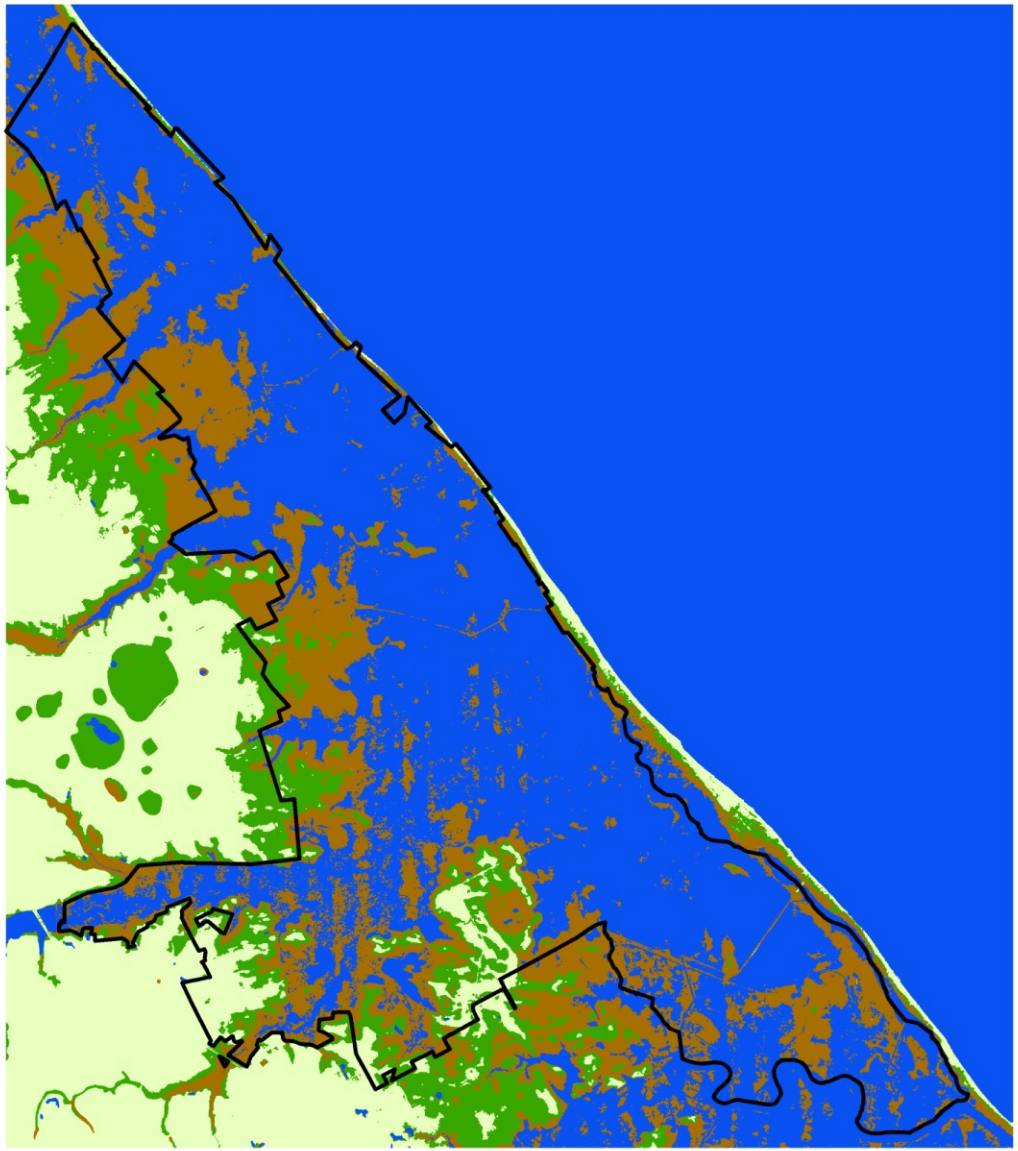
Accretion Rate = 3.1 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2100
SLR Scenario = A1B
Sea Level Rise = 0.50 meter

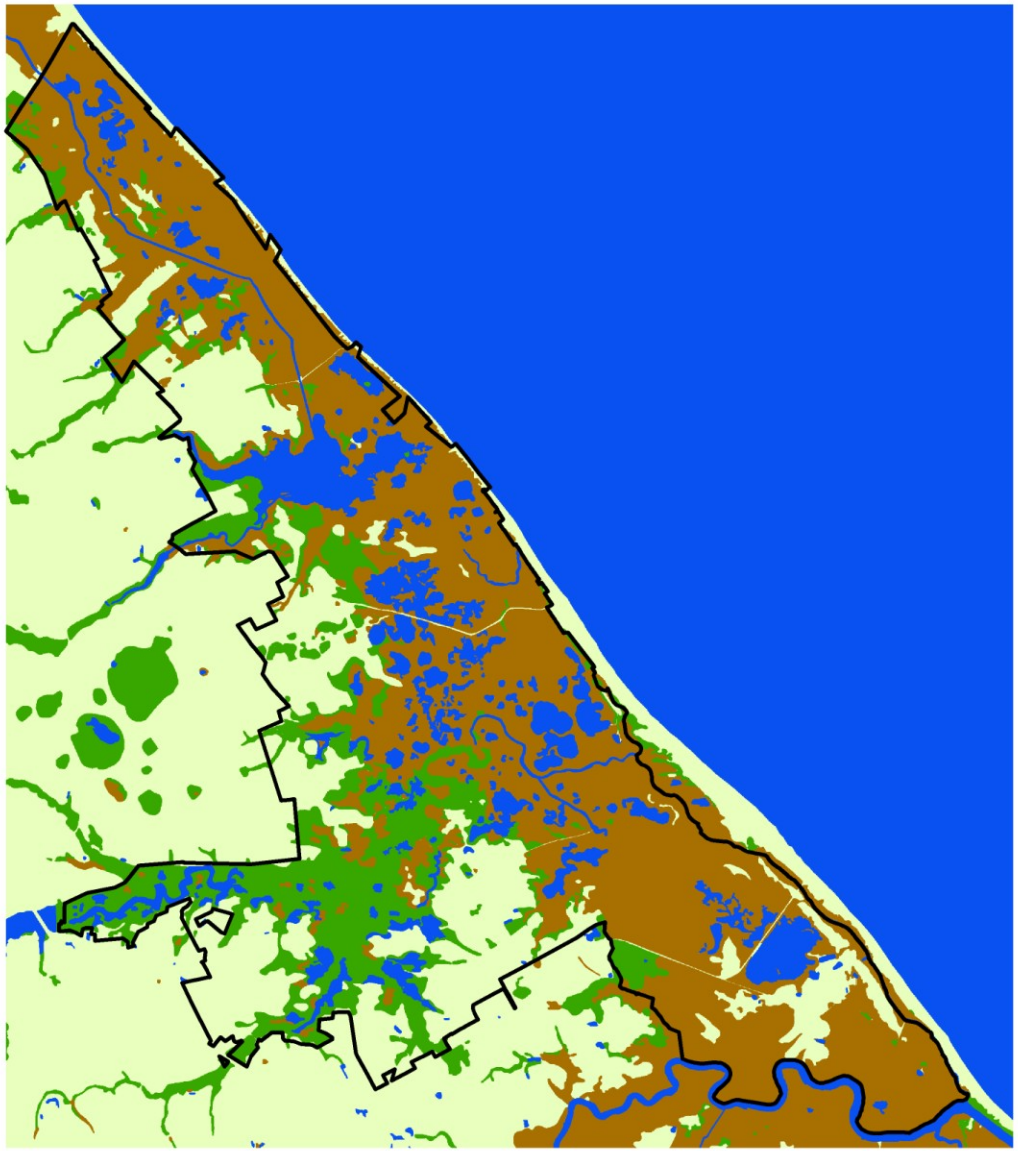
Accretion Rate = 3.1 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2007
SLR Scenario = A1B
Sea Level Rise = 0.00 meter

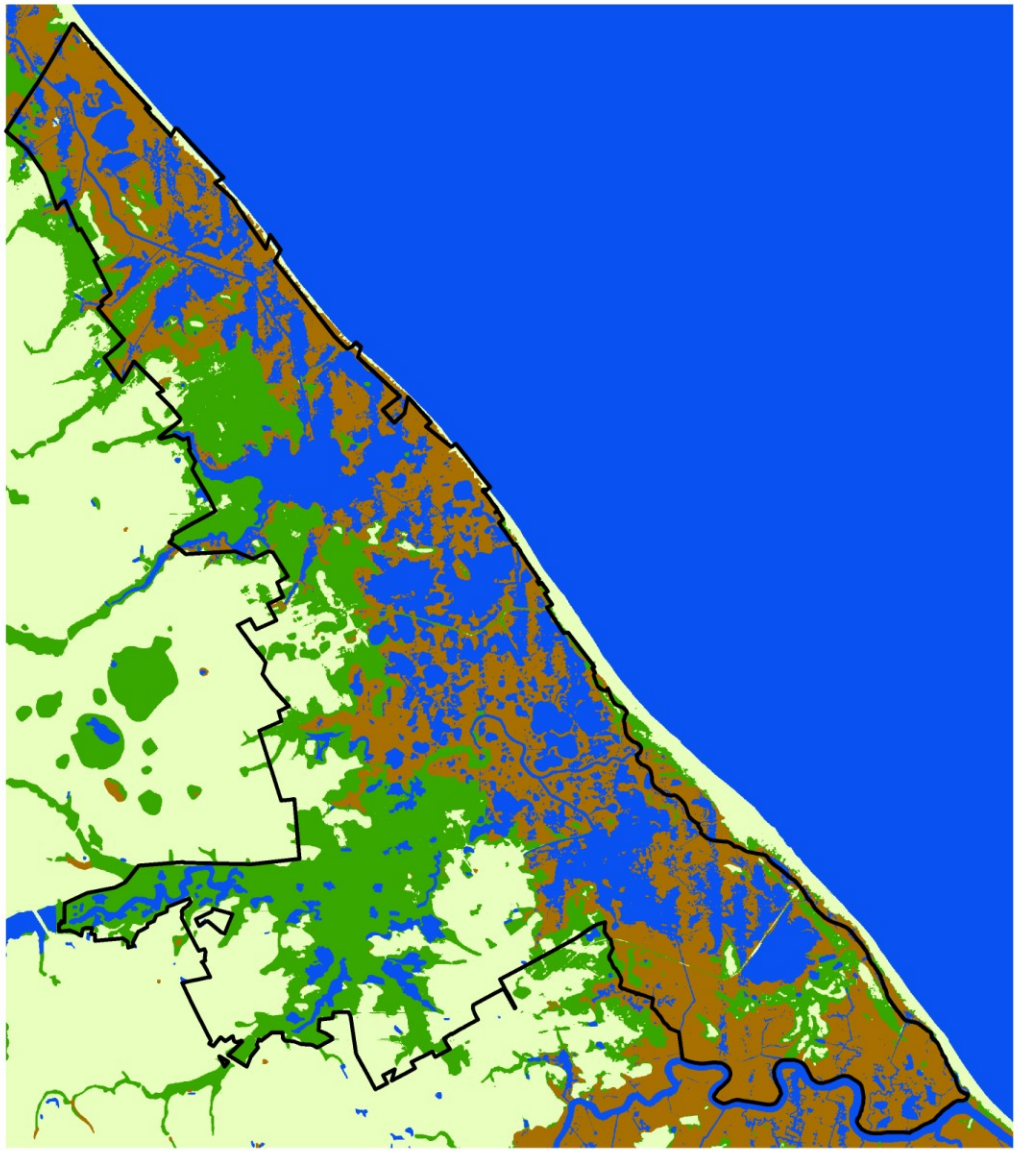
Accretion Rate = 5.0 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2025
SLR Scenario = A1B
Sea Level Rise = 0.07 meter

Accretion Rate = 5.0 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
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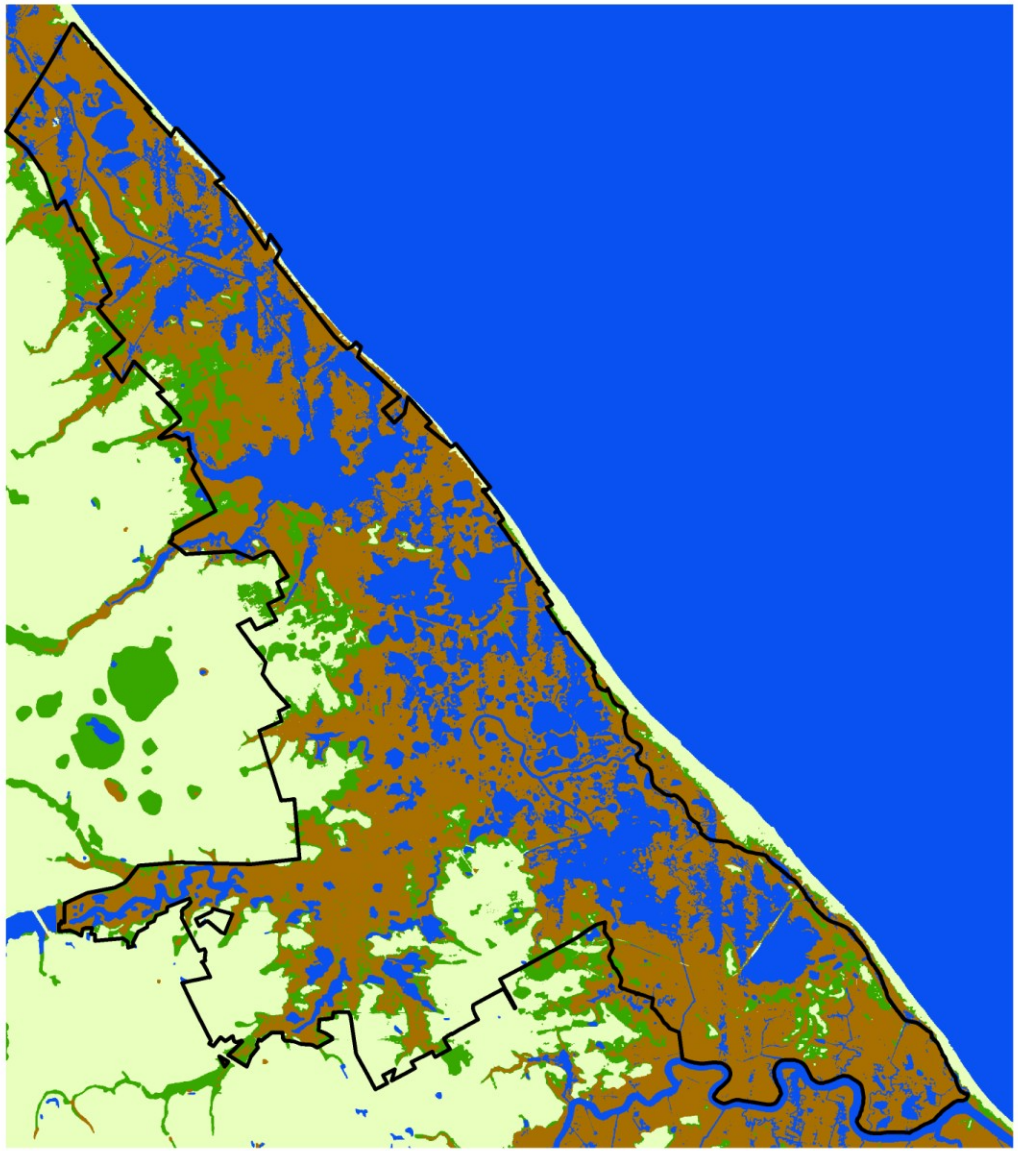
S

