Application of the Sea-Level Affecting Marshes Model to Coastal Maryland

EESLR 2019 Quantifying the benefits of natural and nature-based features in Maryland's Chesapeake and Atlantic Coastal Bays to inform conservation and management under future sea level rise scenarios.

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Acronyms and Abbreviations List

CBNERR	Chesapeake Bay National Estuarine Research Reserve
CoNED	USGS Coastal National Elevation Dataset
DEM	Digital Elevation Map
GIS	Geographic Information Systems
GWMP	George Washington Memorial Parkway
GT	Great Diurnal Tide Range
HTU	Half-Tide Units (highest tide each day minus the mean tide level)
IFM	Irregularly-Flooded Marsh
LiDAR	Light Detection and Ranging– method to produce elevation data
m	Meters
MHHW	Mean Higher High Water (average highest tide each day)
MLLW	Mean Lower Low Water (average lowest tide each day)
MTL	Mean Tide Level
NAVD88	North American Vertical Datum of 1988
NCR	National Capital Region
NLD	National Levee Database from the U.S. Army Corps of Engineers
NOAA	United States National Oceanic and Atmospheric Administration
NPS	(US) National Park Service
NWI	National Wetlands Inventory
NWR	(US) National Wildlife Refuge
RFM	Regularly-Flooded Marsh
RMSE	Root Mean Standard Error
SERC	Smithsonian Environmental Research Center
SET	Surface Elevation Table
SLAMM	Sea-level Affecting Marshes Model
SLR	Sea-Level Rise
UMD	University of Maryland
USGS	United States Geological Survey
VCR/LTER	Virginia Coast Reserve Long-Term Ecological Research
VCU	Virginia Commonwealth University
VDATUM	NOAA Product for converting vertical datums
VIMS	Virginia Institute for Marine Science
WBE	Wetland Boundary Elevation (coastal-wetland to dry land boundary)

1 Background

This application of the Sea-Level Affecting Marshes Model (SLAMM) is part of a project titled: "EESLR 2019: Quantifying the benefits of natural and nature-based features in Maryland's Chesapeake and Atlantic Coastal Bays to inform conservation and management under future sea level rise scenarios." This NOAA funded project was carried out by George Mason University in partnership with The Nature Conservancy and the Maryland Department of Natural Resources. The goal of the project is to quantify the wave attenuation and flood reduction benefits of marshes, Submerged Aquatic Vegetation (SAV) and other natural and nature-based features (NNBF) along the shores of Maryland's Chesapeake and Atlantic Coastal Bays. Ultimately, the project will recommend specific conservation and ecosystem management actions (such as ecosystem restoration) to enhance coastal resiliency of ecosystems and human communities.

The Chesapeake Bay region has one of the highest rates of relative sea-level rise (SLR) in the U.S., due to a combination of rising waters and sinking land. Maryland is already dealing with impacts from one foot of SLR over the past century, and up to two additional feet of SLR is likely in the next 30 years. Fortunately, Maryland is also rich in habitats that can help mitigate the effects of SLR, including marshes and submerged aquatic vegetation (SAV).

SLAMM provides data useful to a range of project stakeholders by creating projections of the potential effects of accelerated sea-level rise on coastal ecosystems. Tidal marshes are dynamic ecosystems that provide significant ecological and economic value. Given that tidal marshes are located at the interface between land and water, they can be among the most susceptible ecosystems to climate change, especially accelerated sea-level rise (SLR). Numerous factors can affect marsh fate including the elevation of marshes relative to the tides, marshes' frequency of inundation, the salinity of flooding waters, the biomass of marsh platforms, land subsidence, marsh substrate, and the settling of suspended sediment into the marshes. Because of these factors, a simple calculation of current marsh elevations as compared to future projections of sea level does not provide an adequate estimation of wetland vulnerability. SLAMM is widely recognized as an effective model to study and predict wetland response to long-term sea-level rise (Park et al. 1991) and has been applied in every coastal US state (Clough et al. 2016; Craft et al. 2009; Galbraith et al. 2002; Glick et al. 2007, 2011; National Wildlife Federation and Florida Wildlife Federation 2006; Park et al. 1993; Propato et al. 2018; Titus et al. 1991).

2 Methods

2.1 Study Area

The study area was comprised of the portion of Maryland shown below. Some counties or partial counties with elevations over 5 meters (NAVD88) were excluded from this analysis.

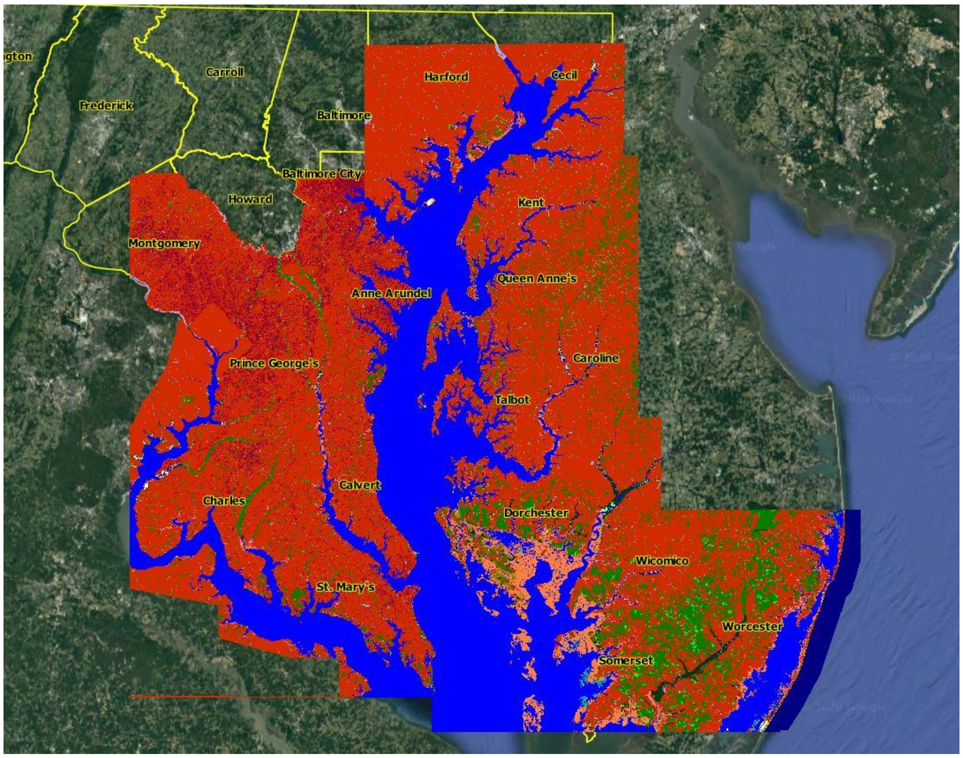


Figure 1. Study Area shown over satellite imagery

2.2 Input Raster Preparation

SLAMM is a raster-based model meaning that input cells are equally-sized squares arranged in a grid. The cell size used in this project was 10 meters by 10 meters. This section describes spatial data sources and the steps used to process the data for use in SLAMM. Data types reviewed here include elevation, wetland land cover, impervious land cover, dikes, and impoundments.

2.2.1 Elevation Data

High vertical-resolution elevation data may be the most important SLAMM data requirement. Elevation data when combined with tidal data are used to determine the extent and frequency of saltwater inundation.

The base dataset for this model application was the 2016 USGS CoNED Topobathymetric Model for Chesapeake Bay Region. This dataset compiles both topography and bathymetry in a single seamless 1m resolution elevation product. Some Maryland counties had more recent LiDAR that was used instead of the CoNED dataset. The counties (or named datasets) for which MD iMAP data were more recent were as follows (LiDAR map date in parentheses):

- Anne Arundel (2017)
- Baltimore (2015)
- Baltimore City (2015)
- Calvert (2017)
- Cecil (2013)
- Harford (2013)
- Montgomery (2018)
- Prince Georges (2014)
- Queen Annes (2013)
- Worcester (2011)

For the counties listed above, 10M DEMs were created by weighted-averaging the smaller-cell-size DEM data over the 10M cells. Areas from MD iMAP that had been hydroflattened (water elevations that were replaced with a flat surface) were overwritten using the bathymetry of the CoNED data. The resulting dataset is a seamless topography and bathymetry dataset for the entirety of coastal Maryland (Figure 2).

There were no high-quality elevation data available over Aberdeen Proving Ground, so model results in this region are subject to considerably more uncertainty. The SLAMM elevation pre-processor was used to estimate wetland elevations in this portion of the study area based on observed wetland elevations and their relationship to tide ranges in adjacent wetlands.

Slope Layer. Slope rasters were derived from the DEMs described above using QGIS software (QGIS version 3.10.11-A Coruña.). Slopes of the marsh surface are used in the calculation of the fraction of a wetland that is lost (transferred to the next class).

Figure 2. LiDAR data from MD iMAP, USGS CONED.
Note, no LiDAR data were available for Aberdeen Proving Ground (yellow boundary at top)

2.2.2 Elevation transformation

An elevation datum correction is required to convert data in NAVD88 to a tidal datum to estimate the frequency of flooding in each cell. A spatial map of datum correction was derived from VDATUM (NOAA's vertical transformation version 4.1.1) and was converted to 10-m rasters in units of "NAVD minus MTL in meters." No-data areas were extrapolated using the nearest cell with VDATUM coverage.

Open water in the Blackwater National Refuge was not covered by the VDATUM model. Due to the partial impoundment of water in this area, the interpolation of VDATUM results was replaced with updated data (Hensel and Allen 2008). These data are uncertain as they are based on individual GPS observations and the error bounds of the instrumentation are comparable to the range of measured values (Hensel and Allen 2008). However, these measured data were considered superior to an interpolation of the VDATUM model and significantly improved "time zero calibration" of the Blackwater region.

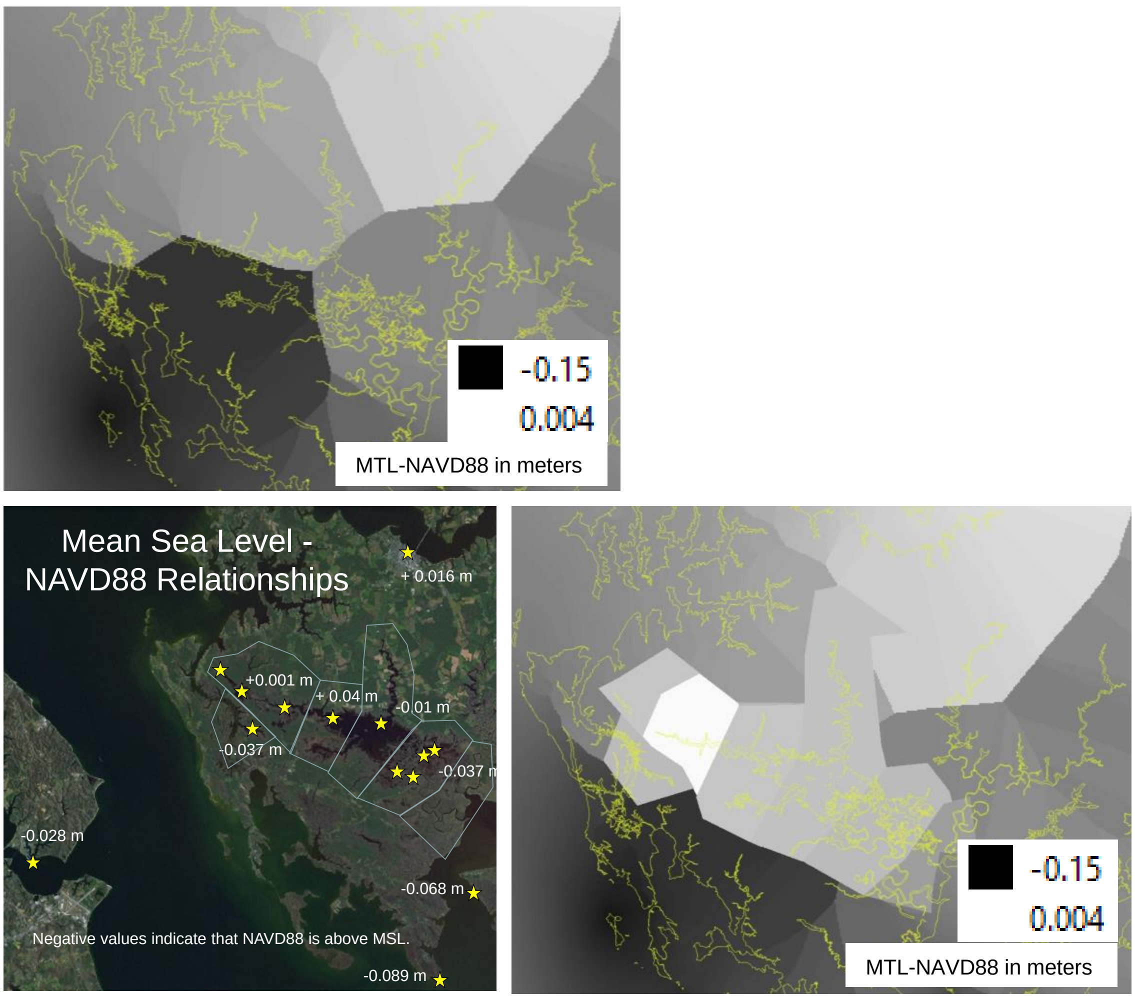


Figure 3. Original MTL-NAVD88 interpolation (top) and corrections based on (Hensel and Allen 2008)

2.2.3 Wetland Layers and translation to SLAMM

The wetland layer used to drive the SLAMM modeling is the "time-zero" result derived within SLAMM from multiple data sources and some site-specific model calibration. The resulting layer is an estimate of current-condition wetlands, dry lands, forested dry lands, and developed lands (based on percent impervious). The model result is based on several data sources and lines of evidence:

- Most current National Wetland Inventory data resampled to 10 M raster cells and converted into SLAMM classes. See Appendix A for information about this conversion.
- Tidal Cypress swamp coverage was determined using MDDNR/Wildlife & Heritage Service spatial data for tidal cypress (Unpublished, Maryland DNR 2021)
- The extent of developed-dry land was determined using Chesapeake Conservancy 2013/2014 MD Land Use Data as discussed in section 2.2.6 below.
- Forested vs. non-forested information was provided by the University of Maryland 1-meter Tree Canopy data set (University of Maryland 2011) converted into 10 M raster cells.
- Elevation data sets and tide-range layers as detailed above.
- The SLAMM conceptual model for wetlands as a function of frequency of inundation.
- A peer review of "time-zero" model results as provided by EESLR Marsh Modeling workgroup.

Since dry land (developed or undeveloped) is not classified by NWI, SLAMM classified cells as dry land if they were initially blank but had a positive elevation in the DEM. The resulting raster was checked visually to make sure the projection information is correct, has a consistent number of rows and columns as the other rasters in the project area, and to ensure that the data looked complete based on the source data. Table 1 shows the current land coverage for the entire study area.