0 0.5 1 2 3
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2050
SLR Scenario = A1B
Sea Level Rise = 0.20 meter

Accretion Rate = 5.0 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
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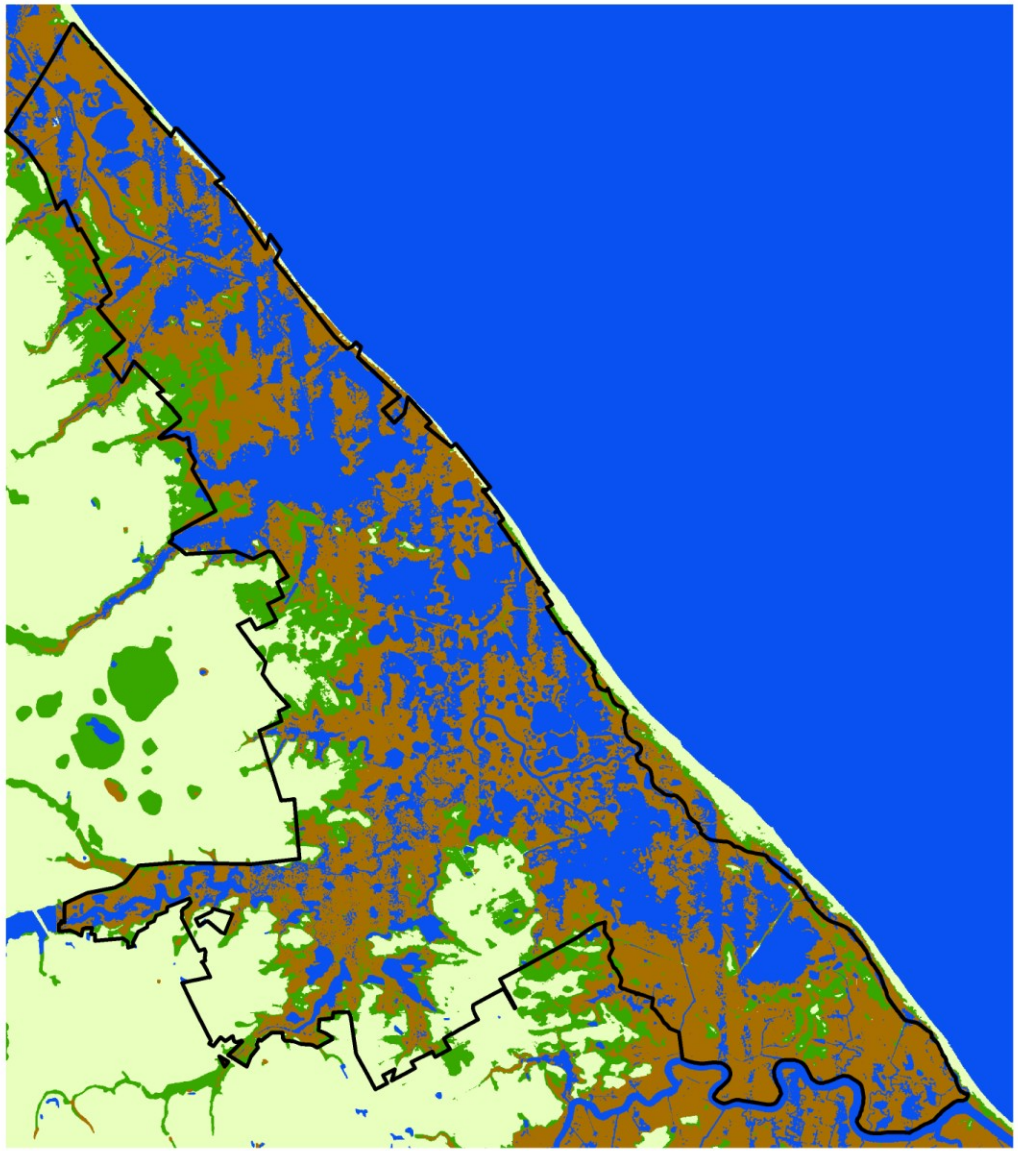
S

0 0.5 1 2 3
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2075
SLR Scenario = A1B
Sea Level Rise = 0.35 meter

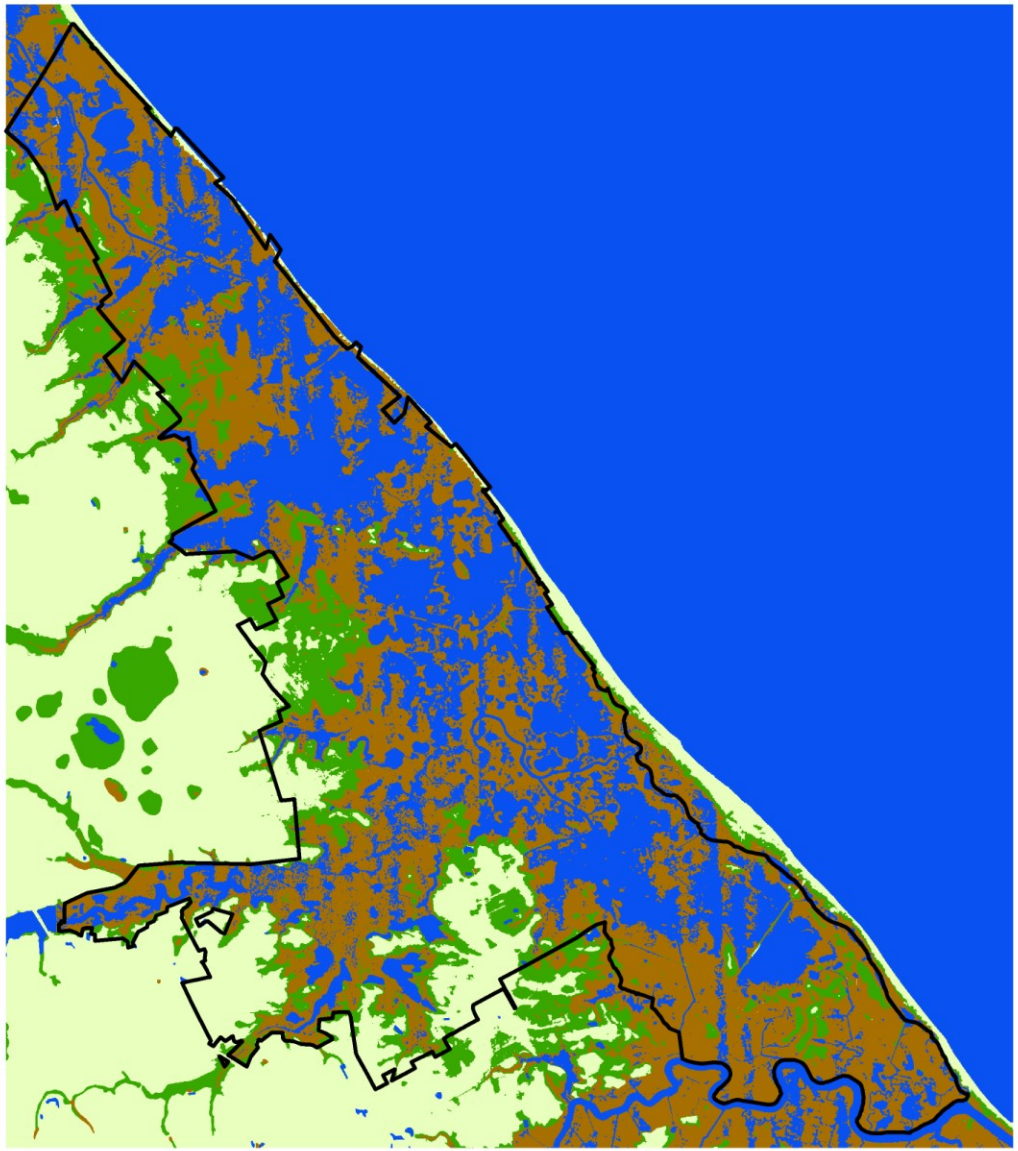
Accretion Rate = 5.0 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2100
SLR Scenario = A1B
Sea Level Rise = 0.50 meter

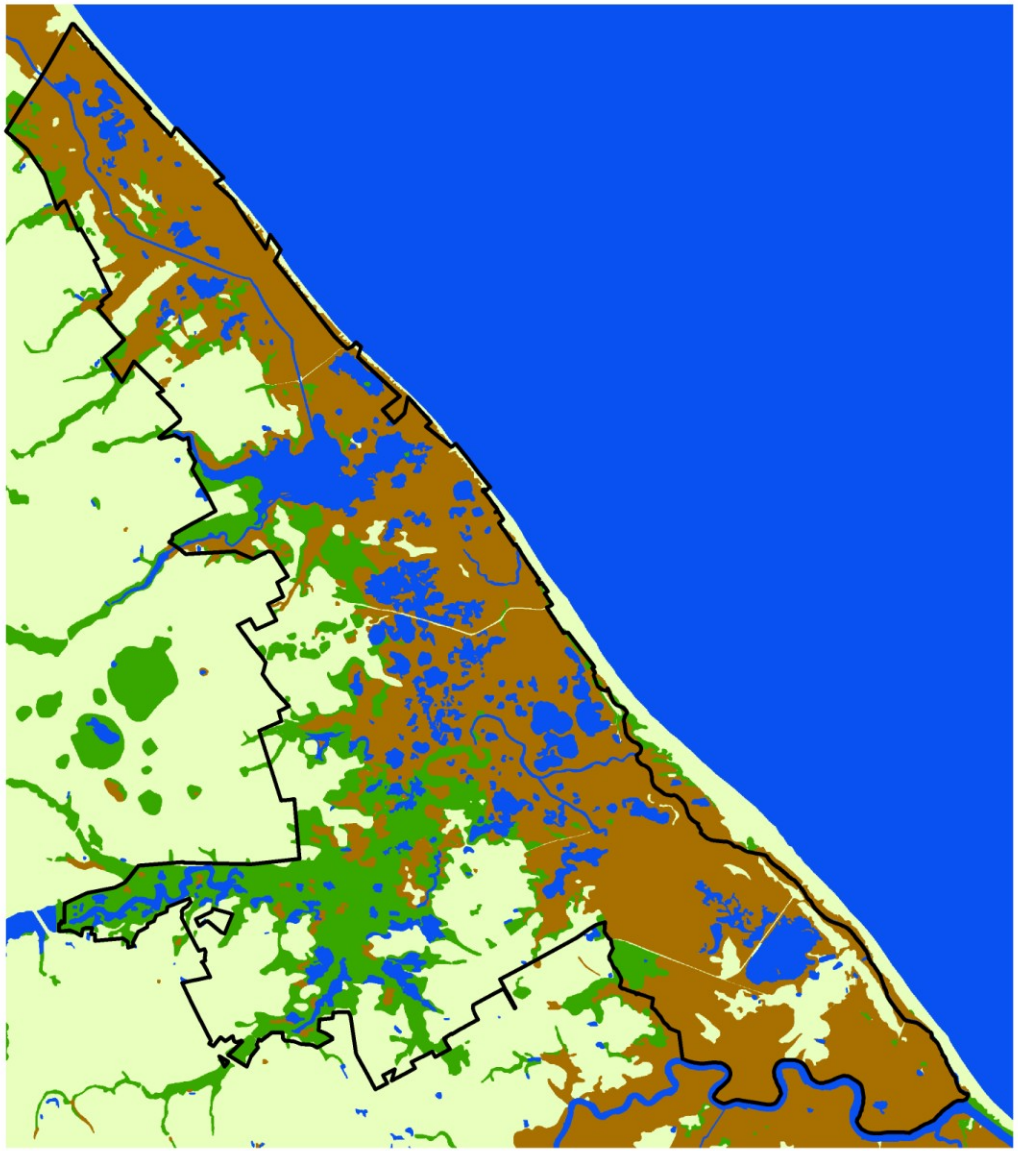
Accretion Rate = 5.0 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2007
SLR Scenario = A1B
Sea Level Rise = 0.00 meter

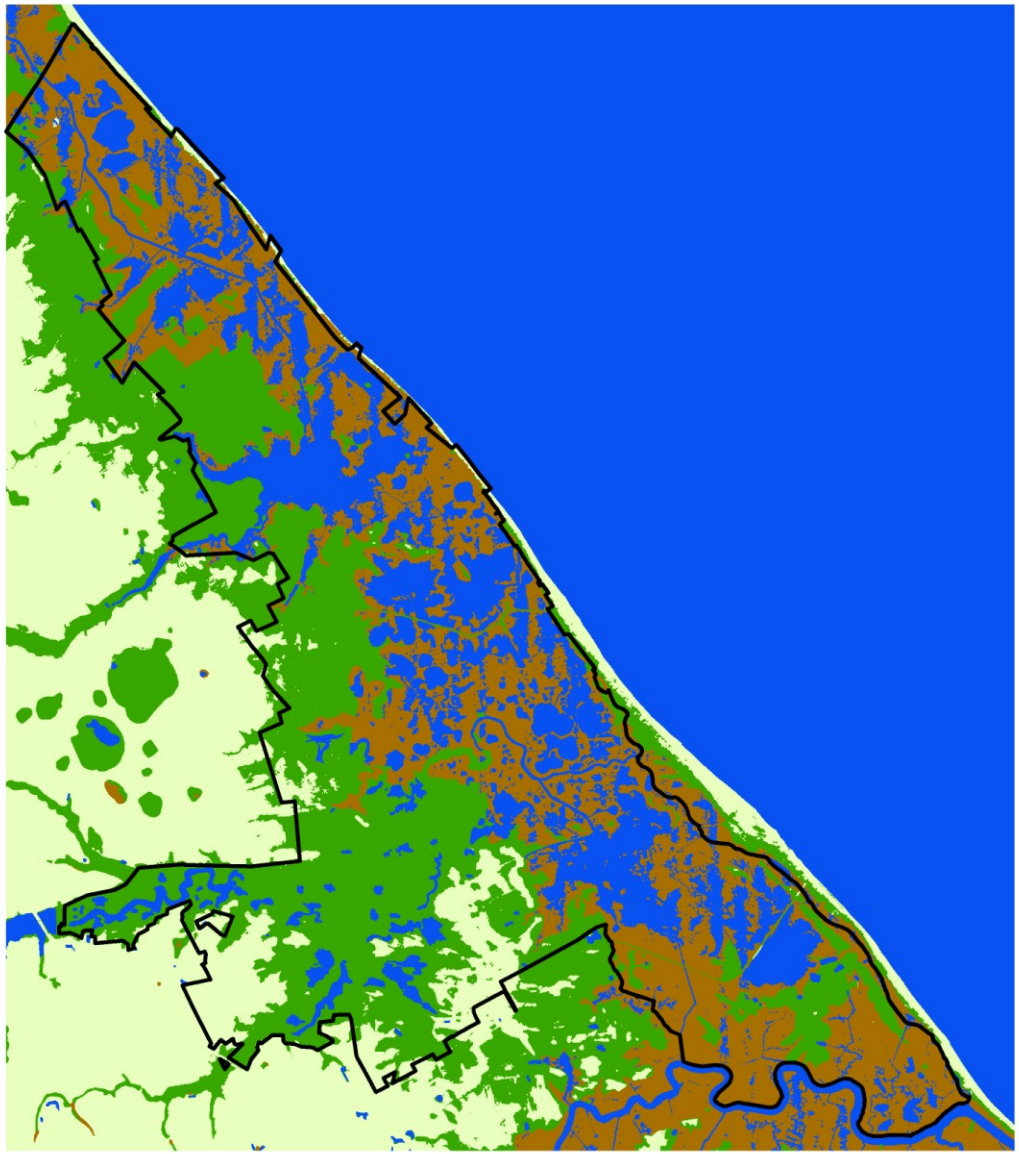
Accretion Rate = 5.0 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2025
SLR Scenario = A1B
Sea Level Rise = 0.07 meter