Table 1. Land cover categories for Coastal MD study area*

Estuarine Open Water	35.4%
Non-forested Dry Land	34.7%
Forested Dry Land	11.2%
Developed Dry Land	9.0%
Non-Tidal Forested Wetland	4.6%
Irreg.-Flooded Marsh	1.0%
Inland Open Water	1.0%
Tidal Forested Wetland	0.9%
Inland-Fresh Marsh	0.7%
Regularly-Flooded Marsh	0.6%
Trans. Salt Marsh	0.3%
Open Ocean	0.2%
Tidal Cypress Swamp	0.2%
Tidal-Fresh Marsh	0.1%
Inland Shore	0.1%
Tidal Flat	0.1%

*A table to identify SLAMM categories from the raster map codes is provided in Appendix B

2.2.4 Modified Habitat Transitions

The SLAMM 6.7 model has been modified to allow flexibility in terms of habitat names and the flow chart of transitions under sea-level rise. Through interactions with the MTAG Marsh Modeling Workgroup and EESLR project team, the standard SLAMM classes were modified. For example, the class Undeveloped Dry Lands was split into Forested Undeveloped Dry Land and Non-Forested Dry Land. Similarly, the habitat transitions (i.e. the switch in class that occurs when a class is inundated more frequently) were also modified from the standard the SLAMM 6.7 model.

Table 2. Habitat Transitions included in this application of SLAMM 6.7

Class (Initial)	**Class (Transition)**
Developed Dry Land	Flooded Developed Dry Land
Forested Undeveloped Dry Land	Transitional Salt Marsh
Non-Forested Undeveloped Dry Land	Irregularly Flooded Marsh
Non-Tidal Forested Wetland	Transitional Salt Marsh
Tidal Cypress Swamp	Flooded Cypress Swamp
Inland Fresh Marsh	Estuarine Open Water
Tidal Forested Wetland	Irregularly Flooded Marsh
Transitional Salt Marsh	Regularly Flooded Marsh
Irregularly Flooded Marsh	Regularly Flooded Marsh
Tidal Fresh Marsh	Partially Vegetated Flat
Regularly flooded Marsh	Partially Vegetated Flat
Estuarine Beach	Estuarine Open Water
Tidal Flat	Estuarine Open Water
Inland Open Water	Estuarine Open Water
Riverine Tidal	Estuarine Open Water

2.2.5 Dikes and Impoundments

Dike rasters were initially created using NWI data sources: All NWI wetland polygons with the "diked or impounded" attribute "h" were selected from the original NWI data layer and these lands were assumed to be permanently protected from flooding. This procedure has the potential to miss dry lands that are protected by dikes and seawalls as contemporary NWI data contains wetlands data only.

NWI wetland data were supplemented with data from the National Levee Database ("US Army Corps of Engineers National Levee Database." 2020). Based on a query of this database, additional levee areas were added in Prince Georges, Cecil, Worcester, and Baltimore counties.

In general, this SLAMM model application assumes that dikes and levees will be maintained under conditions of SLR. For the Deal Island waterfowl management area in Somerset County, an additional model layer was created that defined the perimeter of the dike and the height of the dike. Based on examination of the high-resolution DEM for Somerset County, and a survey report for the site (Maryland DNR and Ducks Unlimited 2013), the low elevation for the wall was assumed to be 0.85 meters above NAVD88 (2.8 feet.)

For Deal Island, the model then predicts saline penetration once the wall elevation is predicted to be overtopped once every 30 days. At this point, the wall, as built, is not assumed to be an effective structure keeping coastal water out of the marshes there. As a note, this is not a prediction of "wall failure" as this would require an engineering model with higher spatial resolution and consideration of building techniques. The SLAMM model found that coastal water overtopping and saline intrusion will regularly occur by 2040 for the 50% SLR scenarios and by 2030 for the more aggressive scenarios.

2.2.6 Percent Impervious

An impervious layer was derived from the Chesapeake Conservancy 1-meter 2013/2014 MD Land Use Data dataset (https://www.chesapeakeconservancy.org/conservation-innovation-center/high-resolution-data/land-use-data-project/). These data were in raster format and were scaled up to 10 meters which is the cell size of this SLAMM simulation. SLAMM cells that were more than 25% impervious and that are not regularly flooded were designated as "developed dry lands." Developed dry lands that are estimated to be flooded at least once every 30 days were designated as "flooded developed dry land."

2.3 Model Timesteps

SLAMM simulations were run from 2010, the newest initial wetland cover layer, to 2100 with decadal model-solution time steps.

2.4 Sea Level Rise Scenarios

For model projections, six SLR scenarios were included from the year 2000 to the year 2100 (Figure 5). Each of the lines on Figure 5 represents a different SLR scenario, corresponding to one of the 2018 MD SLR Projections (Boesch et al. 2018).   Decadal estimates were produced by Robert Kopp for the

Cambridge MD tide gauge data (Table 4). The use of the Cambridge tide gauge statewide was recommended by the MD SLR Projections Advisory Group.

To summarize model results, shorthand names were produced for each of the SLR scenarios, e.g., "50% Paris." The first part corresponds to the likelihood of the scenario and the second part refers to the emissions pathways after 2050. The projections for relative sea-level rise in Maryland through 2050 are based on the Stabilized Emissions pathway. Beyond 2050, Boesch et al. 2018 provides projections for Growing (RCP8.5), Stabilized (RCP4.5), and Paris Agreement (RCP2.6) emission pathways. One SLR scenario, Upper Limit of Likely Range, is based on the high-end or maximum of a range, rather than a single percent likelihood. See Figure 4 for further explanation of the Upper Limit of Likely Range scenario. The 1%-Growing scenario represents the worst-case scenario modeled, and the 50%-Paris scenario represents the best-case scenario (Table 3).

Table 3. SLR scenarios modeled

Scenario Name	**Probability**	**Emissions Pathway after 2050**	**SLR by 2100 (m)**
50% Paris	50% probability SLR meets or exceeds estimated value	Paris Agreement (RCP2.6)	0.59
50% Stabilized	50% probability SLR meets or exceeds estimated value	Stabilized Emissions (RCP4.5)	0.71
50% Growing	50% probability SLR meets or exceeds estimated value	Growing Emissions (RCP8.5)	0.9
Upper Limit of Likely Range	high end or maximum of likely range of SLR	Growing Emissions (RCP8.5)	1.23
5% Growing	5% probability SLR meets or exceeds estimated value	Growing Emissions (RCP8.5)	1.51
1% Growing	1% probability SLR meets or exceeds estimated value	Growing Emissions (RCP8.5)	1.98

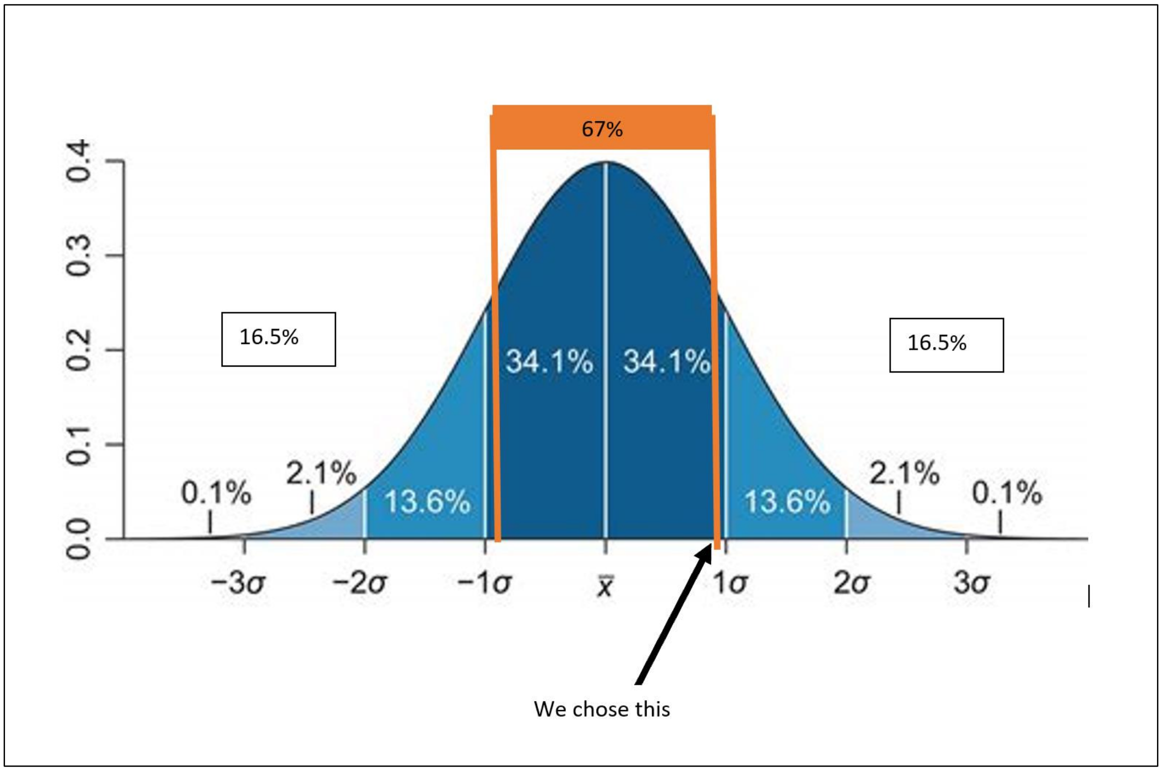


Figure 4. Upper Limit of Likely Range scenario.

The "likely range" is defined as the range which contains the central two thirds, or 67%, of the estimates of sea level rise, for a given emissions pathway. This range is centered on the mean and similar to the mean +/- one standard deviation (which would equate to 68% of estimates). We chose the high-end member of this 67% likelihood range, which corresponds to a 16.5% chance that SLR will meet or exceed that value

Table 4. Cambridge MD projections in meters of SLR above 2010 level

Year	50% Paris (m)	50% Stabilized (m)	50% Growing (m)	Upper Limit of Likely Range	5% Growing (m)	1% Growing (m)
2020	0.06	0.06	0.06	0.09	0.1	0.12
2030	0.13	0.13	0.13	0.18	0.22	0.26
2040	0.21	0.21	0.21	0.29	0.35	0.42
2050	0.31	0.31	0.31	0.42	0.5	0.59
2060	0.36	0.39	0.44	0.56	0.65	0.81
2070	0.42	0.47	0.55	0.71	0.84	1.05
2080	0.48	0.56	0.67	0.87	1.05	1.33
2090	0.54	0.63	0.79	1.05	1.28	1.65
2100	0.59	0.71	0.90	1.23	1.51	1.98

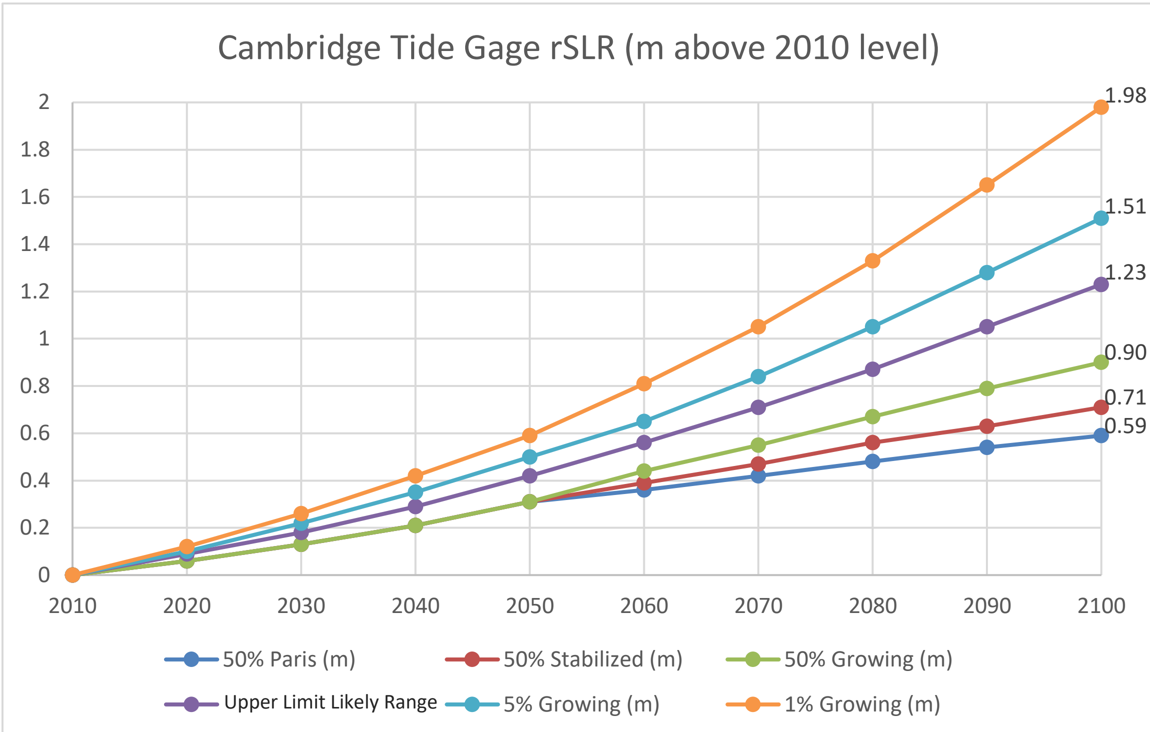


Figure 5. Sea Level Rise Scenarios.

2.5 Tide Ranges

Tide data (great-diurnal tide range or "GT," in meters) were derived from NOAA tide Gauges with published datums (Figure 6) augmented with NOAA tide tables (Figure 7), and were then averaged within polygons with similar tide ranges for input into SLAMM (Figure 8).