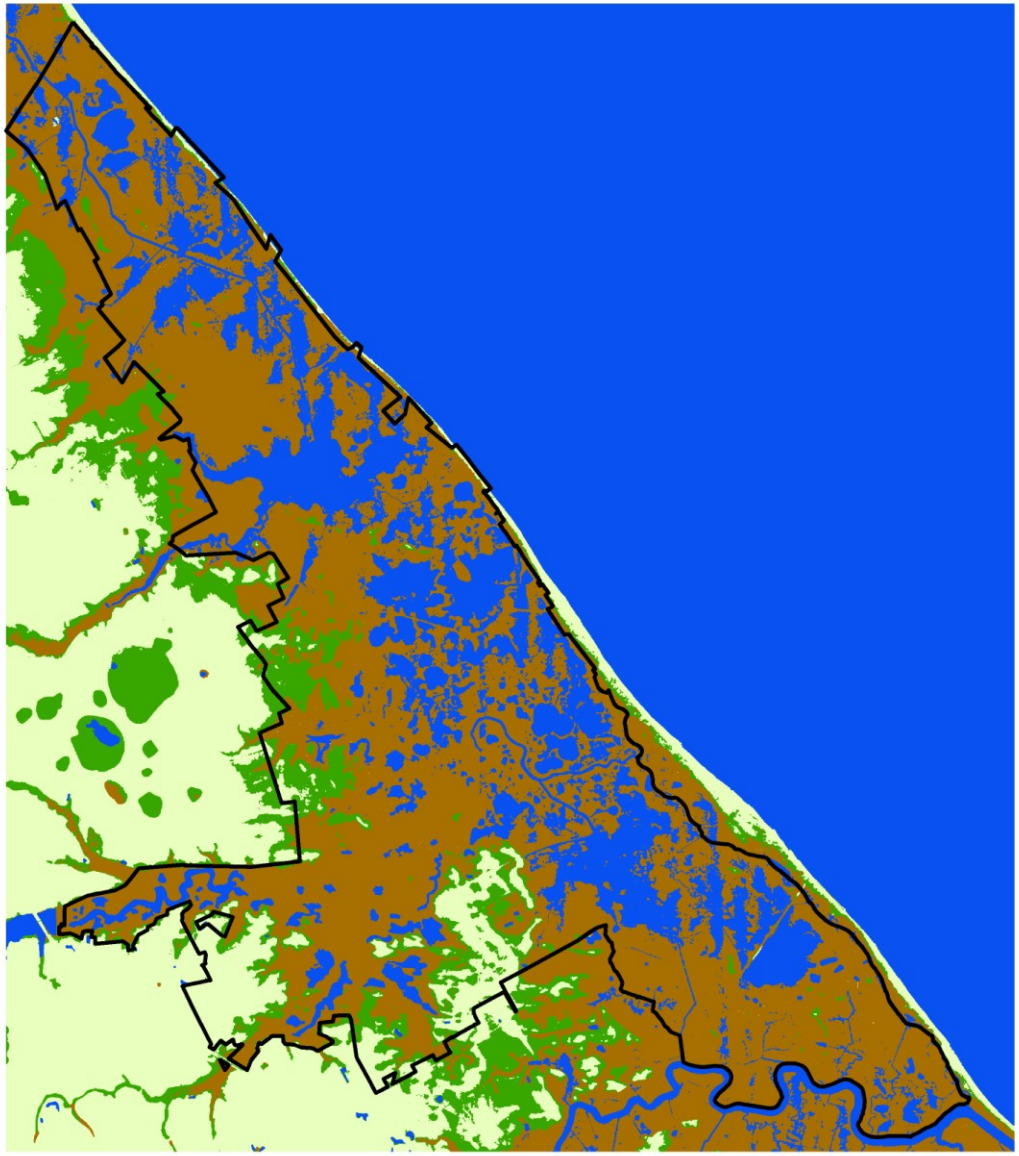
Accretion Rate = 5.0 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2050
SLR Scenario = A1B
Sea Level Rise = 0.20 meter

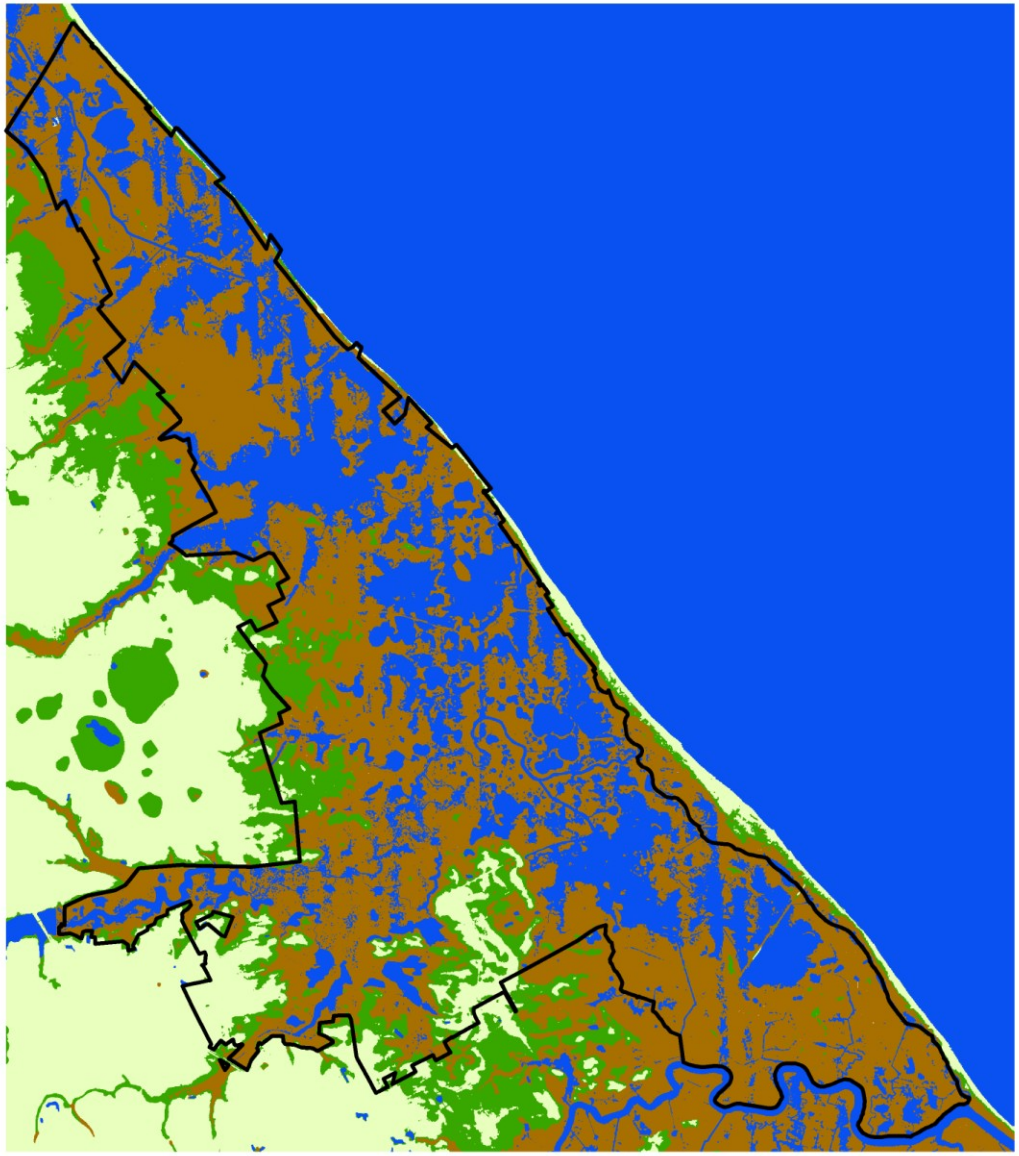
Accretion Rate = 5.0 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2075
SLR Scenario = A1B
Sea Level Rise = 0.35 meter

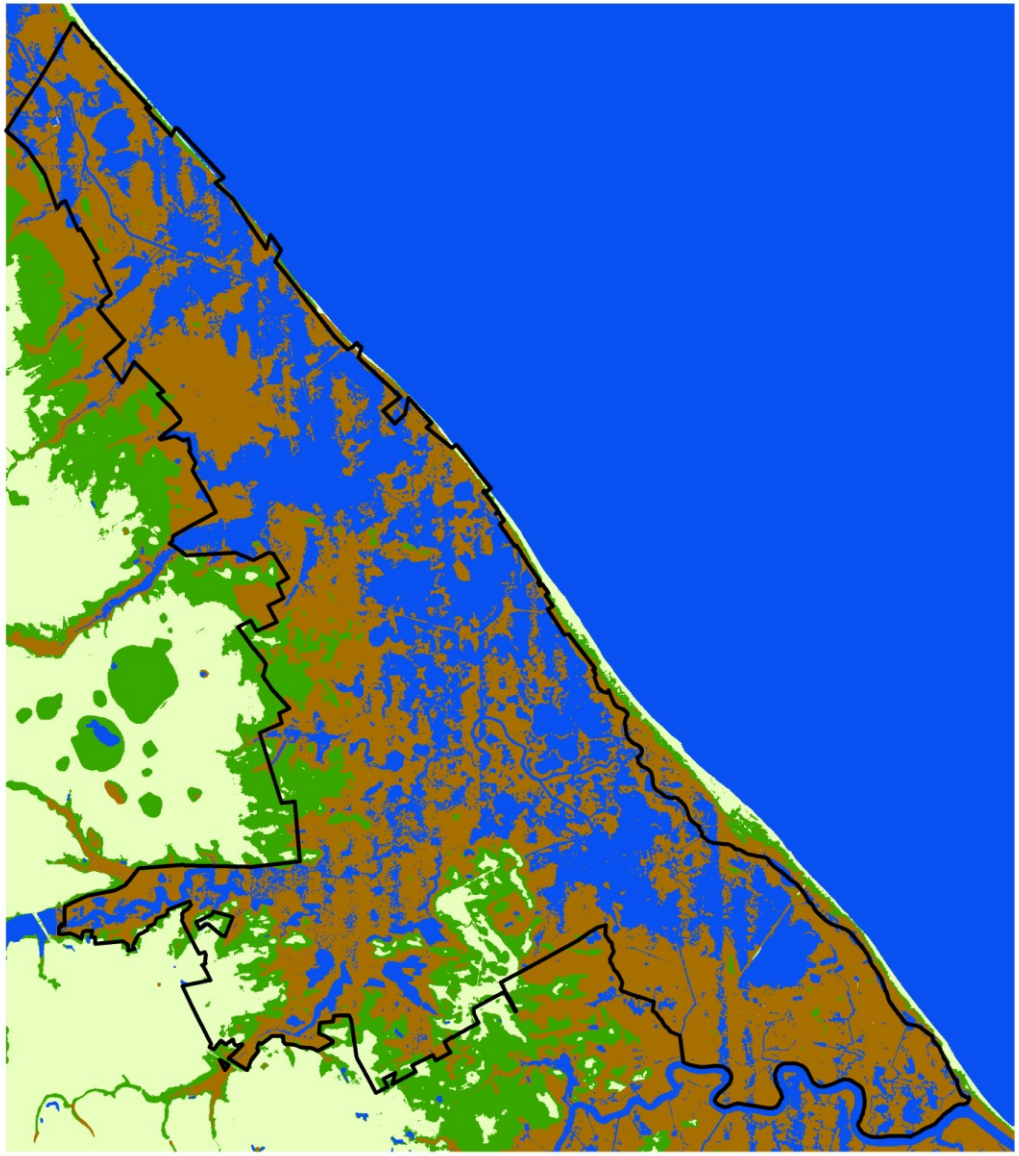
Accretion Rate = 5.0 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2100
SLR Scenario = A1B
Sea Level Rise = 0.50 meter

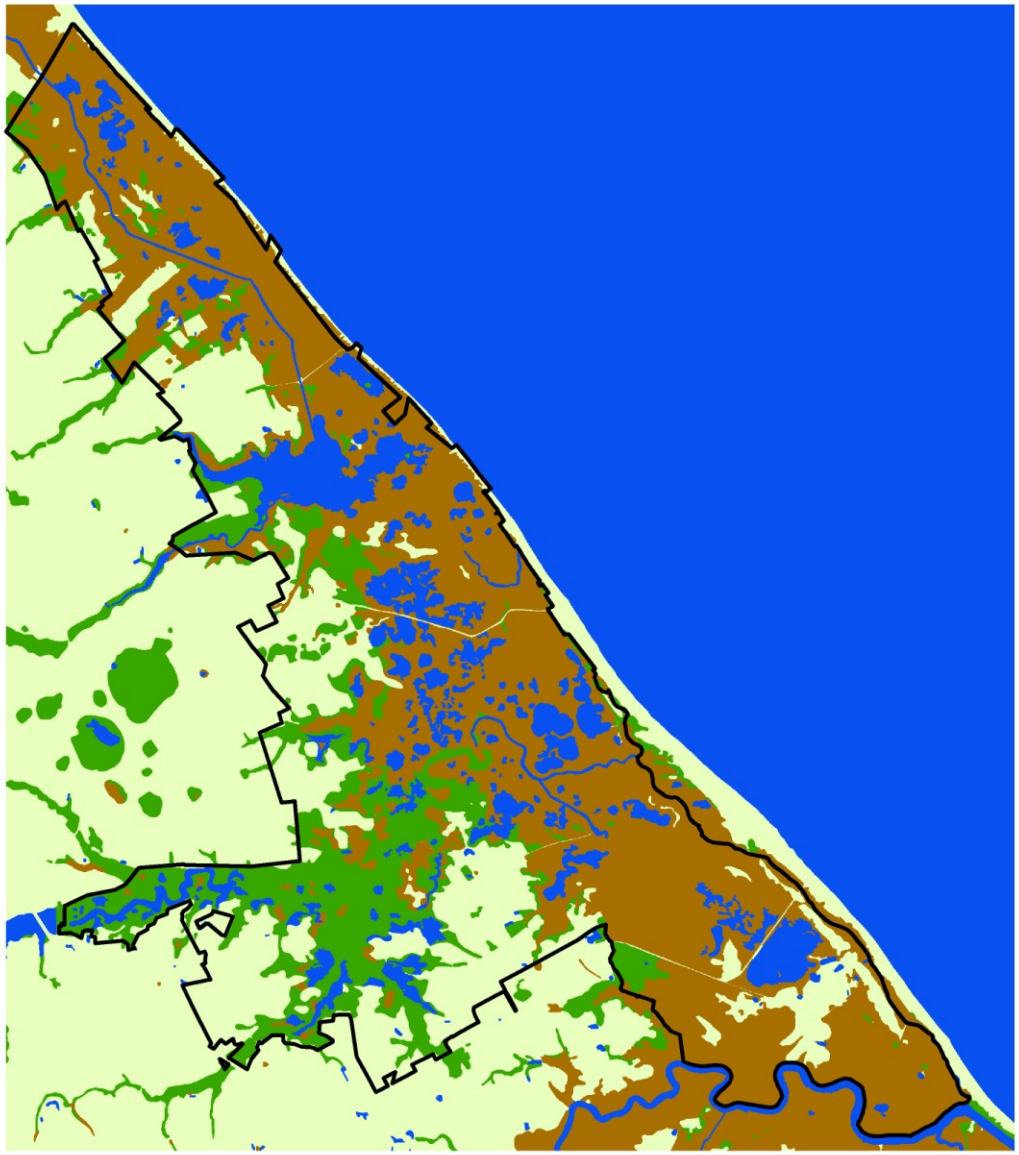
Accretion Rate = 5.0 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2007
SLR Scenario = 1 meter
Sea Level Rise = 0.00 meter