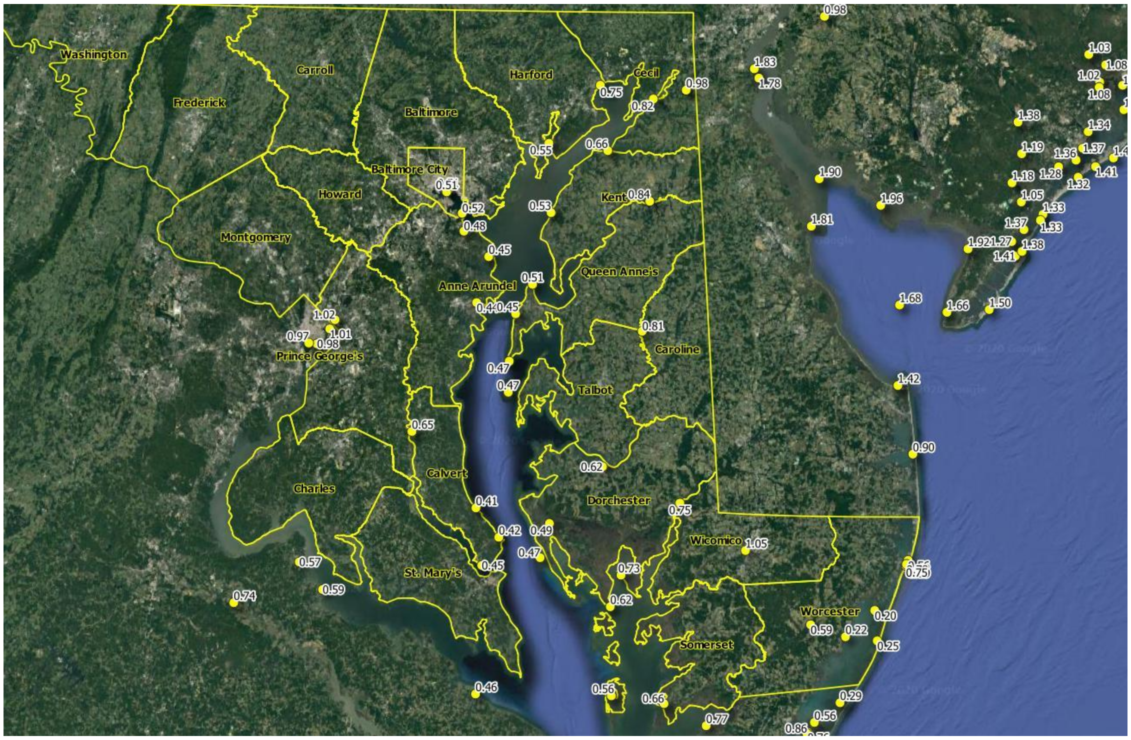


Figure 6. Great diurnal tide range (GT) in meters derived from NOAA tide gauges across the study area

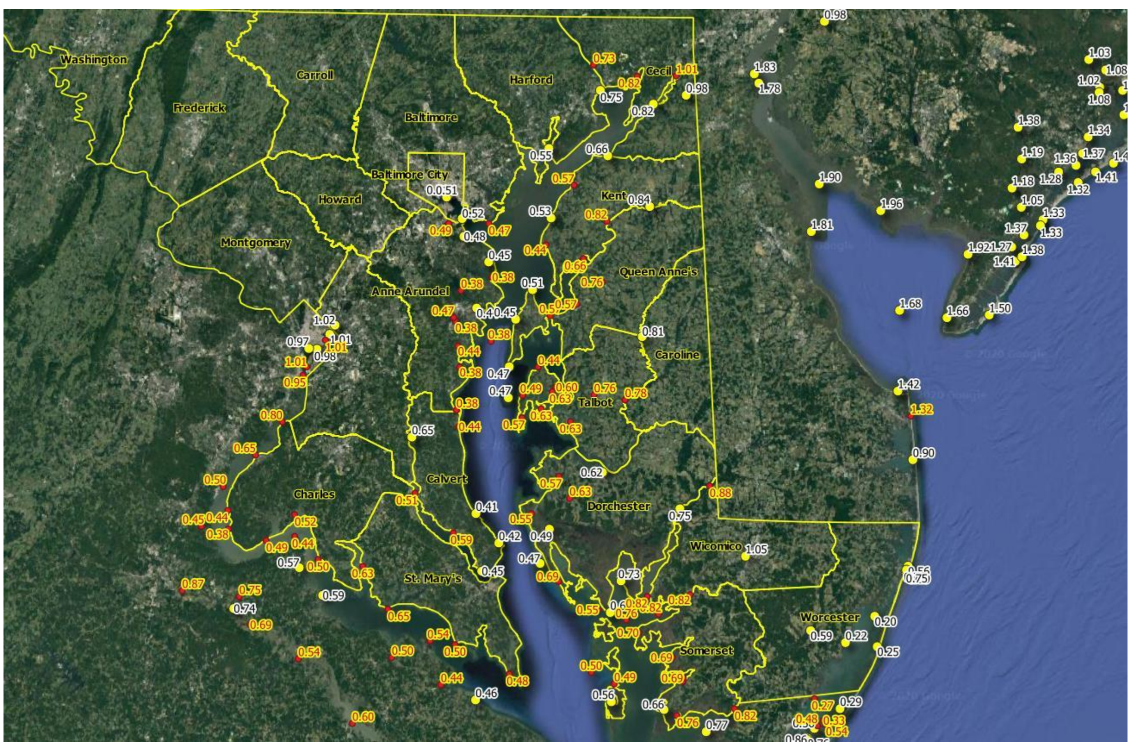


Figure 7. GT in meters from NOAA tide gauges supplemented with tide tables

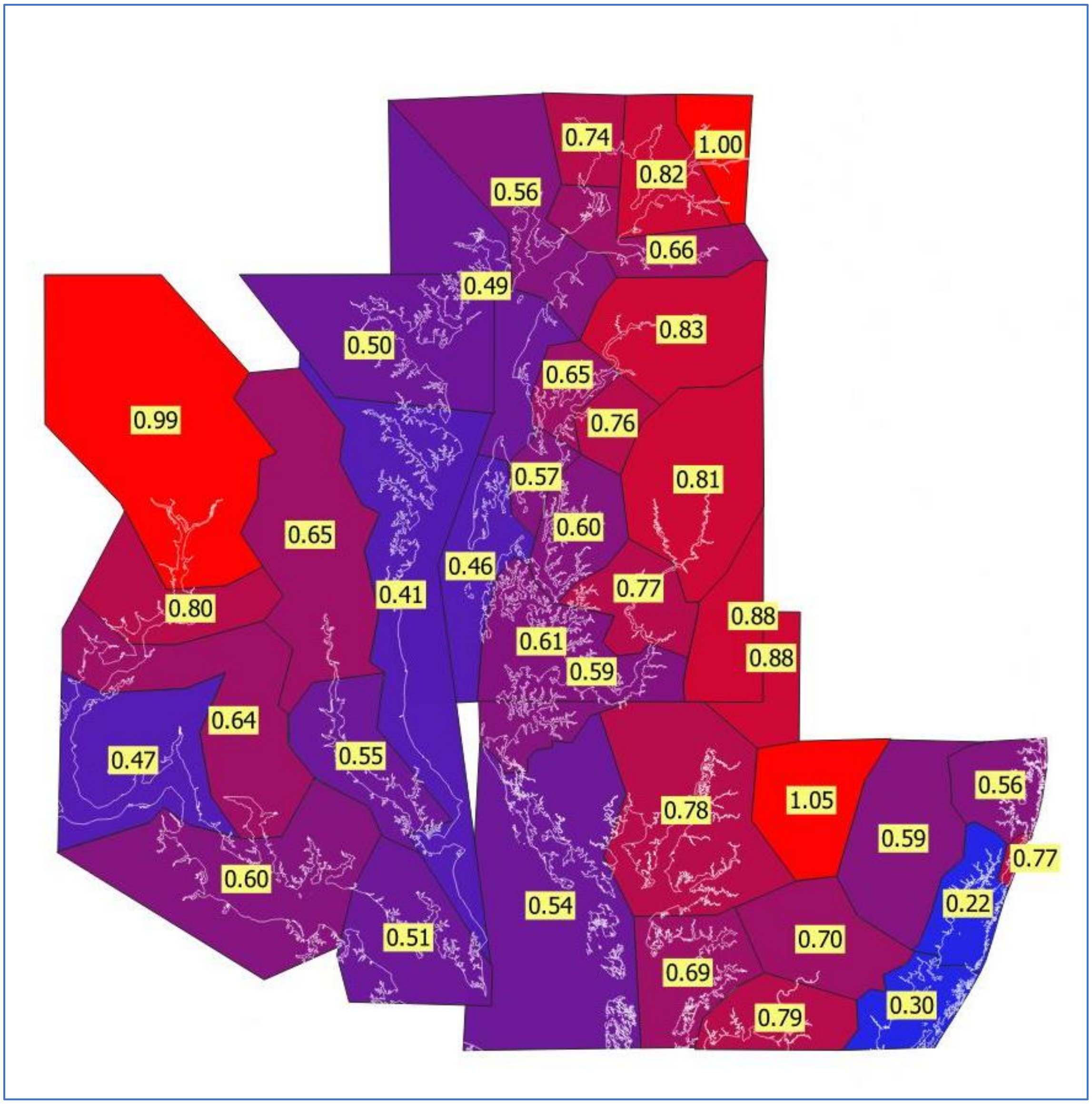


Figure 8. GT in meters as applied to polygons throughout the MD study area

Tide tables do not report GT but data reported can be translated with high precision. The regression presented below was developed from tide-table locations that also report GT as part of their tidal-datum data (Figure 9).

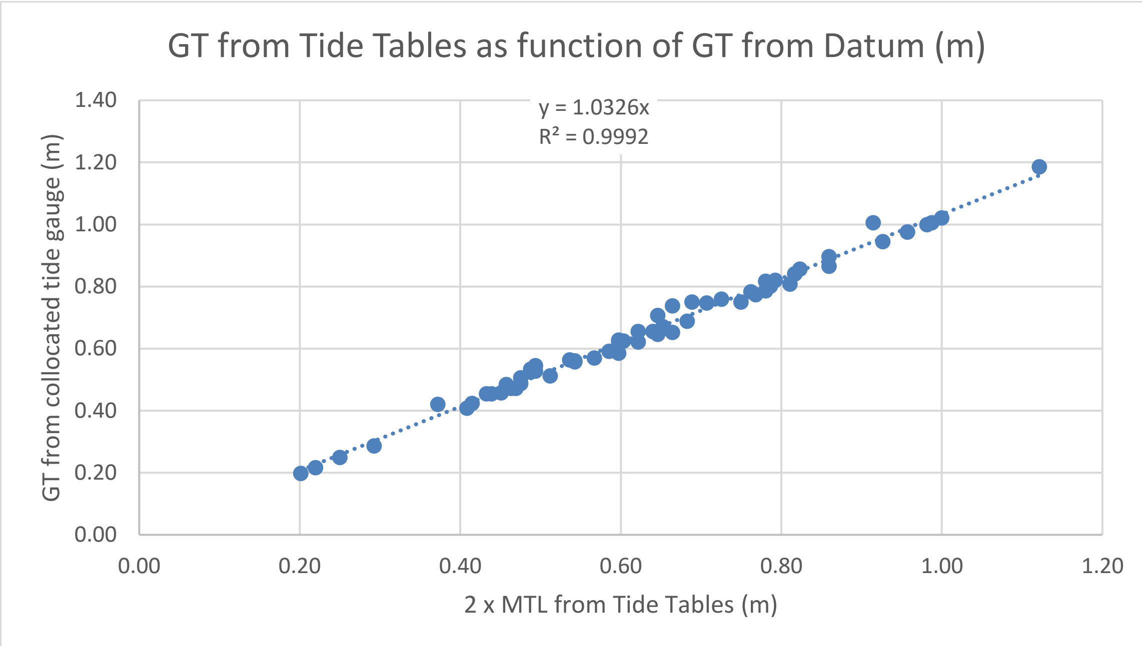


Figure 9. Regression used to estimate GT from NOAA tide-table data

2.5.1 Elevations expressed in half tide units (HTU)

In general, wetlands inhabit a range of vertical elevations that is a function of the tide range (Titus and Wang 2008) - one conceptual example of this is shown in Figure 10. Rather than expressing marsh elevation in absolute values (e.g. meters, feet, cm, etc.), SLAMM uses units relative to the local tide range or "half-tide units." A "half-tide unit" is defined as half of the great diurnal tide range (GT/2). A numerical example follows:

- If a marsh elevation is "X" meters above MTL, its elevation in half tide units (HTU) is given by X/(GT/2).
- This set of units is straightforward to understand if you consider that, mean tide level is defined as 0.0 HTU, high tide (MHHW) is defined as 1.0 HTU, and low tide (MLLW) is defined as -1.0 HTU. A marsh with an elevation above 1.0 HTU falls above the high tide line regardless the height of the tide.

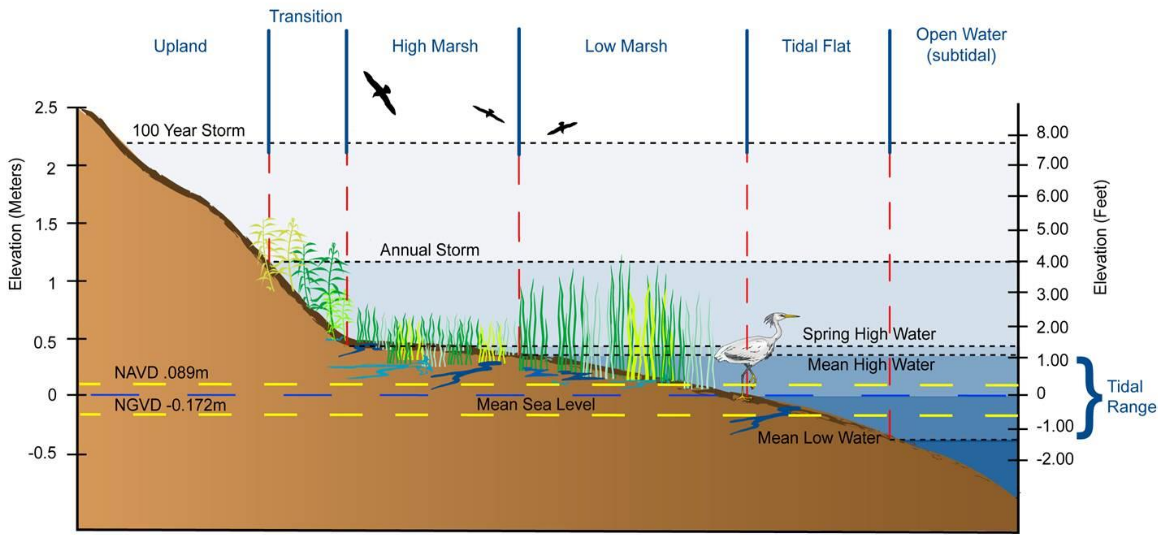


Figure 10. Relationship between tides, wetlands, and reference elevations for an example estuarine shore profile. Source (Titus and Wang 2008)

2.6 “Salt” Elevation

The “salt” elevation parameter in SLAMM (also known as the wetland boundary elevation) defines the boundary between coastal wetlands and dry lands (including non-tidal wetlands). This elevation, relative to mean-tide level, is determined through analysis of “higher high” water levels derived from NOAA observed water levels. In practice, the salt elevation, or the elevation that differentiates coastal wetlands and dry lands is approximately the height inundated once every 30 days.

To estimate the 30-day-inundation height on a site wide basis, a relationship to local tide range was created. First, the 30-day inundation level was determined for twelve locations in (or immediately adjacent to) the study area that had available NOAA-verified water-level observations. An additional data point was analyzed outside the study area Lewes MD to assist in modeling larger tide ranges within the study area. The 30-day inundation heights expressed as function of MHHW are summarized in Figure 11. This relationship was used to derive site-specific salt elevations based on the available local tide range (GT).