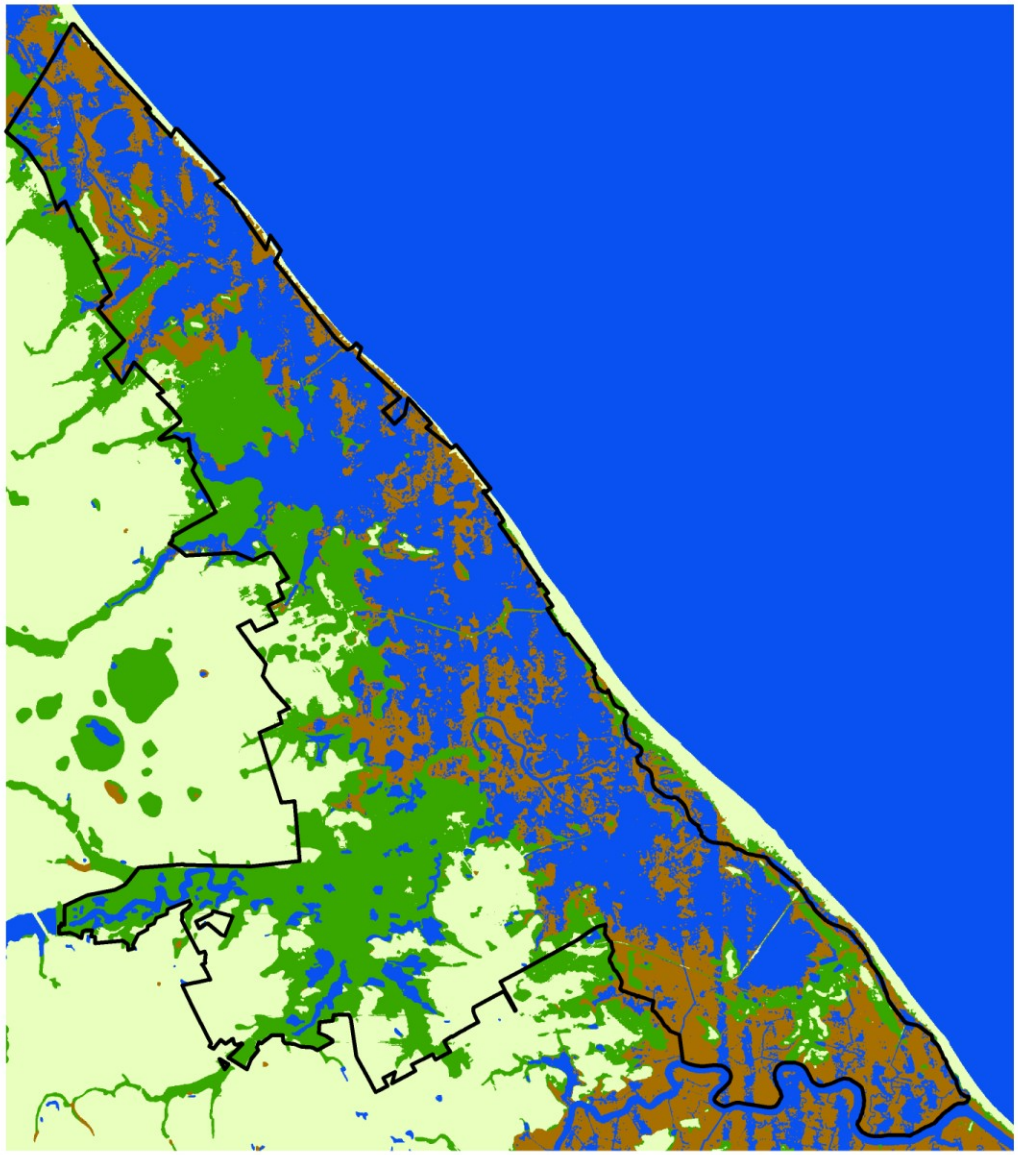
Accretion Rate = 3.1 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2025
SLR Scenario = 1 meter
Sea Level Rise = 0.12 meter

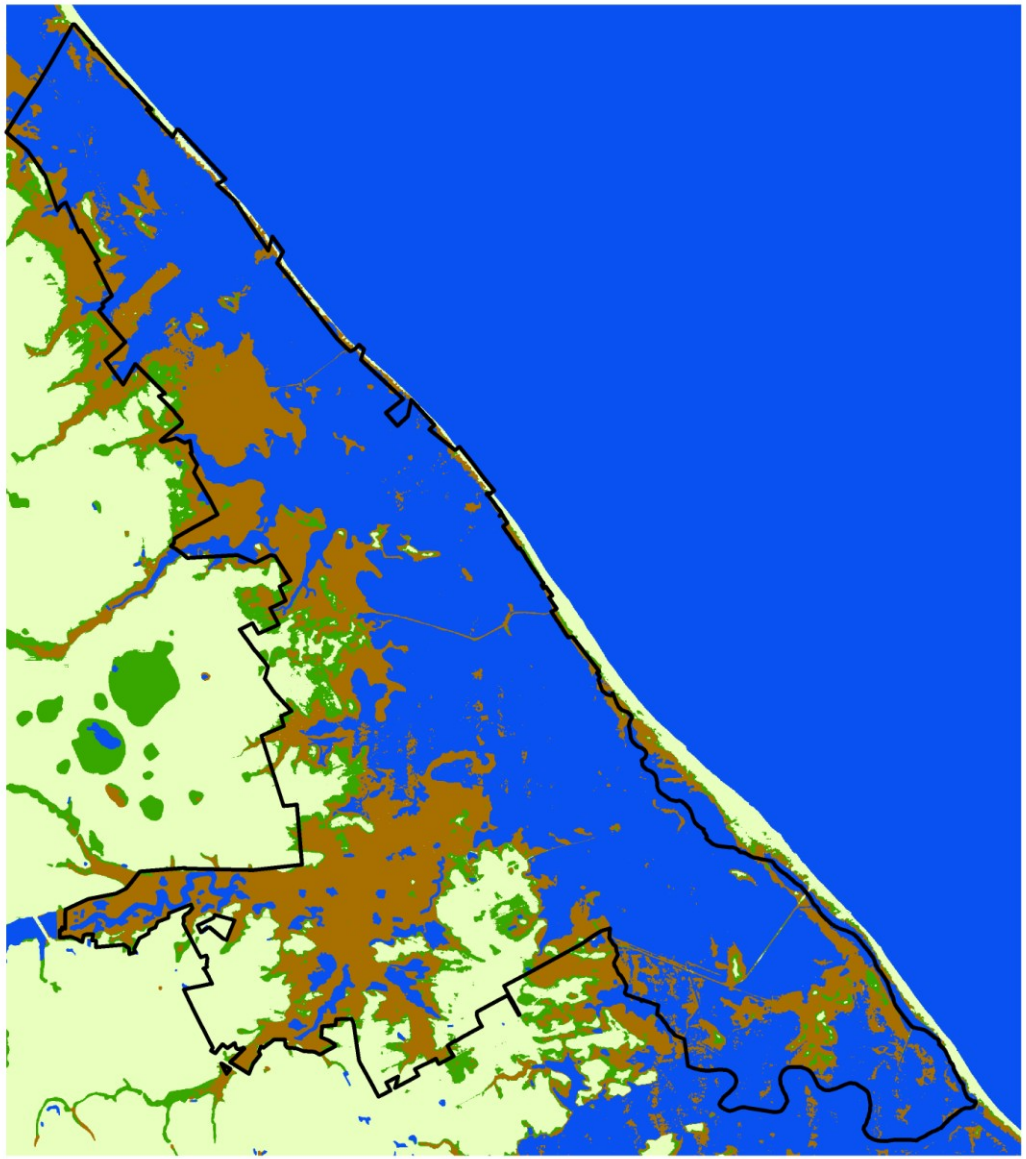
Accretion Rate = 3.1 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2050
SLR Scenario = 1 meter
Sea Level Rise = 0.39 meter

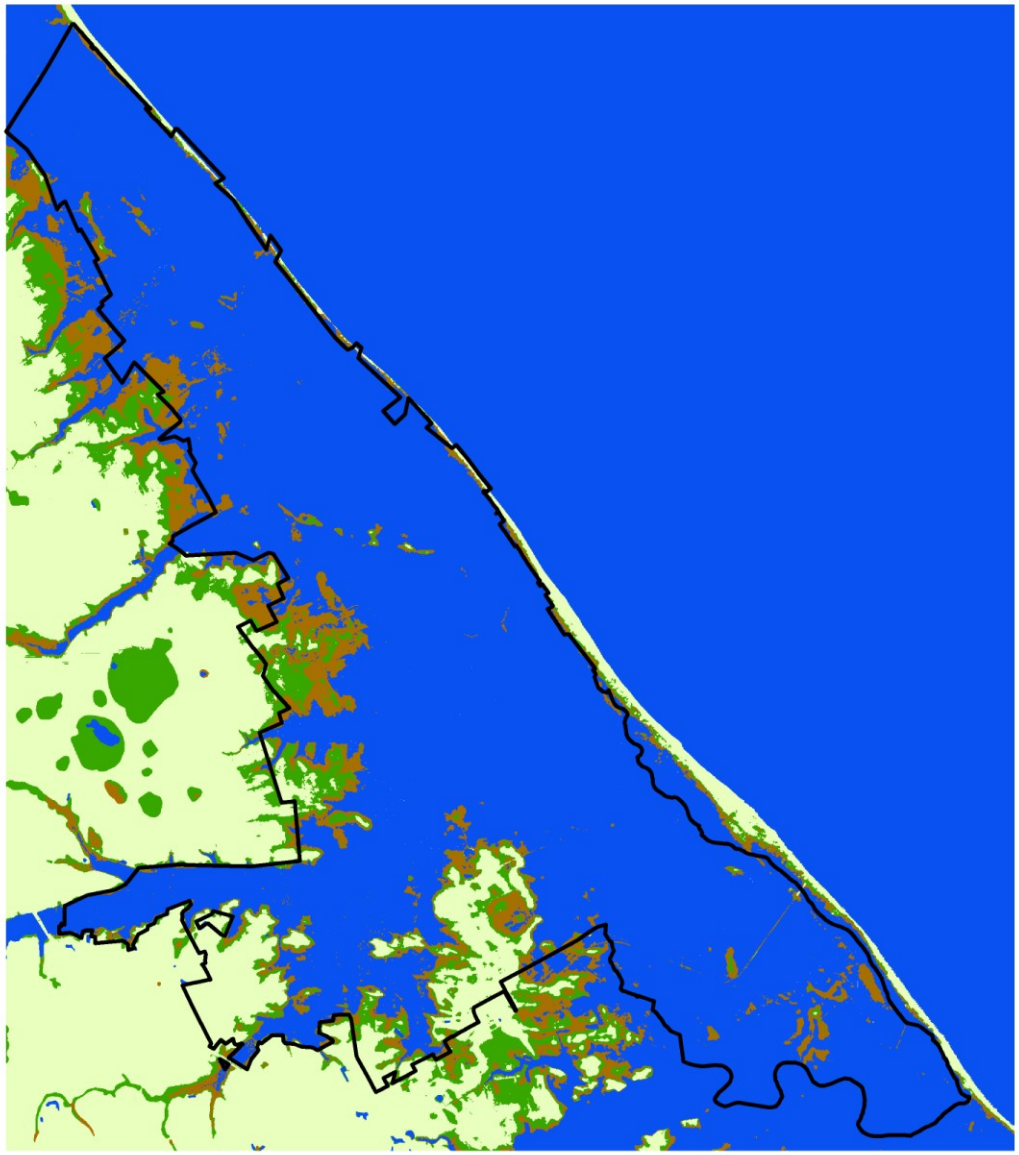
Accretion Rate = 3.1 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2075
SLR Scenario = 1 meter
Sea Level Rise = 0.72 meter

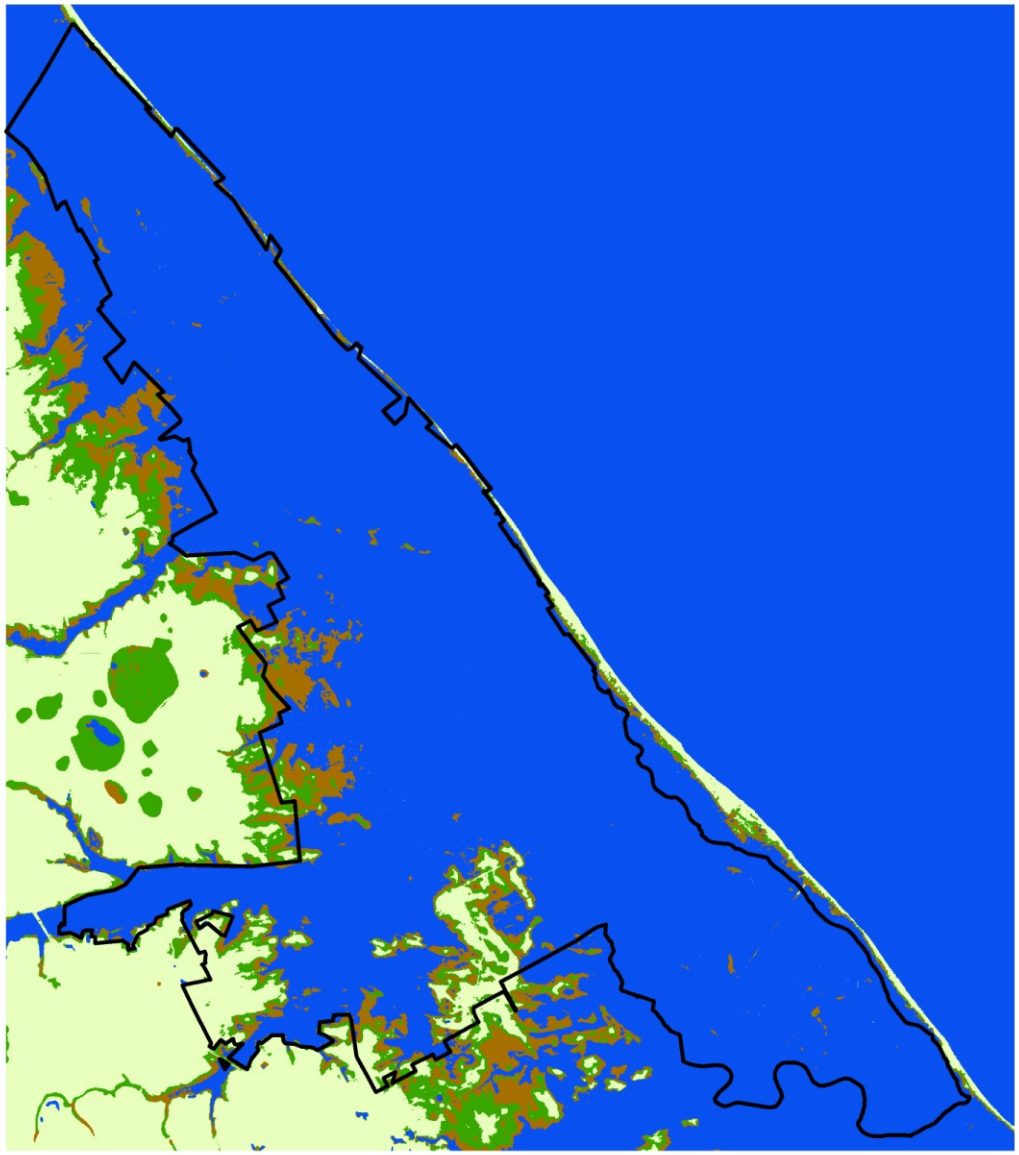
Accretion Rate = 3.1 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
W E
S