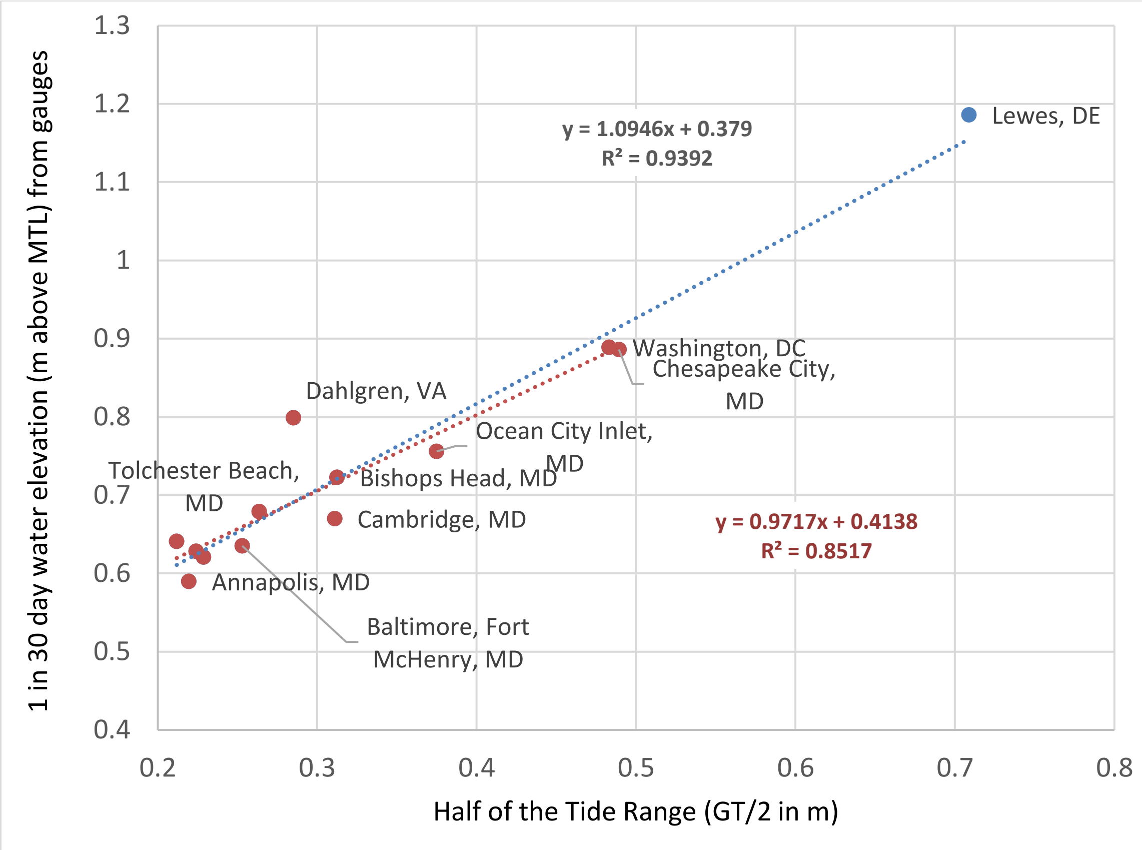


Figure 11. "Salt Elevation" derived as a function of tide range

2.7 Wetland Elevation-Change Rates

Local surface elevation table (SET) data were used to derive relationships between the rate of elevation change within wetlands and their frequency of inundation. SET data providers included the Chesapeake Bay National Estuarine Research Reserve, the National Park Service, the Smithsonian Environmental Research Center, the University of Maryland, the US Fish and Wildlife Service, and Virginia Coast Reserve Long-Term Ecological Research. The full list of data providers and locations can be found in *Acknowledgments* above. Multiple wetland elevation-change relationships were derived based on land-cover type as detailed in this section.

2.7.1 Tidal Marshes

The SLAMM model estimates the extent of the likely-significant feedbacks between tidal-marsh surface elevation change rates and SLR (Kirwan et al. 2010). In tidal marshes, increasing inundation can lead to additional deposition of inorganic sediment that can help tidal wetlands keep pace with rising sea levels (Reed 1995) . In addition, salt marshes will often grow more rapidly at lower elevations allowing for further inorganic sediment trapping (Morris et al. 2002).

There are three primary coastal marsh types within our modeling that may be subject to these feedbacks, generally defined here:

- **Regularly Flooded Marsh (RFM)** includes low to mid elevation marshes. Roughly speaking, these are marshes that are inundated by tidal water at least once per day.

- **Irregularly Flooded Marsh (IFM)** includes high elevation marshes. These marshes are inundated by tidal water once per day or less.

- **Tidal-Fresh Marsh (TFM)** are generally low to mid elevation marshes that are daily inundated with fresh waters.

The persistence and conversion dynamics of RFM and IFM in SLAMM are summarized as follows:

– SLAMM assumes that wetlands will inhabit a range of vertical elevations that is a function of the tide range and the mean-tide level (Titus and Wang 2008).

– When irregularly-flooded marsh (e.g., the IFM platform) falls below the modeled minimum elevation, then the land cover is converted to regularly-flooded marsh (RFM).

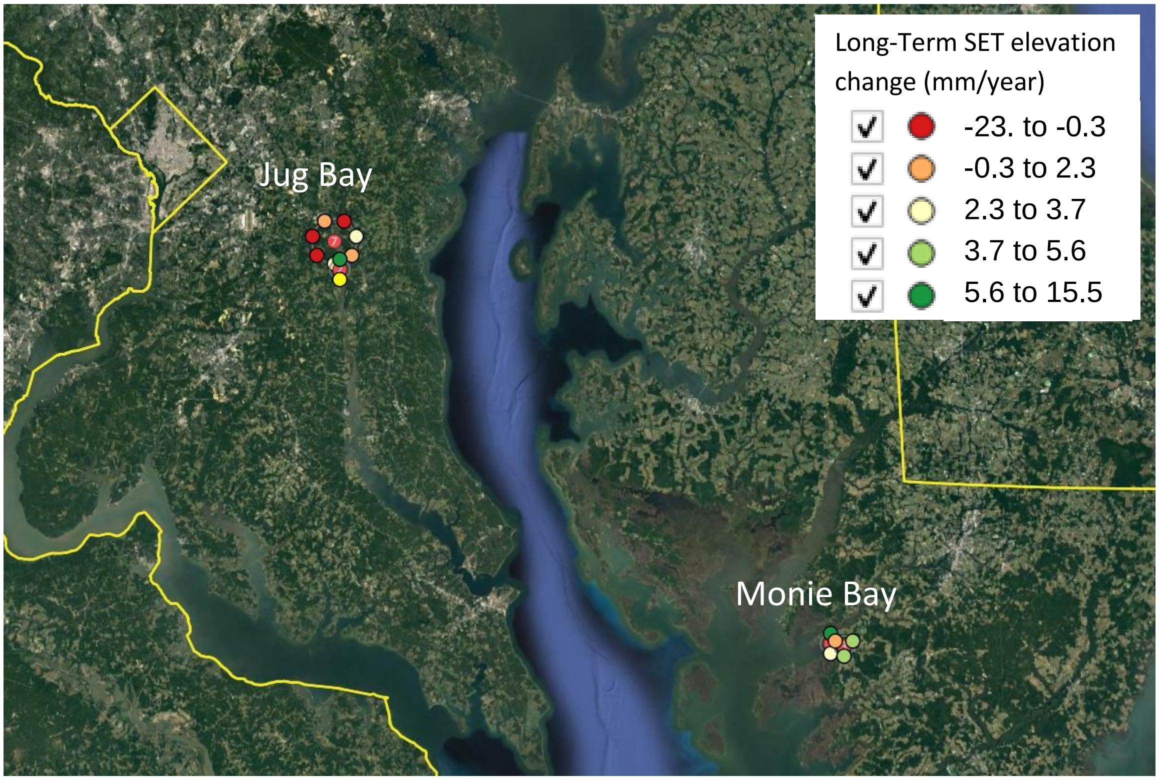
– When RFM falls below the modeled minimum elevation (generally below mean-tide level) then the land cover is assumed converted to non- or partially-vegetated tidal flats.

– The elevation intervals of existence (relative to tide ranges) can be adjusted by the user to reflect local conditions.

As these data were to be used for long-term projections, long term averages were required to avoid the extrapolation of a short-term event. SET data with records of less than five years were therefore omitted from this analysis. Furthermore, some SET data that were spatially identified as marsh edge and that were highly eroding (with elevation change ranges less than -5 mm/year) were also omitted.

Regularly-Flooded Marsh Data. For RFM, site-specific elevation-change data were available from two sites within the Maryland study area: Monie Bay in the southeast of the study area, and Jug Bay in the northwest (Figure 12 top). Differences between the Western Shore and Eastern Shore were not apparent in this relatively small dataset (Figure 12 bottom). The resulting accretion-feedback relationship used in modeling ranges from just below 3 mm/year to approximately 6.5mm/year at optimal elevations (Figure 13).

The assumption in this curve is that coastal marshes have strong relationships between their elevations in the tidal frame and their accretion rates (Kirwan et al. 2010). The parabolic shape of the curves is often driven by parabolic biomass density curves for each marsh type (Morris et al. 2002). Because tide ranges vary throughout the study area, the elevation-change curve is reported with elevations expressed relative to half-tide units (HTU). This allows this curve to be applied throughout the study area regardless of the tidal range differences.



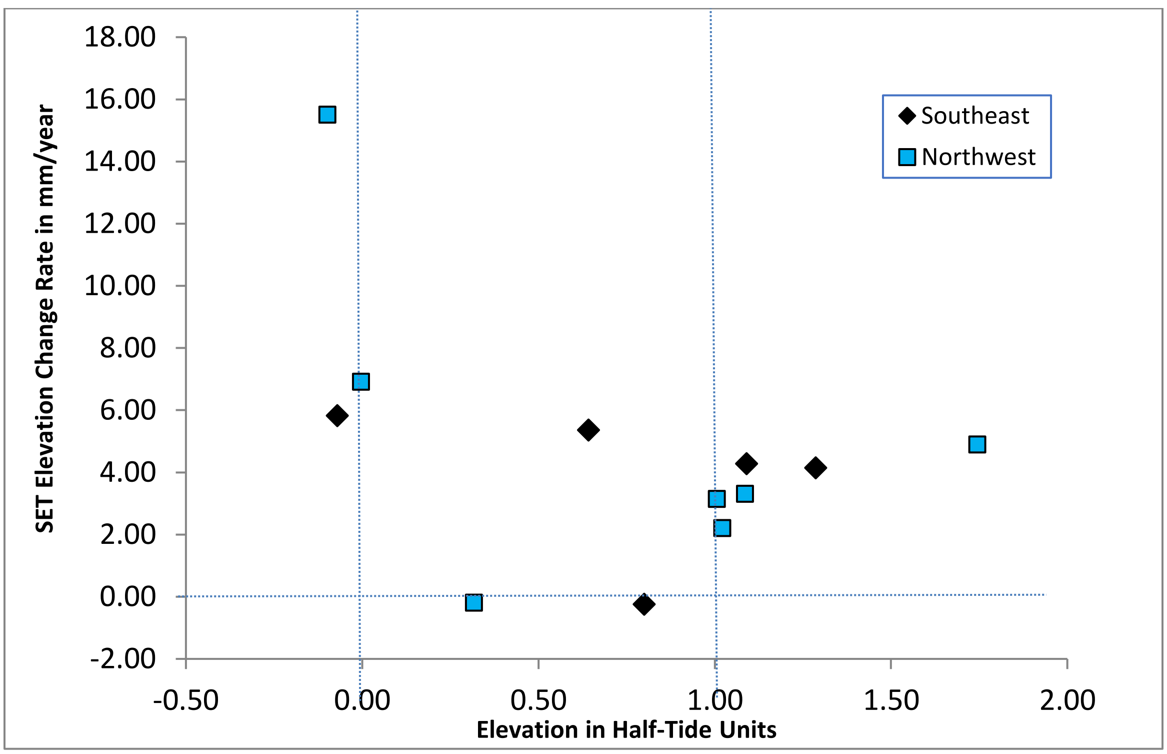


Figure 12. Available regularly-flooded marsh long-term SET data in the study area

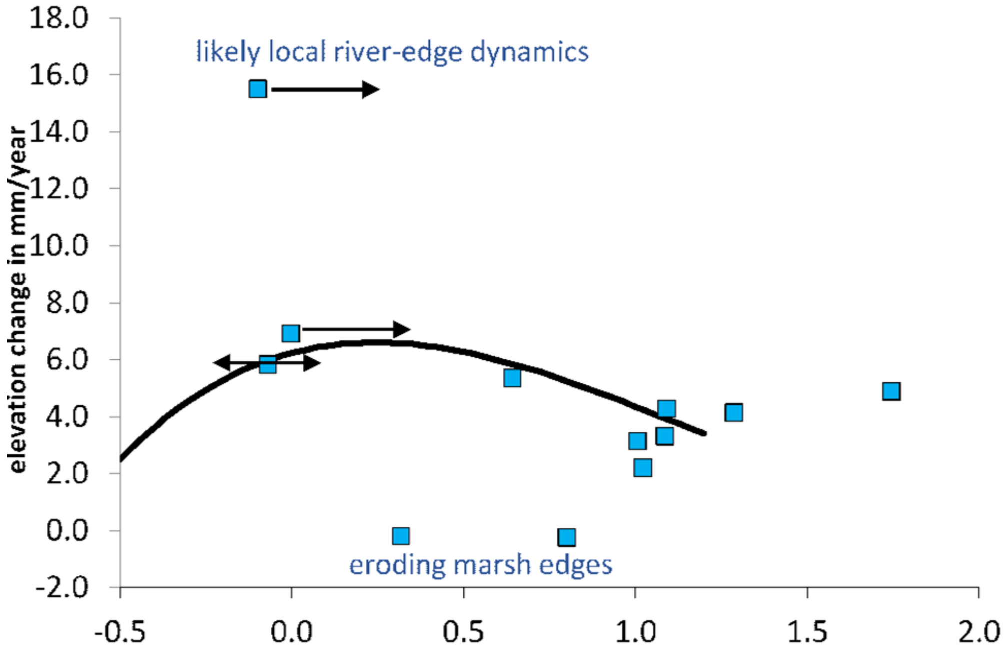


Figure 13. Parabolic accretion-feedback curve used to model regularly-flooded marsh

While some data points are not close to the derived curve (top and bottom of Figure 13), evidence points at local dynamics such as eroding marsh edges or highly depositional river banks driving these outliers. Because of this, it was determined these data would not be appropriate for extrapolation across the marsh surface for long-term model projections.

Irregularly-Flooded Marsh Data. For IFM, site-specific elevation-change data were available from three locations within the Maryland study area: Jug Bay and Kirkpatrick Marsh to the northwest, and Monie Bay and Assateague further to the east (Figure 14 top). The average rate of elevation change measured was 3.2 mm/year and these data did not show a strong relationship to elevation or location (Figure 14 bottom). Furthermore, as irregularly-flooded marshes are subject to less frequent inundation, the relationship to elevation is expected to be less important. For these reasons, irregularly-flooded marsh was modeled using a constant accretion rate of 3.2 mm/year.

Tidal-Fresh Marsh Data. For tidal-fresh marsh, data were available from George Washington Memorial Parkway within the study area, and from Jamestown Island, VA south of the study area (Figure 15). The average of these two datasets was approximately 3 mm/year excluding two highly eroding sites (that had vertical erosion rates of roughly 10 mm/year). No clear spatial patterns were available in these data. Furthermore, there was no evidence of a positive feedback between marsh elevation changes and lower marsh elevations (no higher elevation-change rates were measured for those marshes located lower in the tidal frame). For these reasons, all model projections used 3.0 mm/year for estimated elevation change in tidal-fresh marshes.

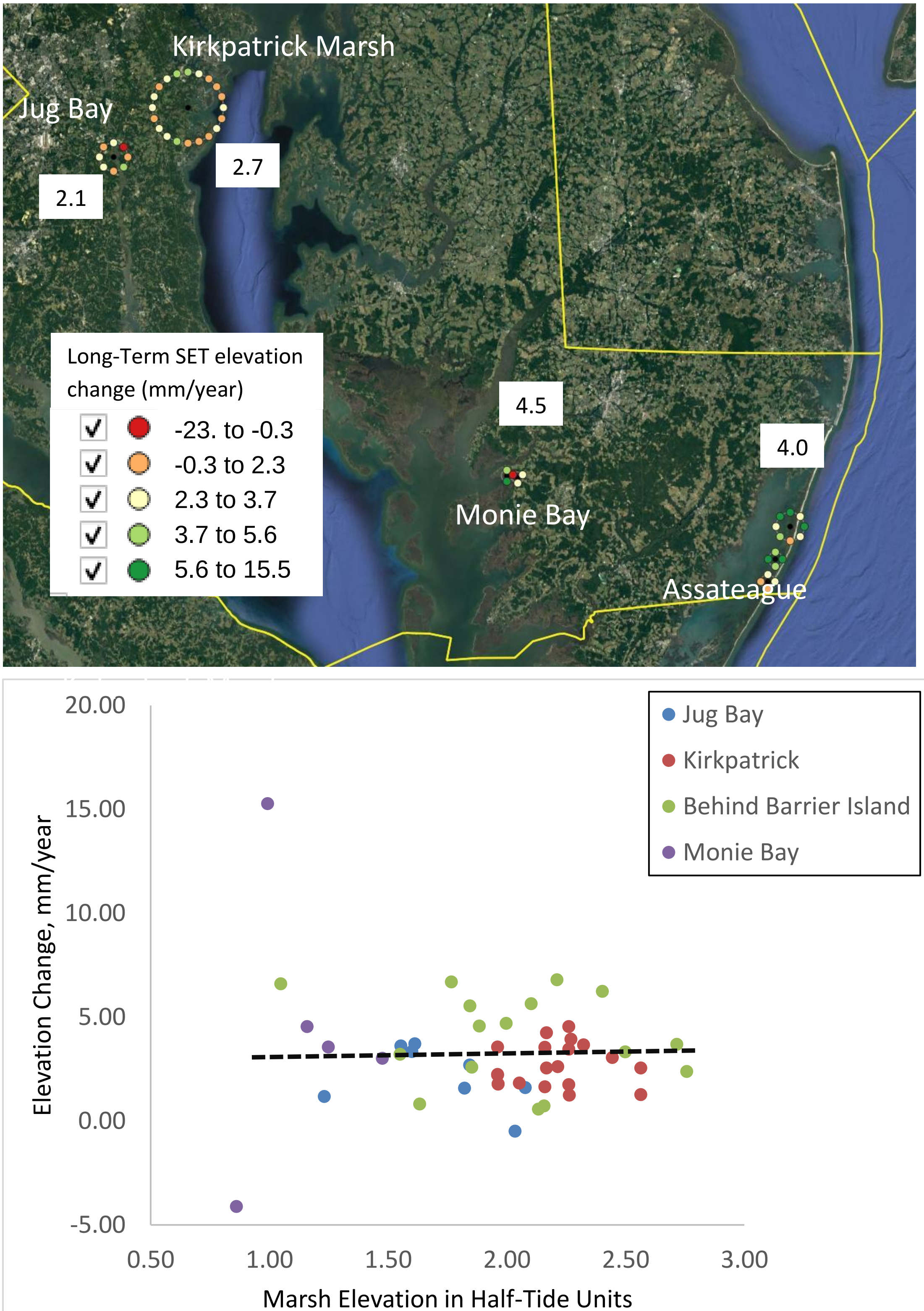


Figure 14. Available irregularly-flooded marsh long-term SET data in the study area
(white boxes display averages at each location in mm/year)

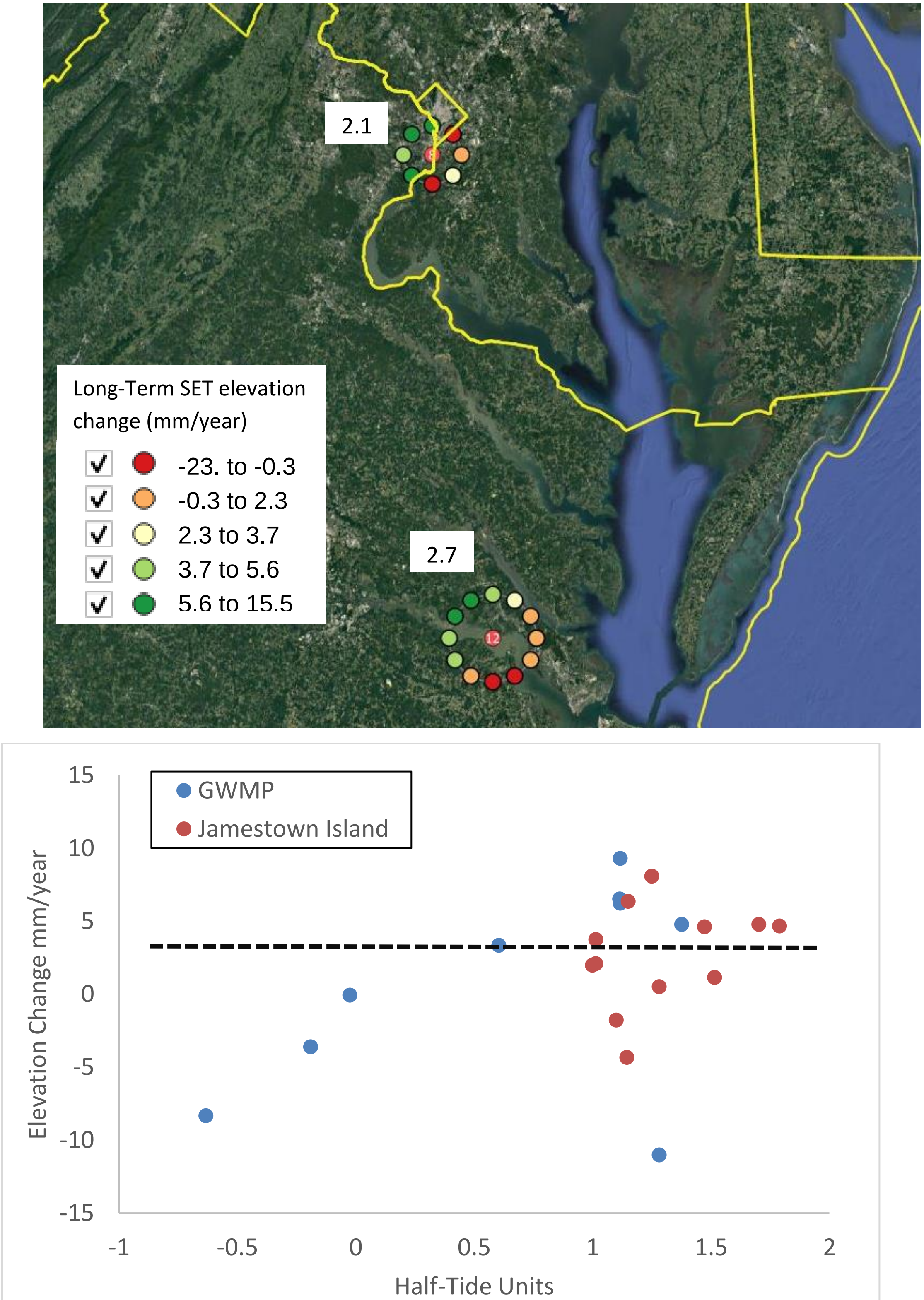


Figure 15. Available tidal-fresh marsh long-term SET data in the study area and surrounding environs *(white boxes display averages at each location in mm/year)*

2.7.2 Elevation-Change Rates of other Wetland Types

The inland-fresh marsh elevation-change rate was set to 1 mm/yr. Studies of fens and freshwater marshes in Michigan and Georgia (Craft and Casey 2000; Graham et al. 2005) suggest this to be an appropriate value based on ^{210}Pb measurements. Lacking site-specific data, values of 1.6 mm/yr. and 1.1 mm/yr. were assigned for forested wetland and tidal forested wetland elevation-change rates, respectively which were measured in Georgia by Dr. Christopher Craft (Craft 2008, 2012).

Beach sedimentation was set to 0.5 mm/yr., a commonly used value in SLAMM applications. Average beach sedimentation rates are assumed to be lower than marsh-accretion rates due to the lack of vegetation to trap suspended sediment, though it is known to be highly spatially variable. In addition, it is worth noting that future beach nourishment, should it occur within the study area, is not accounted for in these SLAMM simulations.

2.8 Erosion Rates

SLAMM models erosion as additive to inundation; horizontal wetland erosion is assumed to be the effect of wave action. Four sources of erosion data were considered in this analysis:

- Maryland Geological Survey (MGS) 2003
  - Erosion rates based on shoreline change for the roughly 50-year era ending ca. 1990
- 2006 VIMS Update of MGS 2003
  - reflect the current status (2002-2006) of shoreline protection
  - improve on the shoreline segments previously classified as “unknown” or “no data”
- MGS 2017 30 to 40-year erosion rates
  - Western Shore only
- MGS 2017 10-year erosion rates
  - Western Shore only

Based on examination of these four data sets, and the desire to use the most current long-term erosion rates for projecting erosion, the following priority was utilized:

- 2006 VIMS Update of MGS (1988-1995) for most of study area
- 2017 MD 30-year erosion rates were used preferentially
  - “no-data” segments were filled in with 2006 VIMS update when available
- 2003 MGS data was used behind barrier islands where it is the only dataset
- 2003 MGS data was also used in southern bay islands where it is the only dataset
- 2017 MD 10-year erosion rates – were not used, preferentially choosing longer-term data

The resulting coverage of erosion data is shown in Figure 16.

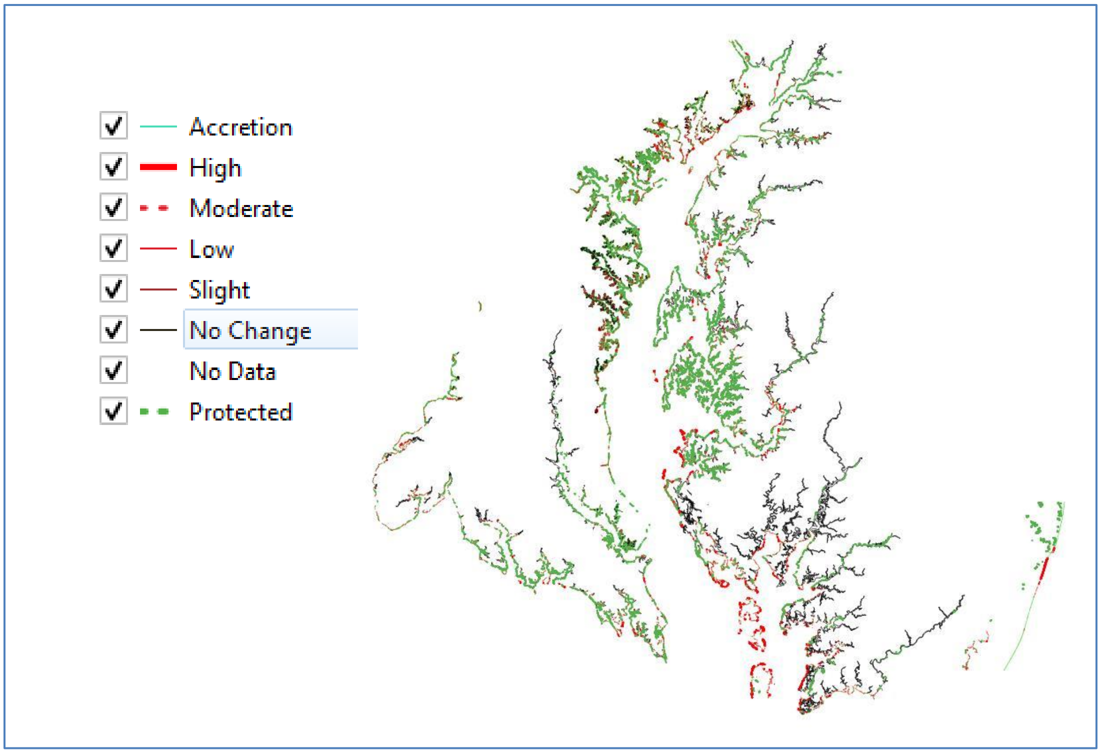


Figure 16. Master Erosion Dataset derived by combining best available long-term erosion rate data

To derive a spatial coverage of erosion rates, protected shorelines were first removed from the dataset. (These areas were not modeled as subject to erosion as discussed below.) For the remaining unprotected shorelines, spatial averages of erosion rates were calculated. The procedure utilized took each shoreline with measured erosion estimates and calculated an average weighted by the length of the shoreline. When erosion data were provided as a range, the midpoint erosion rate within the range was assumed.

The tidal polygons derived above (Figure 8) were used to distribute these average erosion rates; these polygons were modified when necessary. For example, some polygons were joined (for example, behind the barrier islands where erosion data were sparse). Other polygons were split when there were areas where erosion data were not reasonably uniform. For example, an area of high-erosion ocean beach was added to the east of the study area. Polygons were visually examined for the similarity of their erosion regime. Also, the standard deviations of erosion rates for each polygon were compared to ensure that the same degree of uniformity was observed for each polygon. The resulting erosion rate inputs follow.

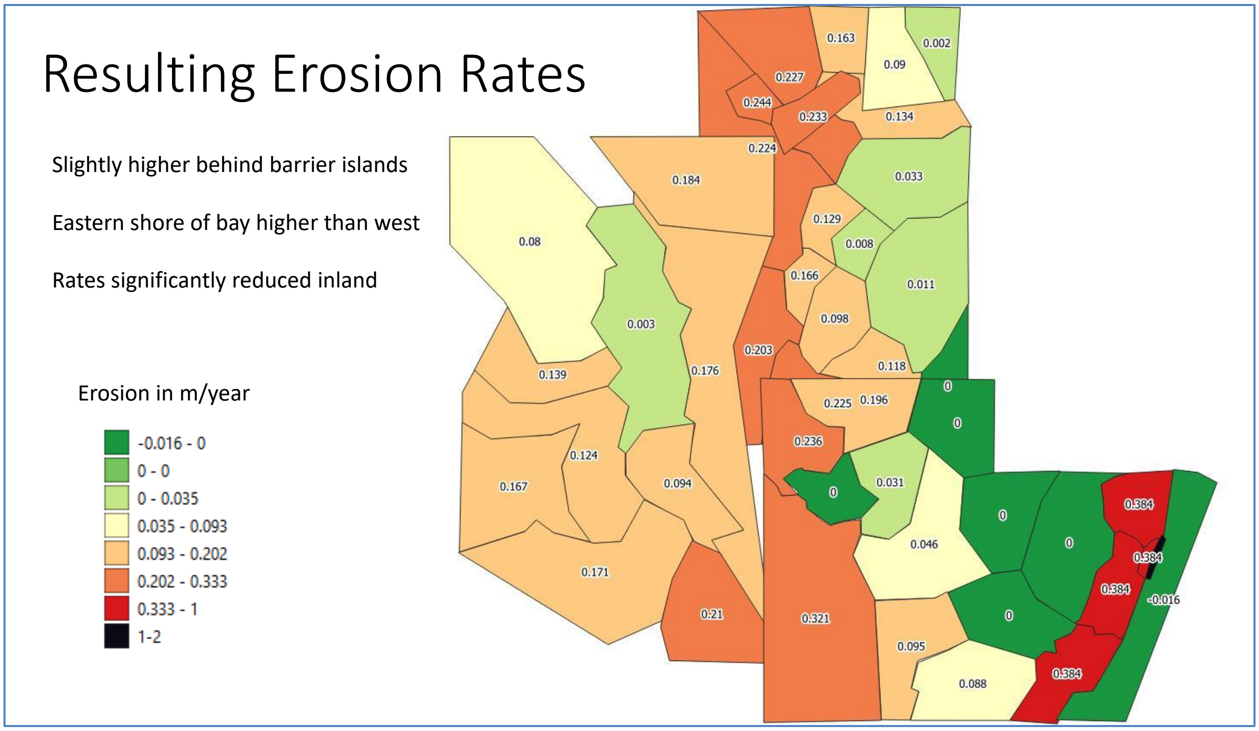


Figure 17. Resulting erosion rate polygon dataset.