0 0.5 1 2 3
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2100
SLR Scenario = 1 meter
Sea Level Rise = 1.06 meter

Accretion Rate = 3.1 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

N
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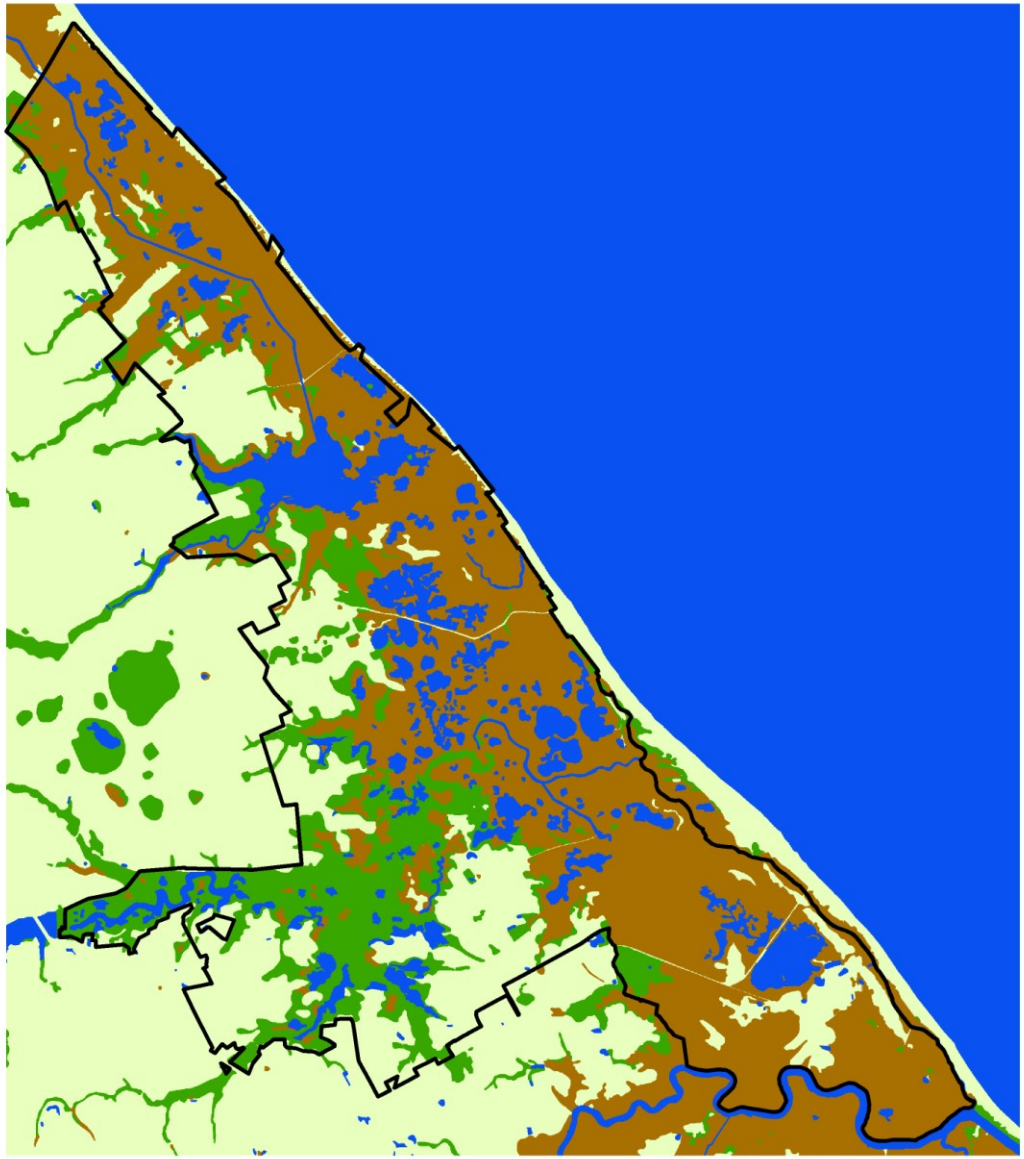
0 0.5 1 2 3
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2007
SLR Scenario = 1 meter
Sea Level Rise = 0.00 meter

Accretion Rate = 3.1 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

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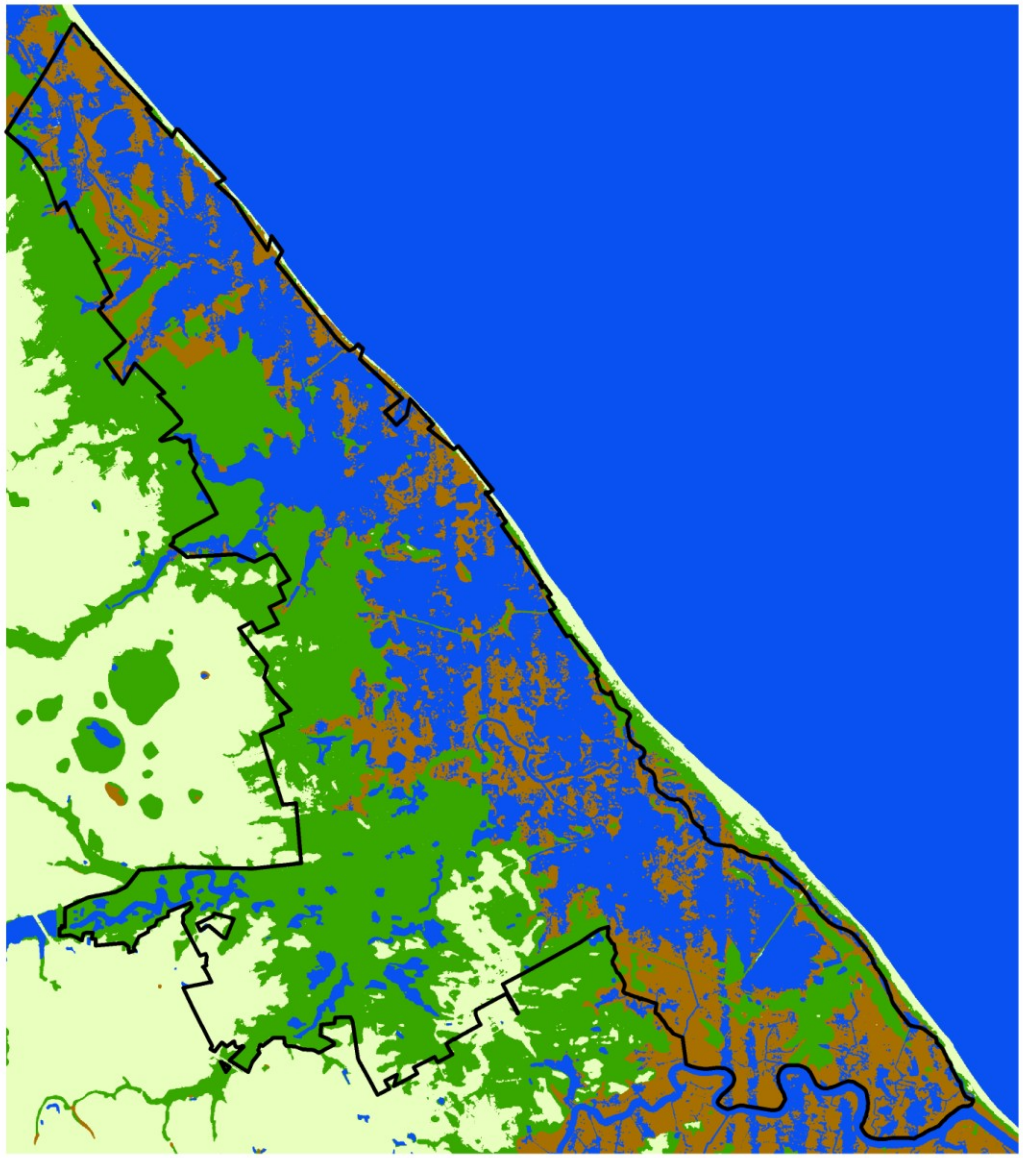
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2025
SLR Scenario = 1 meter
Sea Level Rise = 0.12 meter

Accretion Rate = 3.1 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

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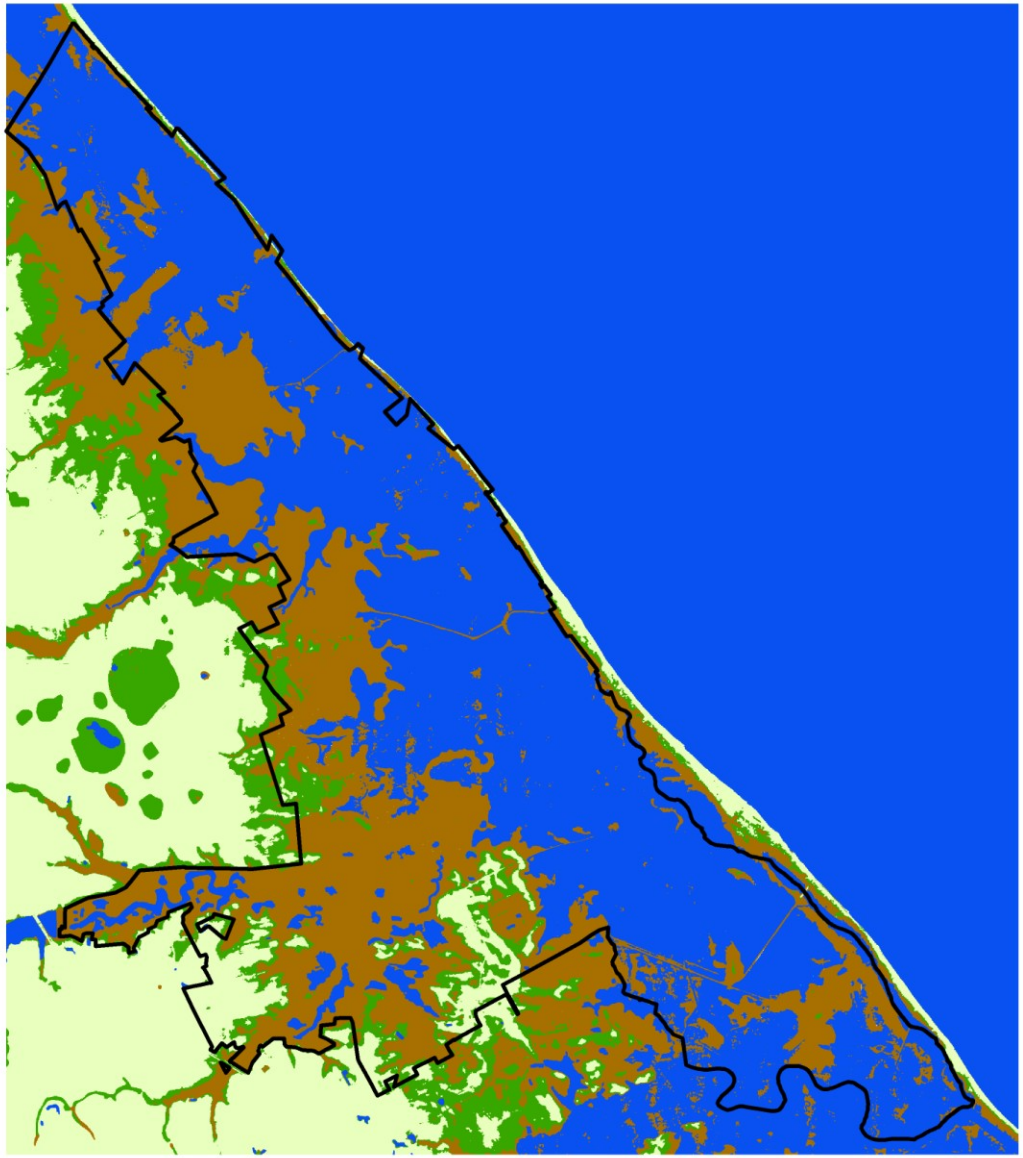
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2050
SLR Scenario = 1 meter
Sea Level Rise = 0.39 meter

Accretion Rate = 3.1 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

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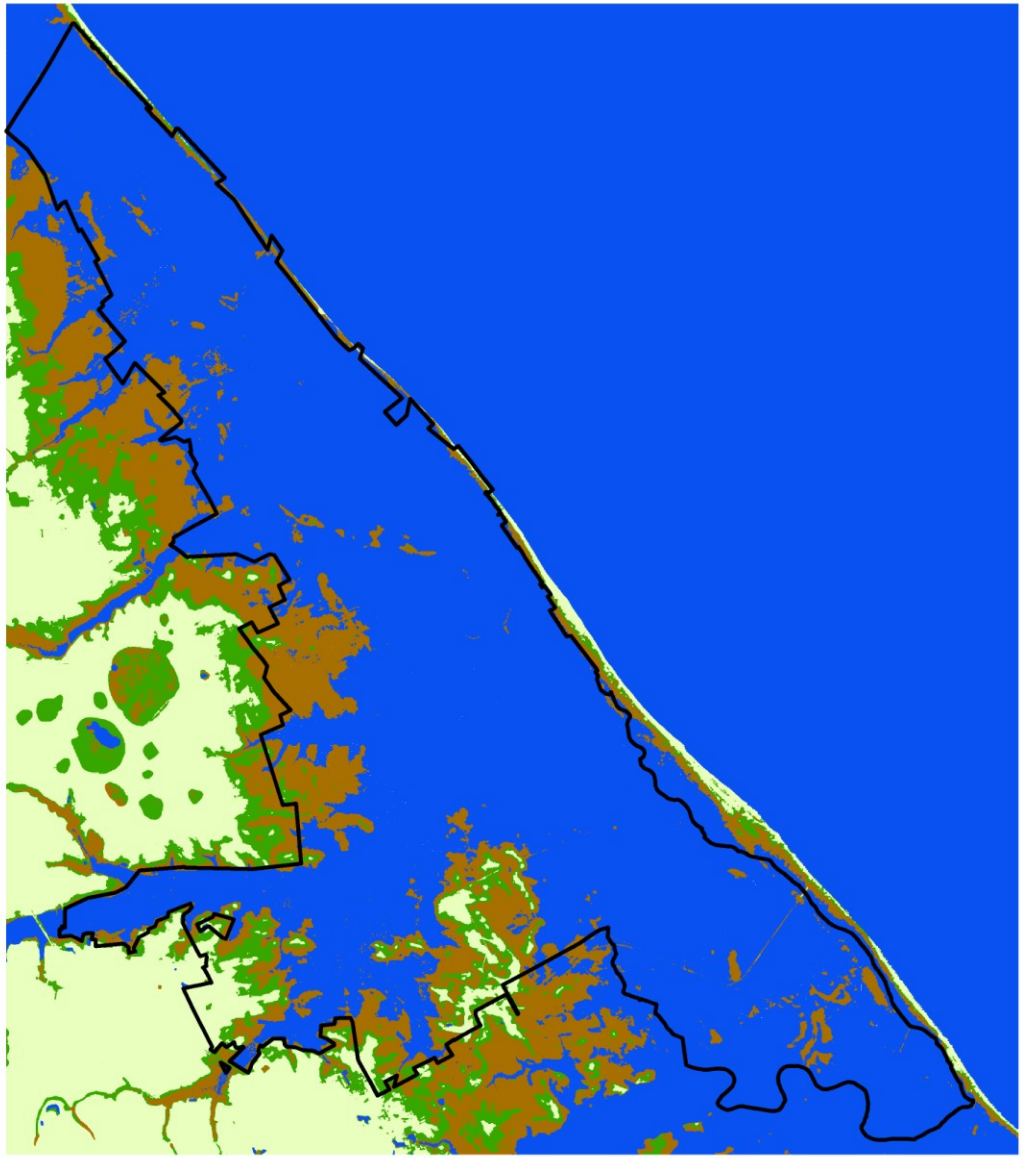
Miles

DELAWARE COASTAL PROGRAMS
DCMP



Prime Hook NWR SLAMM Output

Year = 2075
SLR Scenario = 1 meter
Sea Level Rise = 0.72 meter

Accretion Rate = 3.1 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

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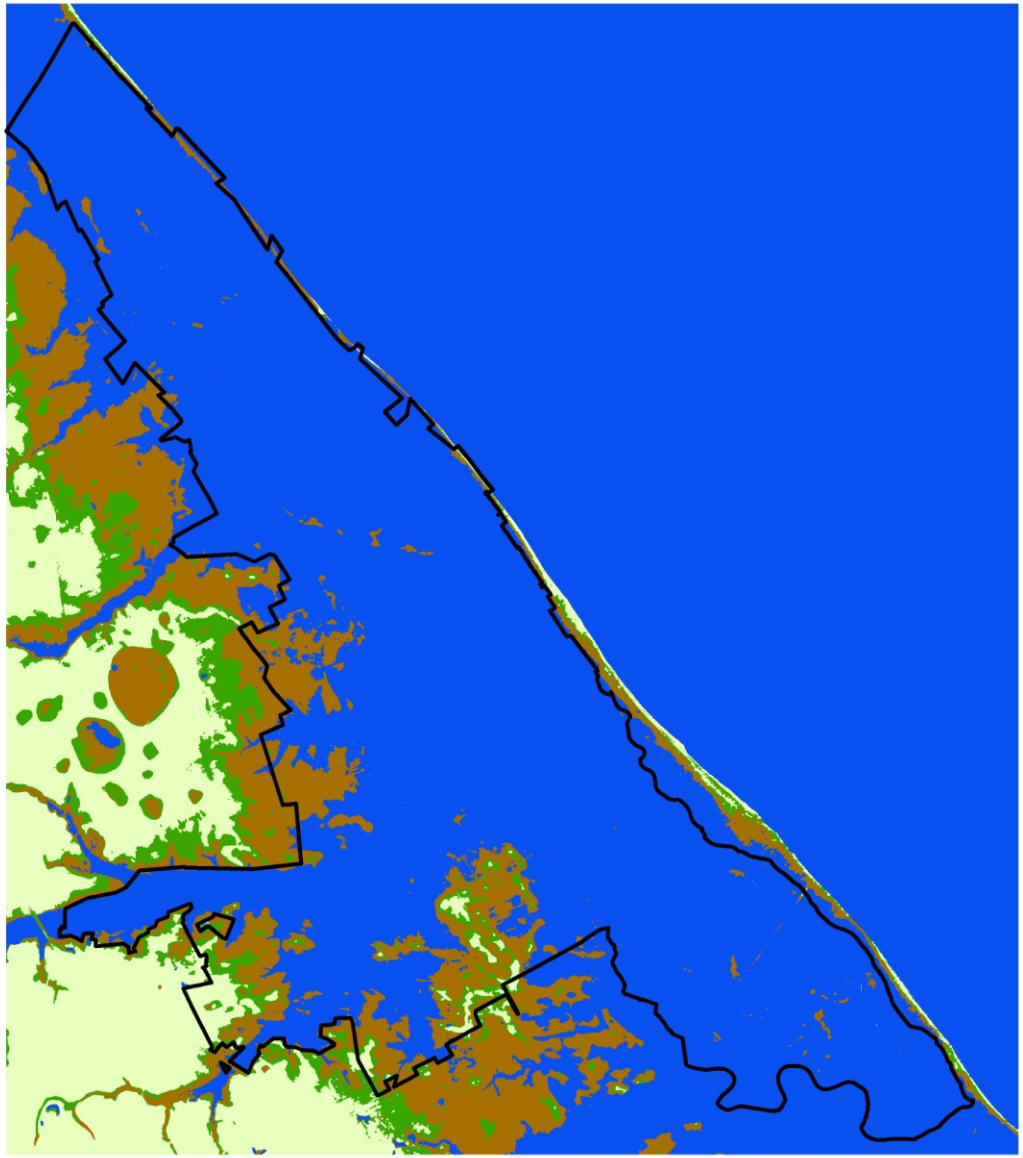
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2100
SLR Scenario = 1 meter
Sea Level Rise = 1.06 meter

Accretion Rate = 3.1 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

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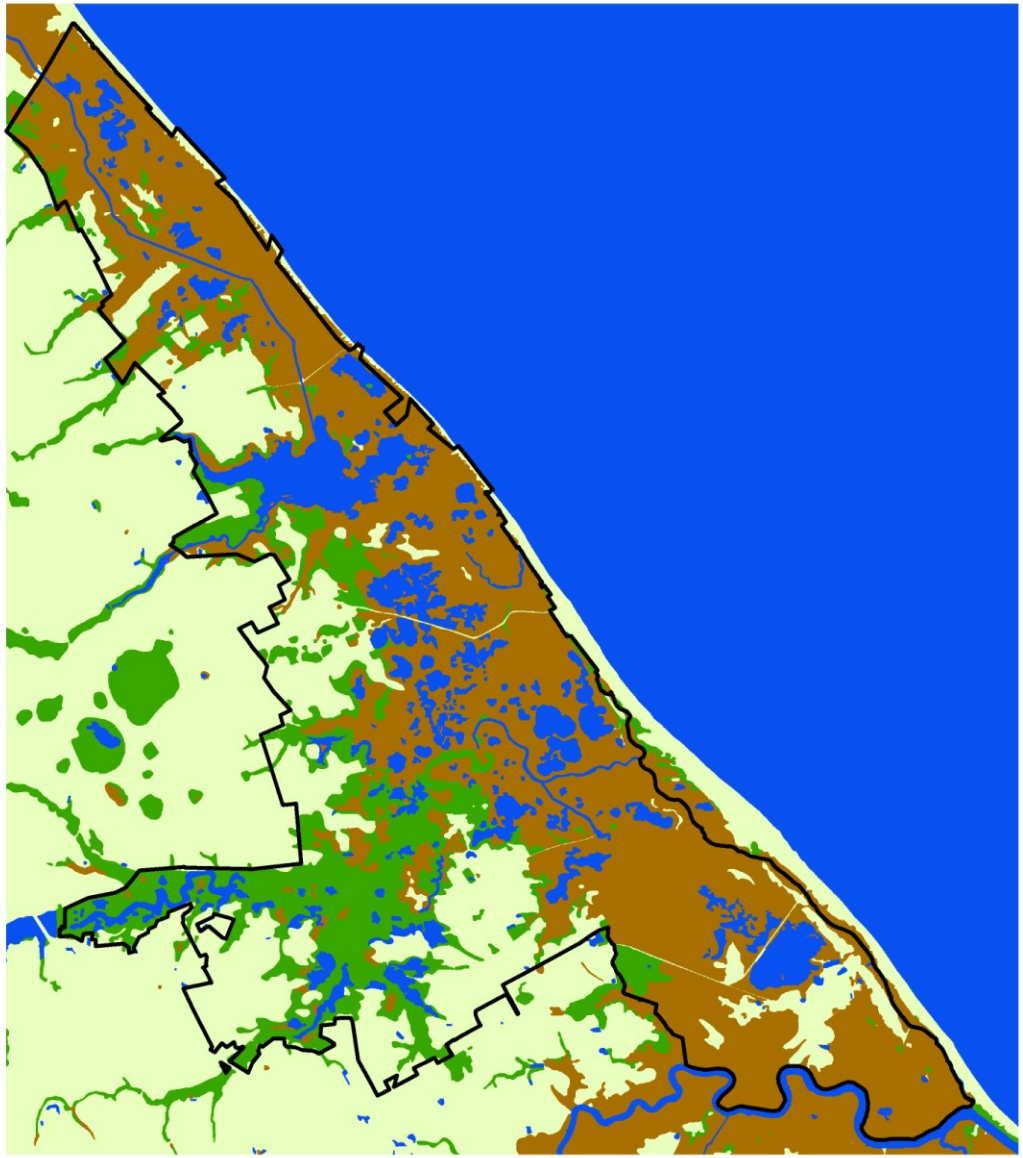
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2007
SLR Scenario = 1 meter
Sea Level Rise = 0.00 meter

Accretion Rate = 10.0 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

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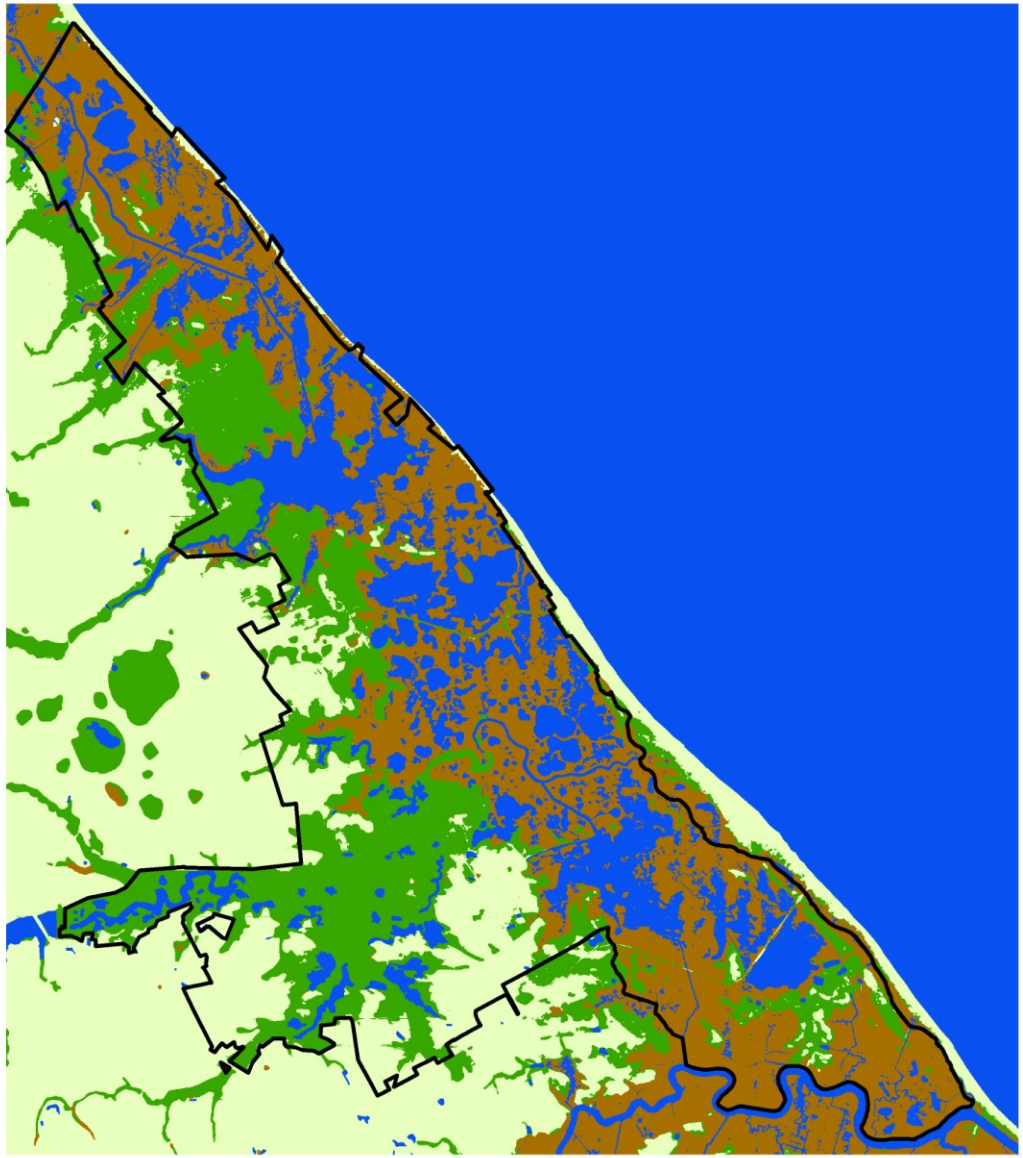
Miles

Delaware Coastal Programs
DCMP



Prime Hook NWR SLAMM Output

Year = 2025
SLR Scenario = 1 meter
Sea Level Rise = 0.12 meter

Accretion Rate = 10.0 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
- Uplands
- Forested Wetlands/Scrub Shrub
- Marsh
- Open Water/Tidal Mud Flats