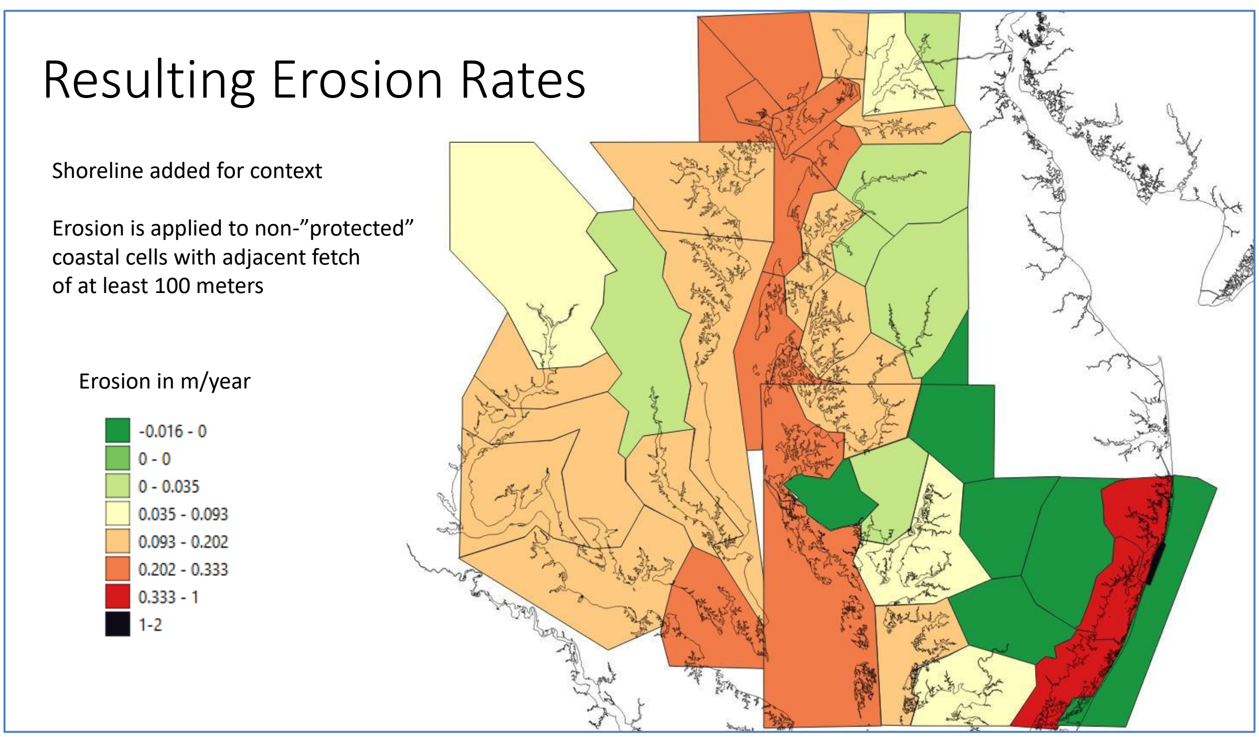


Figure 18. Resulting erosion rate dataset with shoreline for context.

2.8.1 Shoreline Protection

Within the erosion datasets detailed above, extensive portions of Maryland's shoreline were designated as "protected" (Figure 16). To account for this, all cells within 25 meters of a protected shoreline polyline were designated as "protected." No erosion was assumed to take takes place in these cells. This change required a minor change to the SLAMM 6.7 source code; a version of SLAMM 6.7 that accepts a "shoreline-protection" raster input has been archived along with model inputs and are available upon request.

2.9 Model Calibration

In order to test the consistency of key SLAMM modeling inputs, such as current land cover, elevations, modeled tidal ranges and hydraulic connectivity, SLAMM is run at "time zero" in which tides are applied to the study area but no sea-level rise, accretion or erosion are considered. Because of DEM and NWI uncertainty, local factors such as variability in the water table, and simplifications within the SLAMM conceptual model, some cells may initially be below their lowest allowable elevation land cover category and are immediately converted by the model to a different land cover category. For example, an area classified in the wetland layer as fresh-water forested wetland subject to regular saline tides, according to its elevation and tidal information, would be converted by SLAMM to a tidal forested wetland at time zero.

Where model calibration results in significant land-cover changes, additional investigation is required to confirm that the current land cover of a particular area is correctly represented by time-zero conversion results. If not, it may be necessary to better calibrate data layers and model inputs to the actual observed conditions. Land-coverage conversion maps at time zero are always reviewed to identify any initial problems, and to make necessary adjustments to correct them.

In some cases, the initial land-cover re-categorization by SLAMM better describes the current coverage of a given area. For example, the high horizontal resolution of the elevation data can allow for a more refined wetland map than the original NWI-generated shapefiles used in this project. The standard mapping protocol for the NWI maps is to include wetlands with an area of 0.5 acres (2023 m^2). In addition, "long, narrow rectangles …, such as those following drainage-ways and stream corridors…may or may not be mapped, depending on project objectives" (Federal Geographic Data Committee, 2009).

Initial inundation of dry land could not always be explained by the low resolution of the land-cover layer. Sometimes, initial inundation of dry land was due to an assigned "salt elevation" that was too high for the area in question. Because of the lack of fine-scale spatial data and the inherent uncertainty of the wetland-boundary elevation estimates, adjustments were sometimes required on a site-by-site basis to correct initial dry land conversion.

The occurrence of tidal-freshwater wetlands in riverine environments, such as tidal forested wetlands and tidal-fresh marshes, is generally found to be more closely correlated with the salinity content in the water than the marsh platform elevation. However, the SLAMM salinity sub-model was not used in these simulations because of the model's data requirements (often the required data, such as up-river bathymetry and salinity, were not available) and the significant time required for model calibration. The simplified model concept used here is that water salinity is correlated with marsh elevation on an estuary-specific basis. To implement this assumption, the minimum allowable elevations for these tidal-freshwater habitats were set to heights based on the measured marsh elevations using site-specific LiDAR data. Table 5 presents the minimum elevations applied for the study area.

Table 5. Default minimum wetland elevations in SLAMM conceptual model.

SLAMM Category	Min Elev.	Min Unit
All Dry Lands	1	"Salt elevation"
Non-Tidal Forested Wetland	1	"Salt elevation"
Inland Open Water	1	"Salt elevation"
Inland-Fresh Marsh	1	"Salt elevation"
Irreg.-Flooded Marsh	0.5	HTU
Trans. Salt Marsh	0.5	HTU
Tidal Forested Wetland	0.28	HTU
Tidal Cypress Swamp	0	HTU (=MTL)
Riverine Tidal	0	HTU (=MTL)
Tidal-Fresh Marsh*	-0.4	meters
Regularly-Flooded Marsh	-0.5	HTU
Tidal Flat	-1	HTU
Ocean and Estuarine Beaches	-1	HTU

*For these marsh habitats lower-boundary elevations are assumed to be highly dependent on freshwater flow and therefore are generally set based on site-specific data (see text for more detailed discussion).

As inundated developed land is unlikely to immediately convert to a coastal wetland, the "Flooded Development" category was included in the model. This category occurs when developed dry land is inundated by salt water at least once every 30 days. Flooded developed land is not subject to additional land-cover conversions. There is additional uncertainty as to whether a marsh could inhabit this land cover, so the model is likely somewhat conservative with respect to marsh transgression in these locations.

Several iterations of layer refinement were necessary in order to get an acceptable calibrated model to the initial conditions. After each step, time zero maps were compared to the initial condition maps using GIS software and annotating where large conversions of wetlands were observed. These issues were consequently explained or fixed by additional calibration or layer refinement. In addition, inundation-frequency maps were compared to wetland maps to ensure that identified wetlands were predicted to be flooded as frequently as expected.

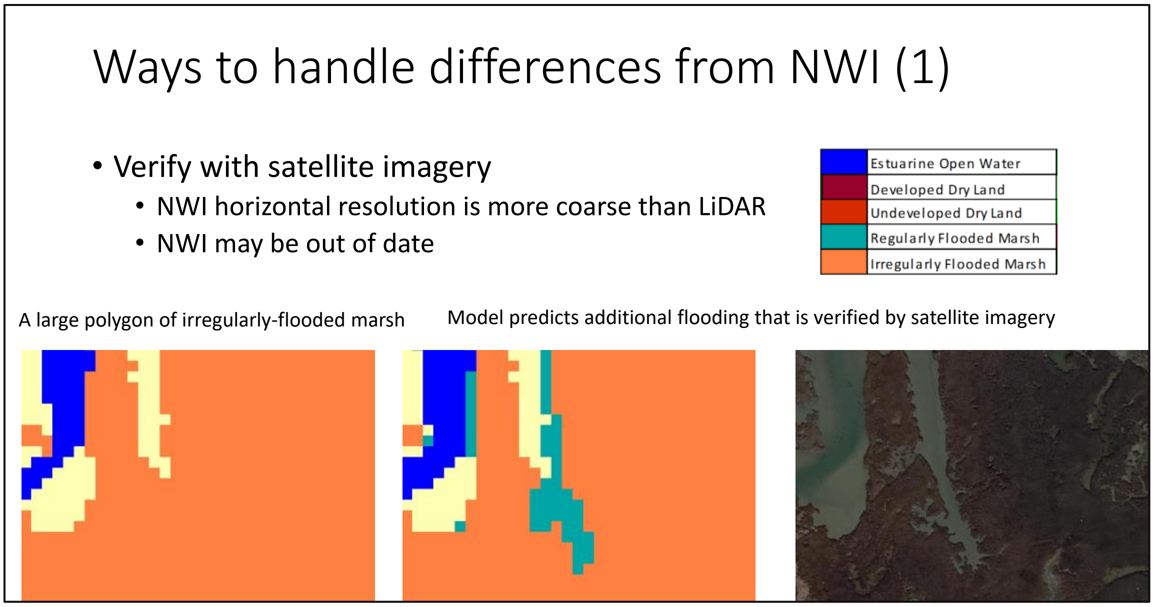
In general, there are four primary ways to manage calibration problems within the SLAMM model. Figure 19 provides site-specific examples in which model predictions were verified using satellite imagery or in which NWI inputs were updated based on local data sets. In the latter case, SHARP wetland data were used to update model results at Hazard Island ("SHARP 2017. Marsh Habitat Zonation Map. Saltmarsh Habitat and Avian Research Program. Ver: 26" 2017). Figure 19 provides site-specific examples of updating dike layers based on site-specific knowledge, and modifying tide ranges based on alternative data sources (Allen and Gill Undated).

Overall, the southeast of the study area required the most calibration, especially the area in and surrounding Blackwater NWR. The partial impoundment of open water at Blackwater NWR meant that interpolating tides and water levels using statewide datasets was not appropriate. These datasets were replaced using the best available local information. On the other hand, the northeast and west portions of the study area required minimal calibration, as the model conformed to the conceptual model without significant modification.

Following the initial model calibration, time-zero results were presented to a marsh-modeling workgroup convened as part of the EESLR project including team members from NOAA, University of Maryland, MDNR, and Audubon (please see the *Acknowledgements* page for a full list of members). Based on feedback from this group, several additional modifications were made to the project's "time-zero" results:

- The SLAMM "swamp" category was renamed to "forested wetland" to be more appropriately descriptive of local habitat.
- The initial footprint of tidal swamps and tidal cypress swamps were refined based on local knowledge and site-specific maps.
- NWI designations were changed in select locations based on local information, e.g. from transitional marsh to irregularly-flooded marsh.
- Impoundment maps were expanded in some cases based on expert knowledge.
- Tides were reduced in some locations based on excessive flooding predicted according to local knowledge.
- Open water (ponding) was added to some NWI marsh polygons based on local information and satellite imagery.

In many cases, model predictions effectively matched boots-on-the-ground knowledge and no additional modifications were required. Following requested updates, the time-zero model result was again presented to the marsh-modeling workgroup and no additional modifications were suggested. Model "time-zero" results are labeled as 2010 in model results (and are unchanged across all model projections).



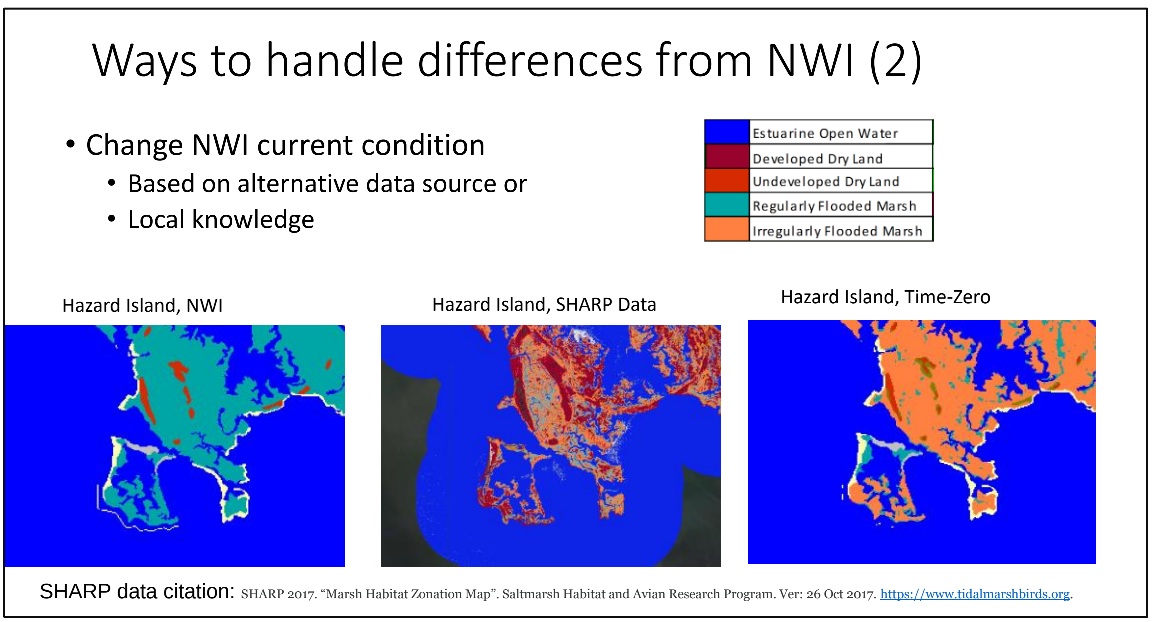
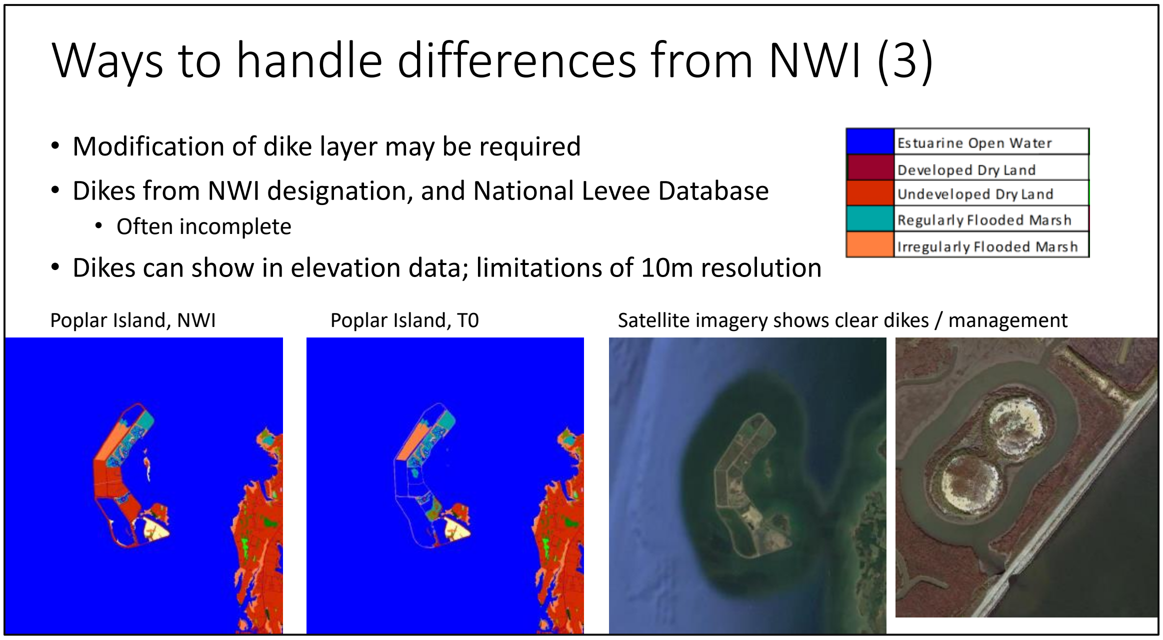