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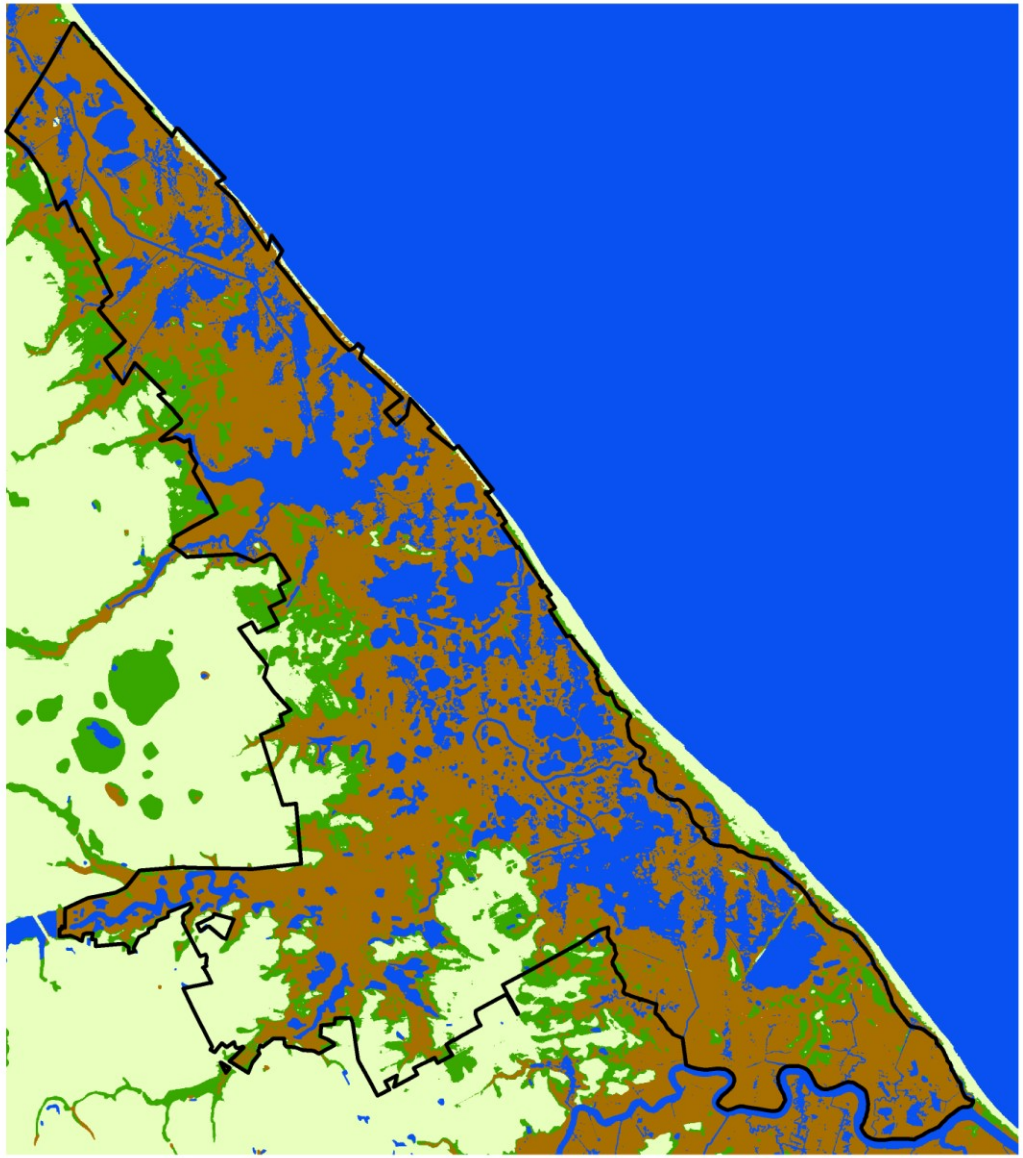

Prime Hook NWR SLAMM Output

Year = 2050
SLR Scenario = 1 meter
Sea Level Rise = 0.39 meter

Accretion Rate = 10.0 mm/yr
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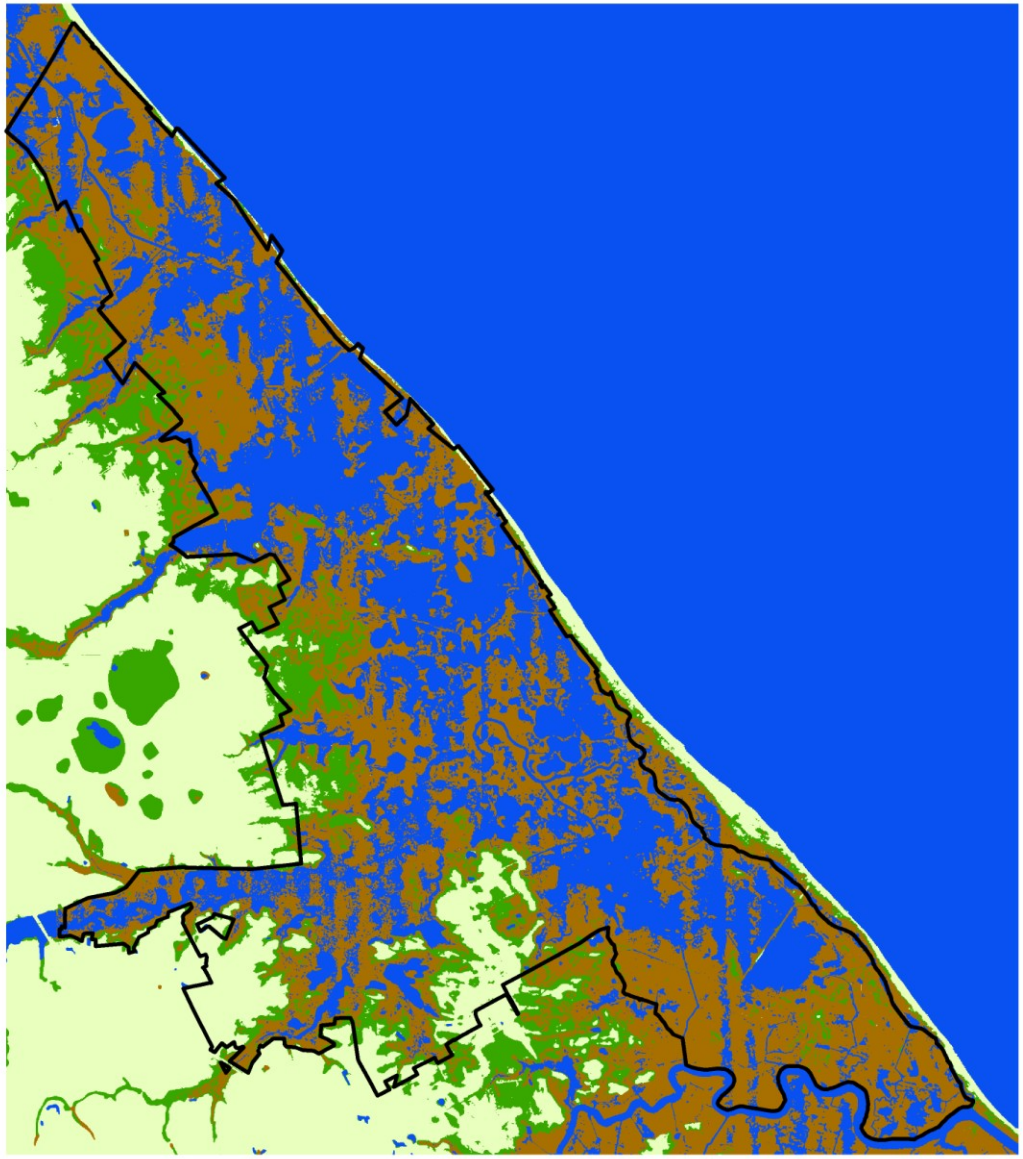

Prime Hook NWR SLAMM Output

Year = 2075
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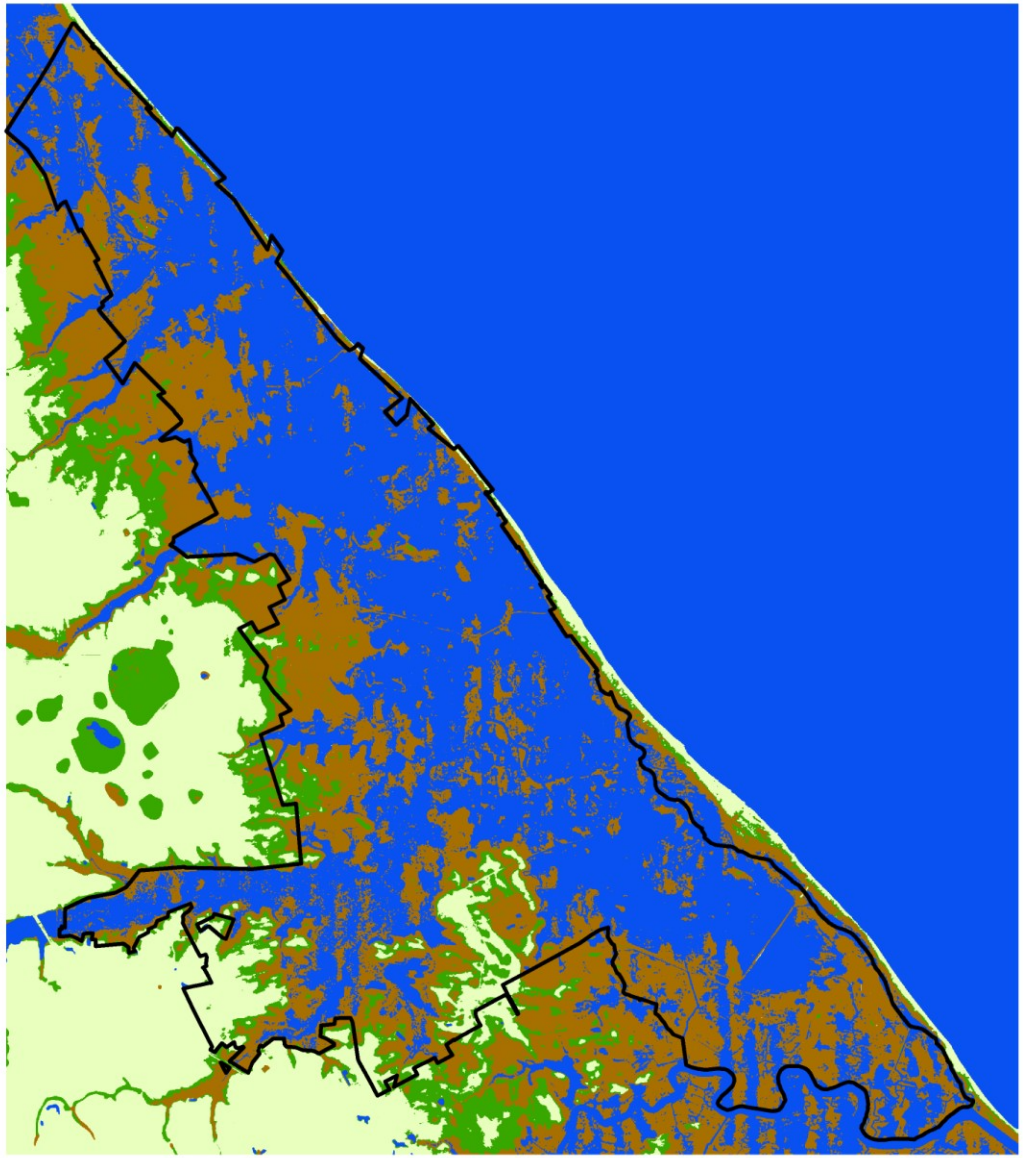

Prime Hook NWR SLAMM Output

Year = 2100
SLR Scenario = 1 meter
Sea Level Rise = 1.06 meter

Accretion Rate = 10.0 mm/yr
Inland Tide = 50% Coastal Tide

- NWR Boundary
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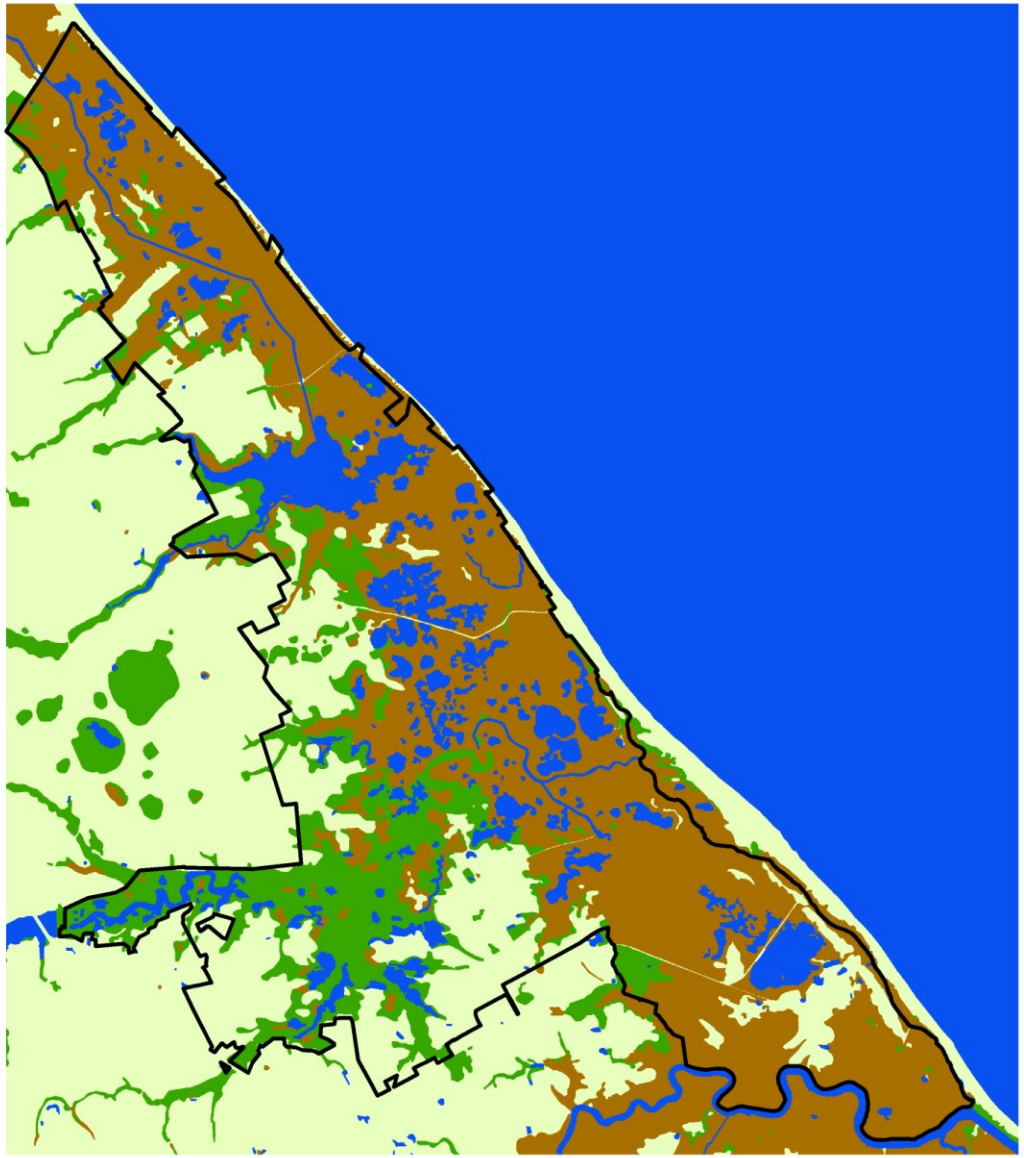