Figure 19. Calibration techniques summary. Methods 1 and 2



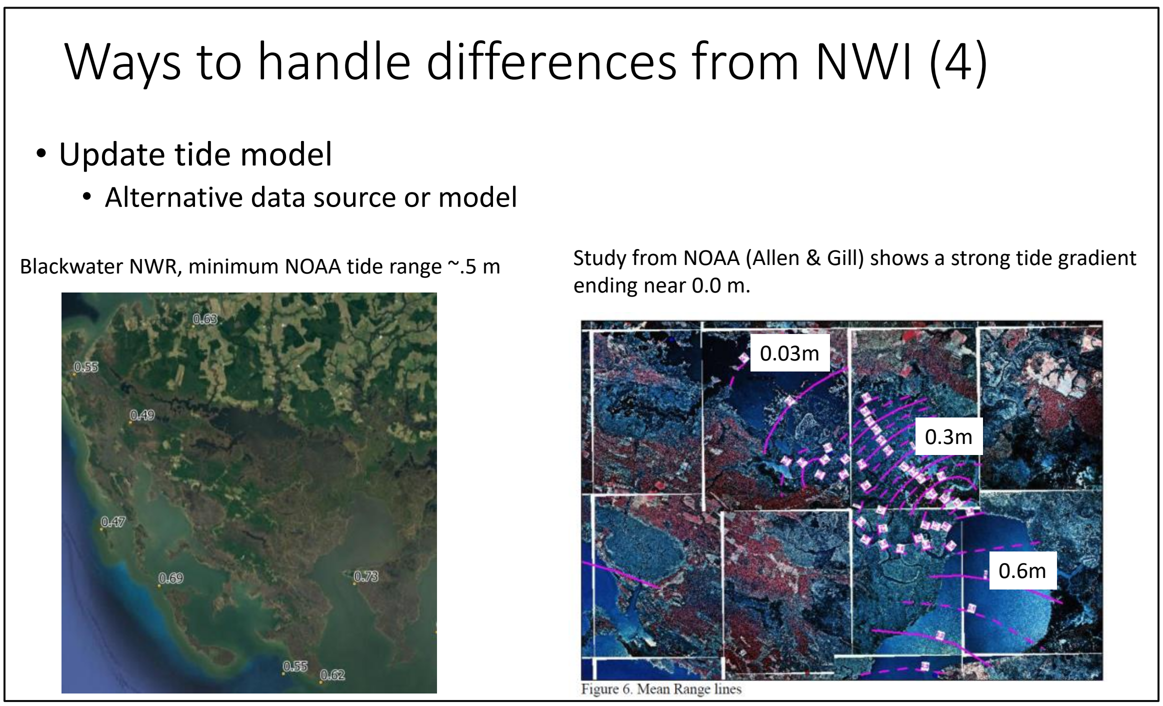


Figure 20. Calibration techniques summary. Methods 3 and 4

2.10 Model Setup

Following time-zero calibration, the study area had been divided into over 60 input subsites to effectively represent the variability in tide ranges and erosion rates. The input subsite boundaries are summarized in Figure 21. GIS shapefiles and the full set of model input parameters are availableupon request.

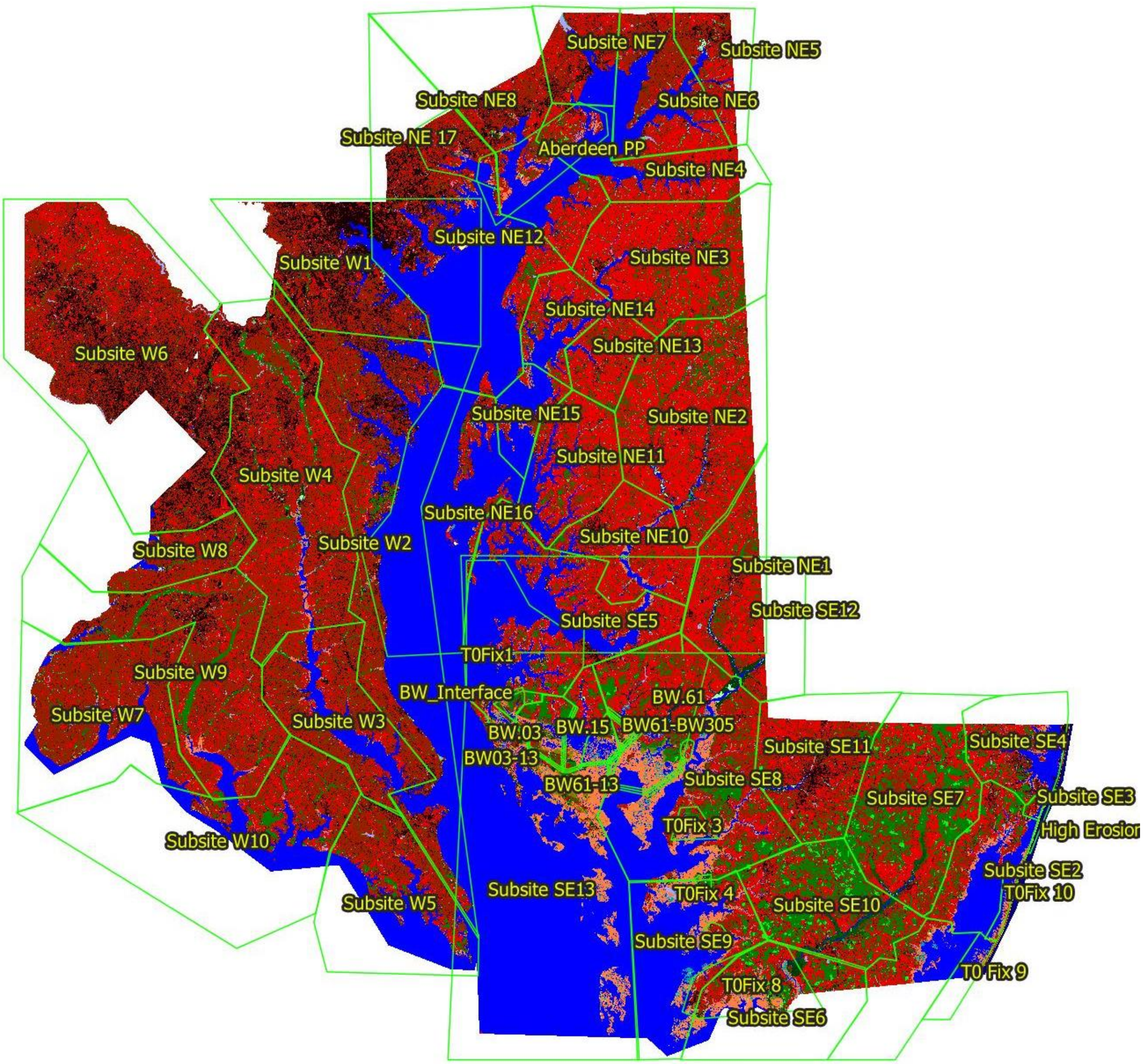


Figure 21. Summary of Maryland input subsites

3 Results

The general pattern indicated by model results is that a small amount of sea-level rise can potentially increase total marsh area as existing marshes keep up with rising waters, and new marshes are formed on dry lands. An important caveat is that this result assumes that all agricultural, forested, and non-developed lands that *could* convert to marshes due to their tide range, *will* successfully convert into marshes. For example, no future vertical-wall development, is included in the projection. Because of this, these model results are certainly a best-case scenario for the marshes. Note also that model projections are reported from time-zero forward so that projected land-cover changes are only due to SLR and not due to the initial model calibration.

Figure 22 shows total marsh areas over time (through the year 2100) for three different SLR scenarios. In the 50% Paris scenario (0.59 meters of SLR by 2100, on the top), total-marsh area increases from about 90,000 to 120,000 hectares across Maryland. The acreage of irregularly-flooded marsh goes down during this period, but regularly-flooded marsh increases significantly. In the Upper Limit of Likely Range scenario (1.23 meters of SLR by 2100, middle), total marsh area declines by the end of the period as the regularly-flooded marsh gains start to be replaced by tidal flats and open water. In the worst-case scenario (1% growing, or 1.98 meters of SLR by 2100) marsh hectares remain relatively flat from 2070 to 2100 as the predicted SLR (since 2010) increases to nearly two meters. However, this maintenance of marsh acreage requires a significant loss of dry land that is converted to marshes in that scenario.

Figure 22 shows total dry land losses over time (through the year 2100) for the same three SLR scenarios. Four times as much dry land in Maryland is predicted to be lost under the highest scenario, over 100,000 hectares or nearly 400 square miles.

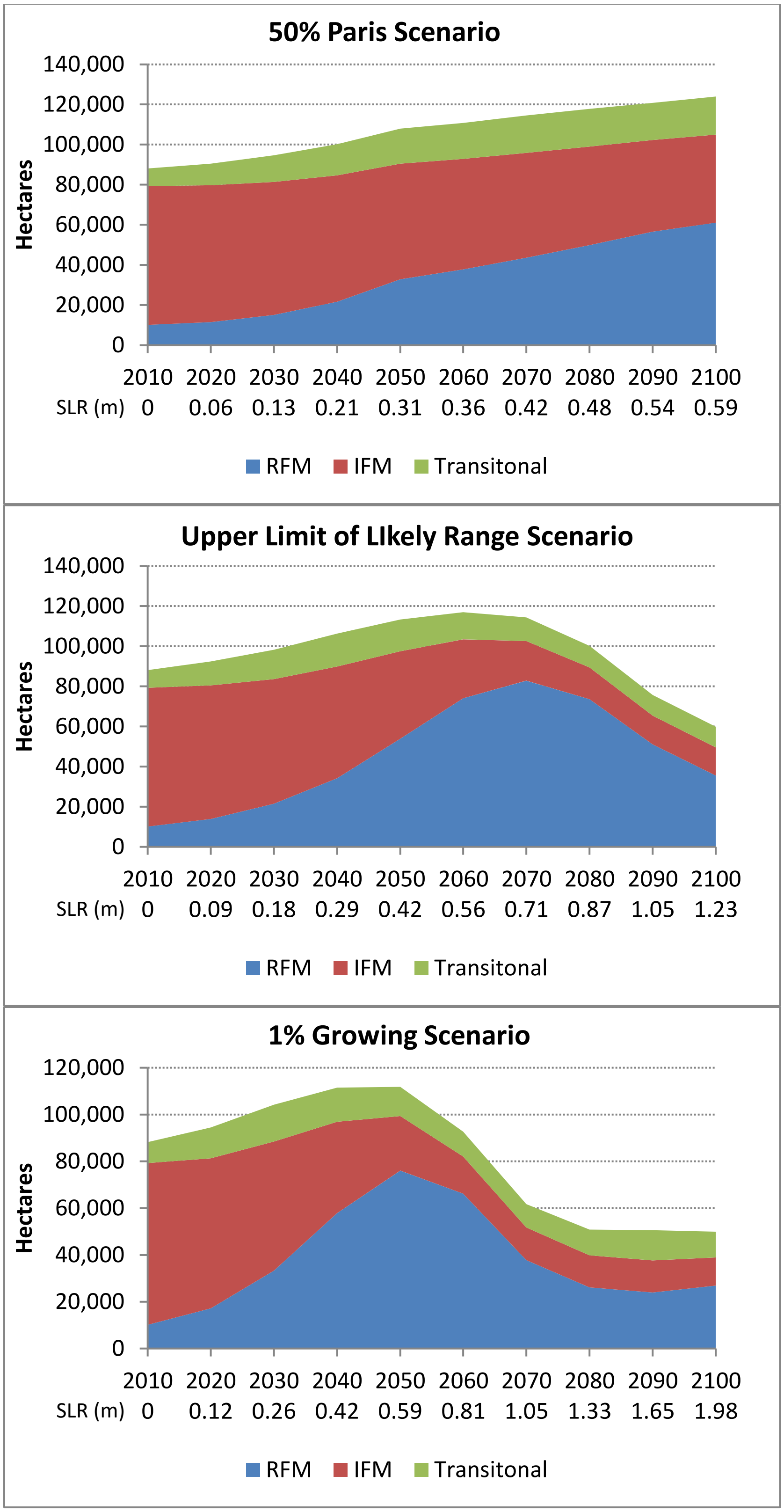


Figure 22. Marsh area graphs showing total marsh areas and types predicted under three different SLR Scenarios