Prime Hook NWR SLAMM Output

Year = 2007
SLR Scenario = 1 meter
Sea Level Rise = 0.00 meter

Accretion Rate = 10.0 mm/yr
Inland Tide = 100% Coastal Tide

- NWR Boundary
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- Forested Wetlands/Scrub Shrub
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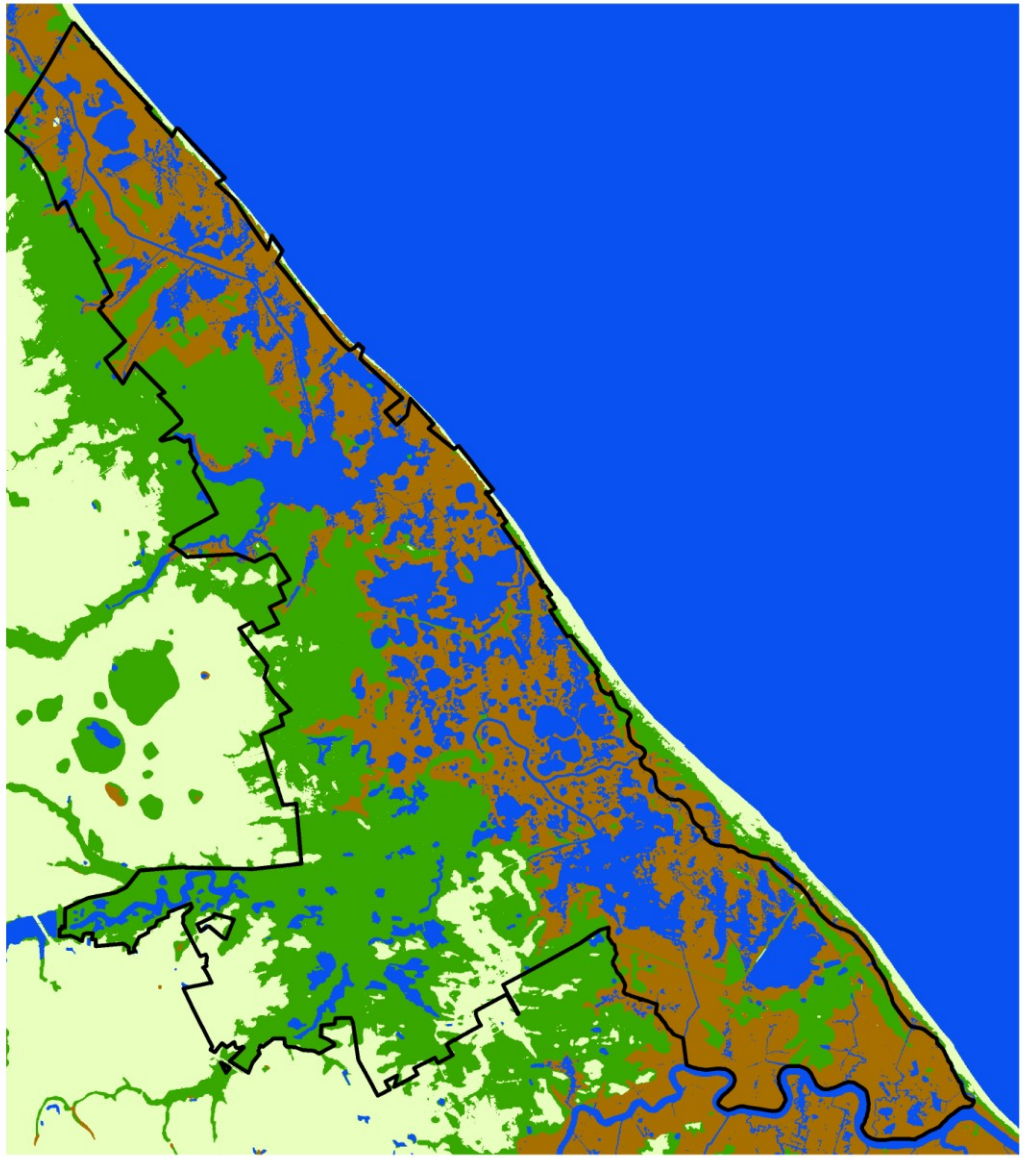

Prime Hook NWR SLAMM Output

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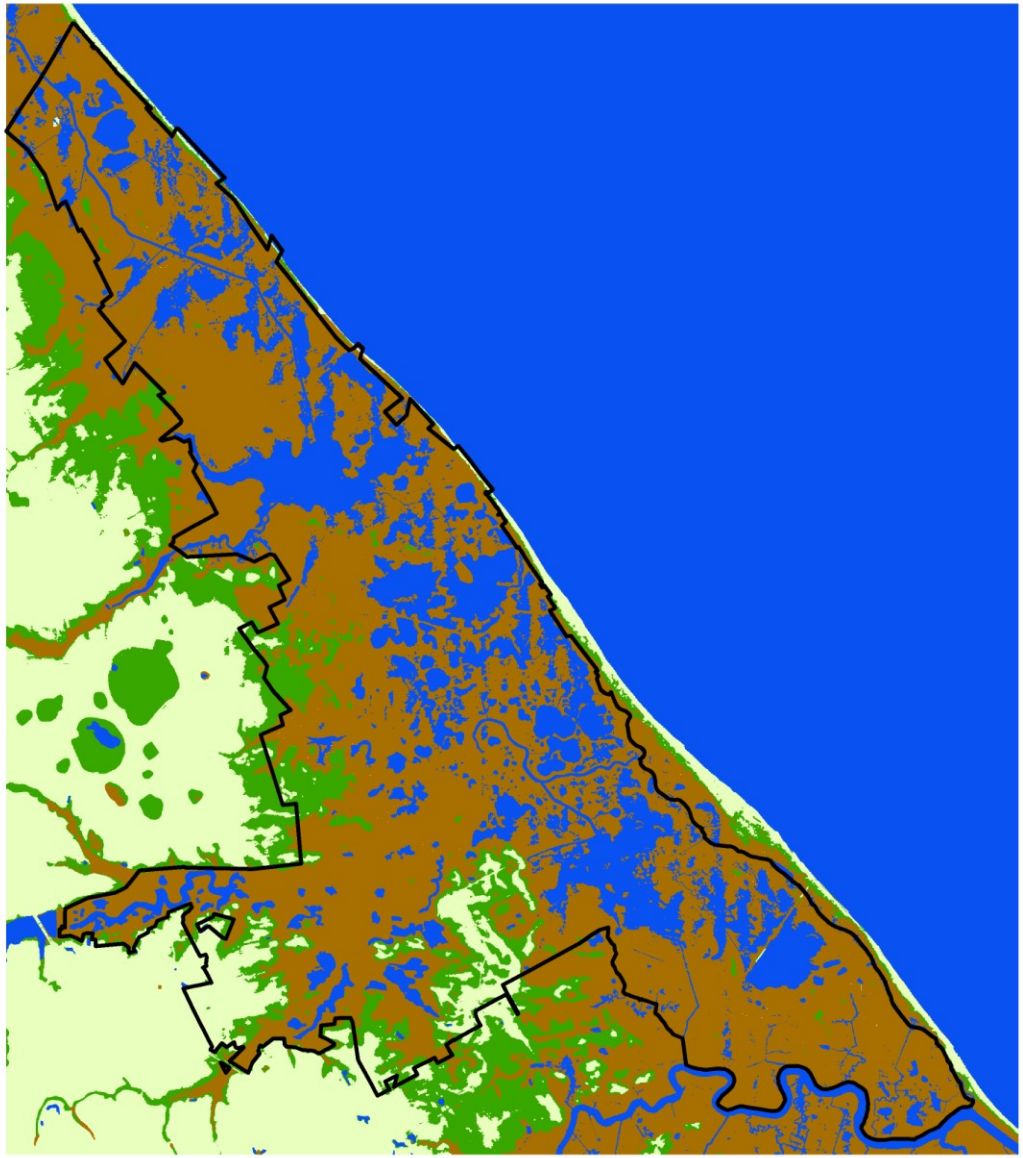

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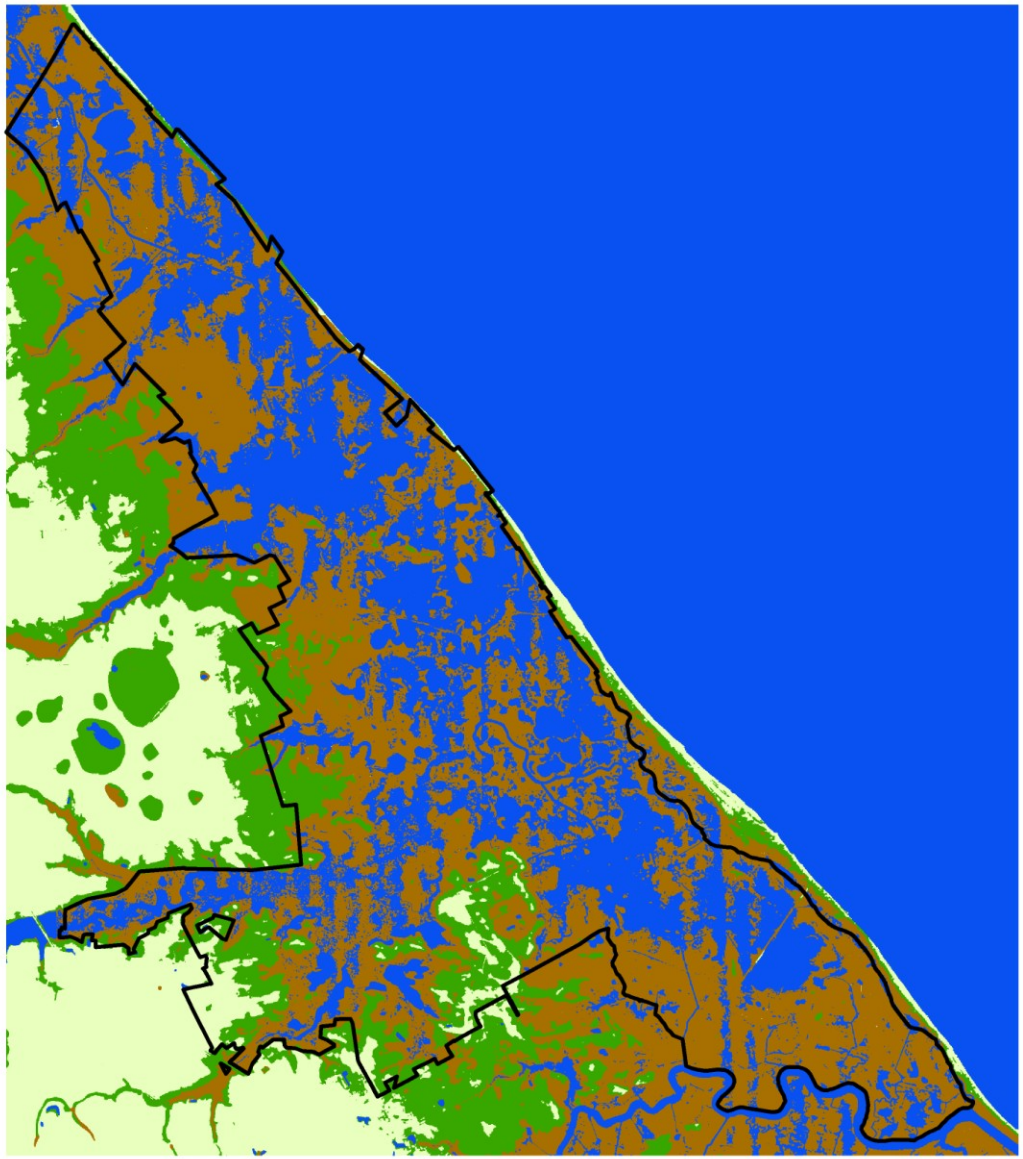

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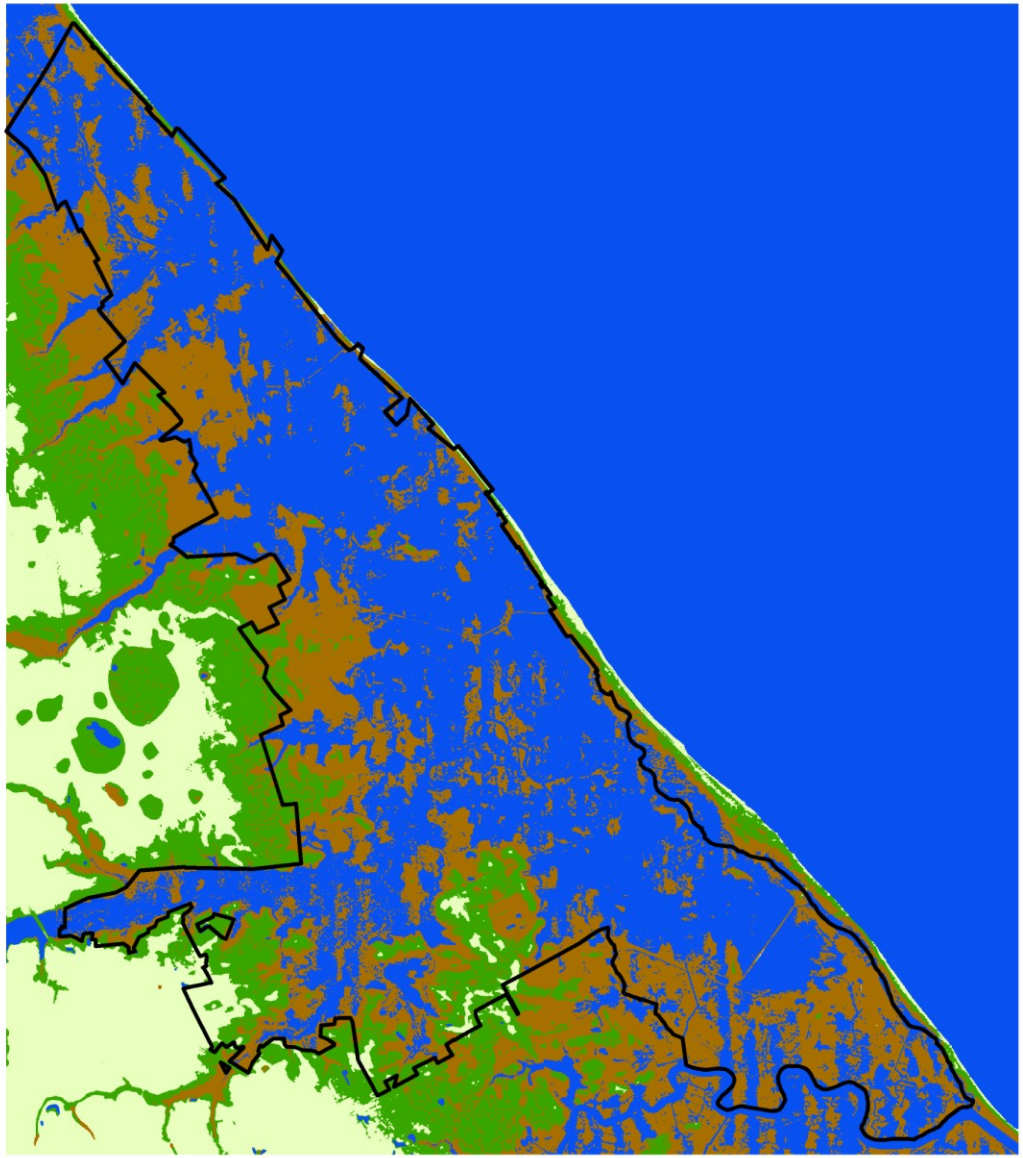

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N
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