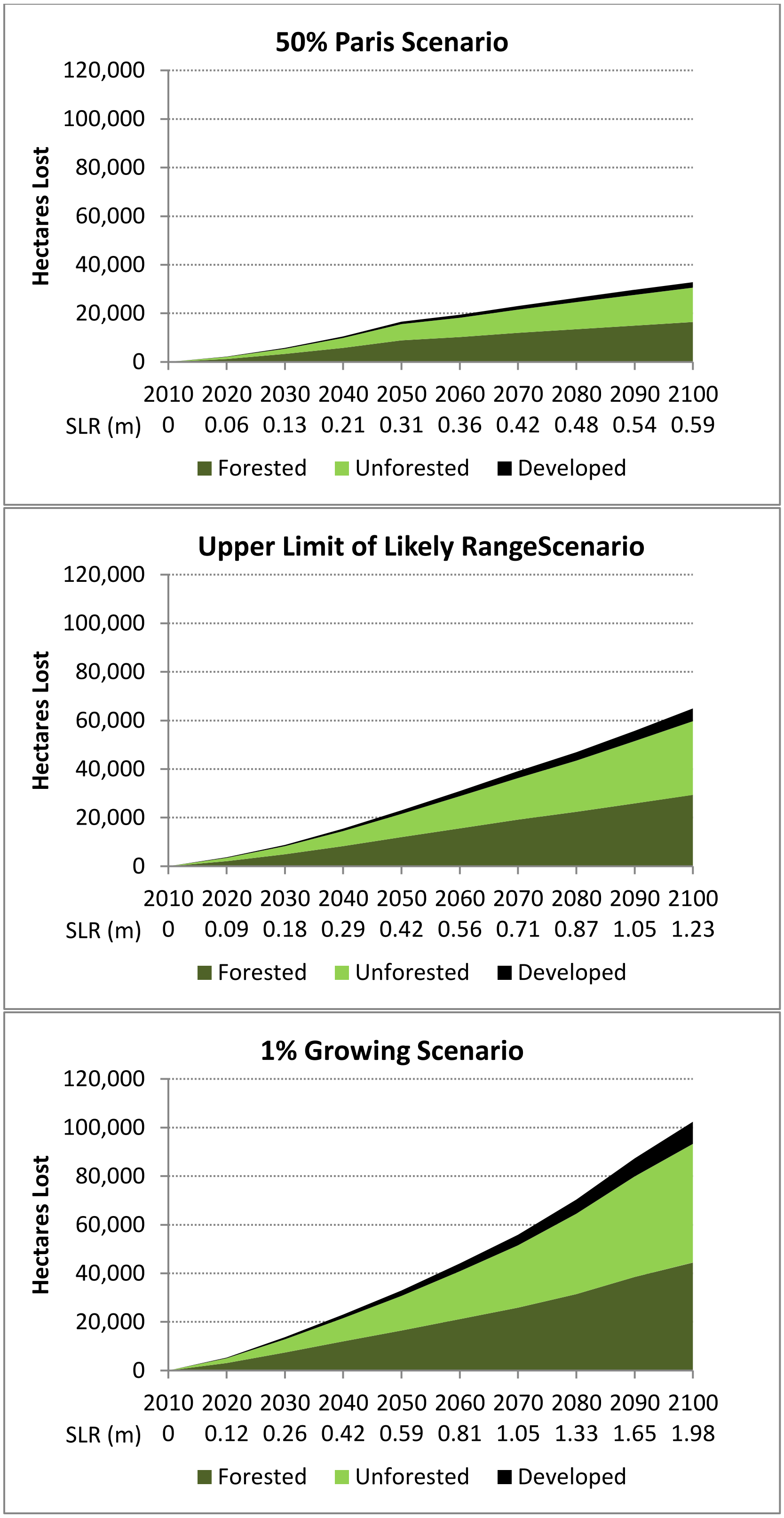


Figure 23. Area graphs showing **losses** of dry lands predicted under three different SLR Scenarios

Maps of model results also exhibit spatial variability. For example, Figure 24 shows that Blackwater NWR and its surrounding regions see some impacts of SLR under the best-case scenario, with much irregularly-flooded marsh becoming regularly flooded and some expansion of open water.

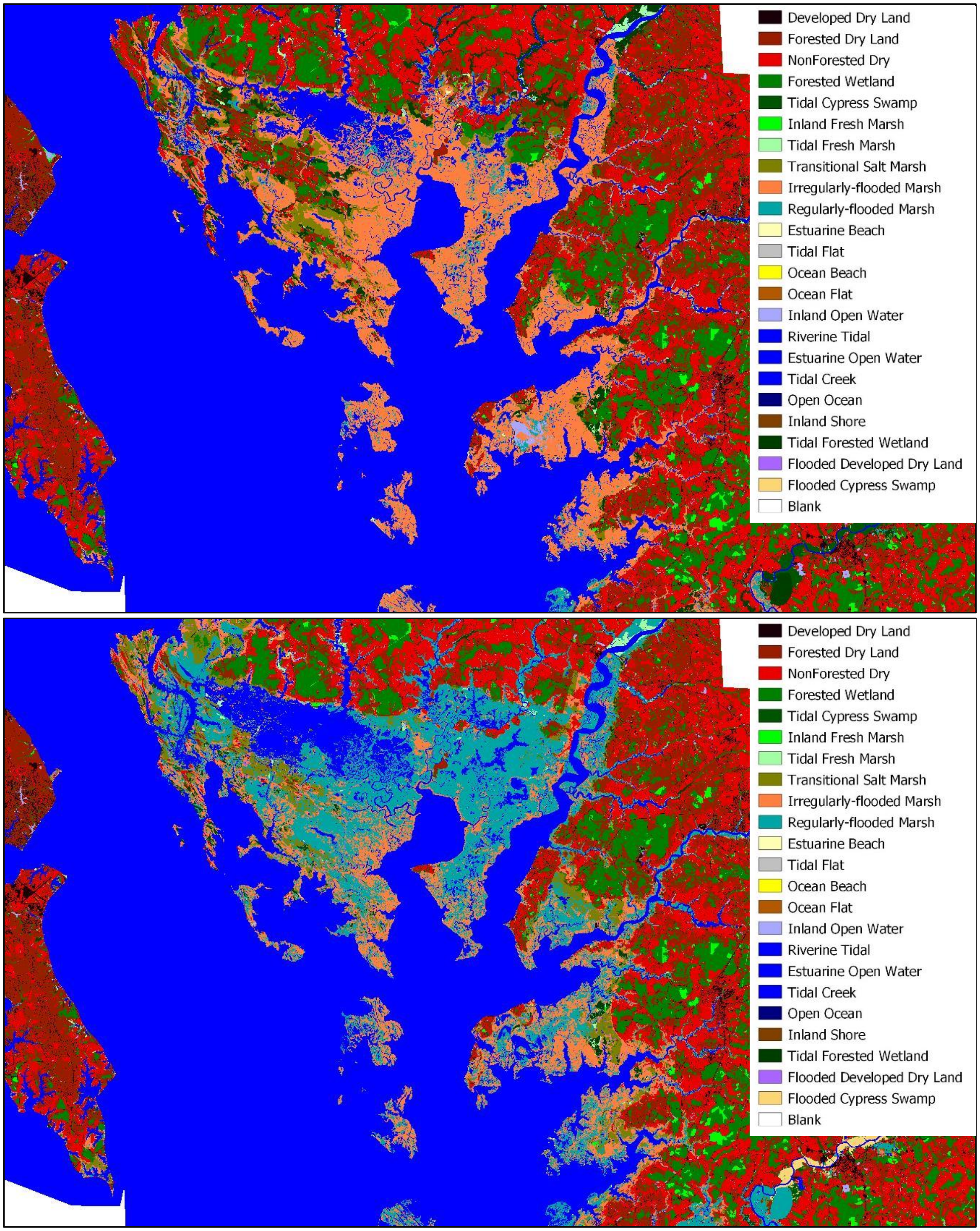


Figure 24. Blackwater NWR and surrounding regions in the year 2010 (top, time zero) and the year 2100 (bottom, Paris 50% simulation, or 0.59 m of SLR since 2010)

Figure 25 suggests that this same area will largely become open water by 2100 under the higher scenarios investigated (1.23 and 1.98 meters)

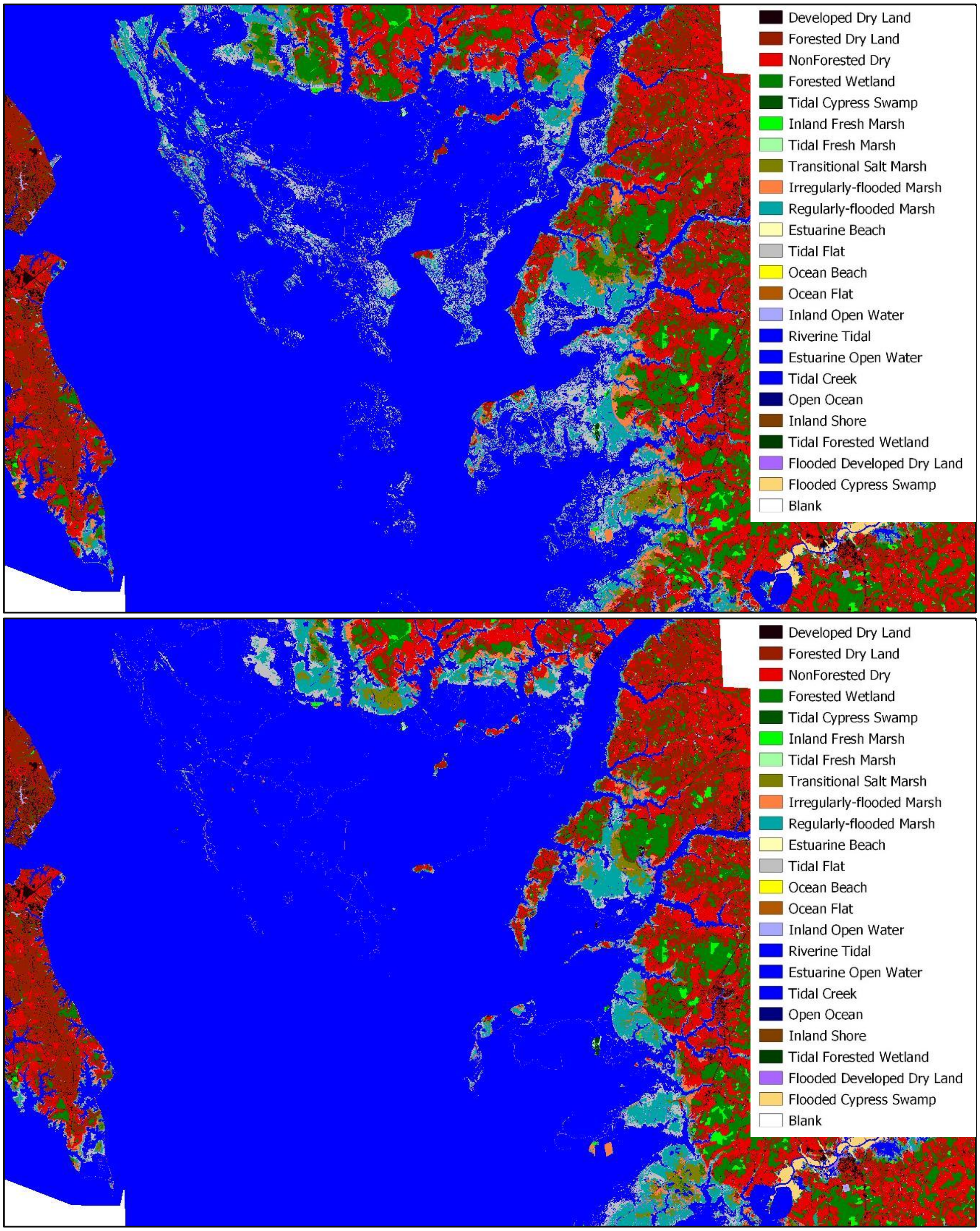


Figure 25. Blackwater NWR and surrounding regions in the year 2100 under two higher SLR scenarios. Top is 1.23 meters (Upper Limit of Likely Range); bottom is 1.98 meters (1% growing)

Like Blackwater Figure 26 suggests that marshes adjacent to Assateague Island will become more regularly flooded. However, less open water is opening up than was seen at Blackwater, and less dry land is predicted to convert to marshes or open water (due to higher land elevations in this location).

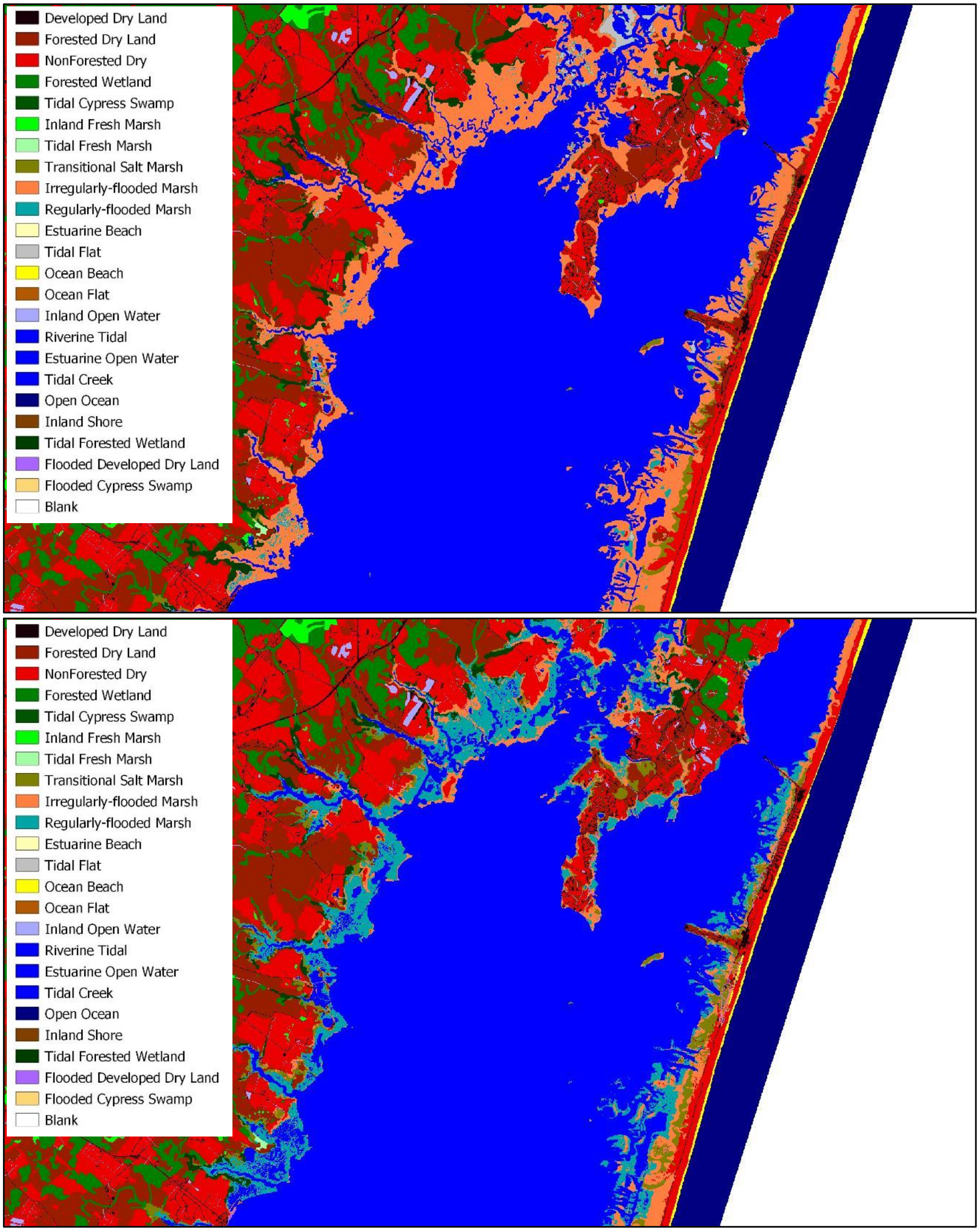


Figure 26. Assateague Island and surrounding regions in the year 2010 (top, time zero) and the year 2100 (bottom, Paris 50% simulation, or 0.59 m of SLR since 2010)

Figure 27 does suggest that many marsh acres will be converted to open water under the higher scenarios investigated (1.23 and 1.98 meters). Less dry land is predicted to be lost at this site, however, and there appears to be less viable habitat for new marshlands under the higher SLR scenarios.

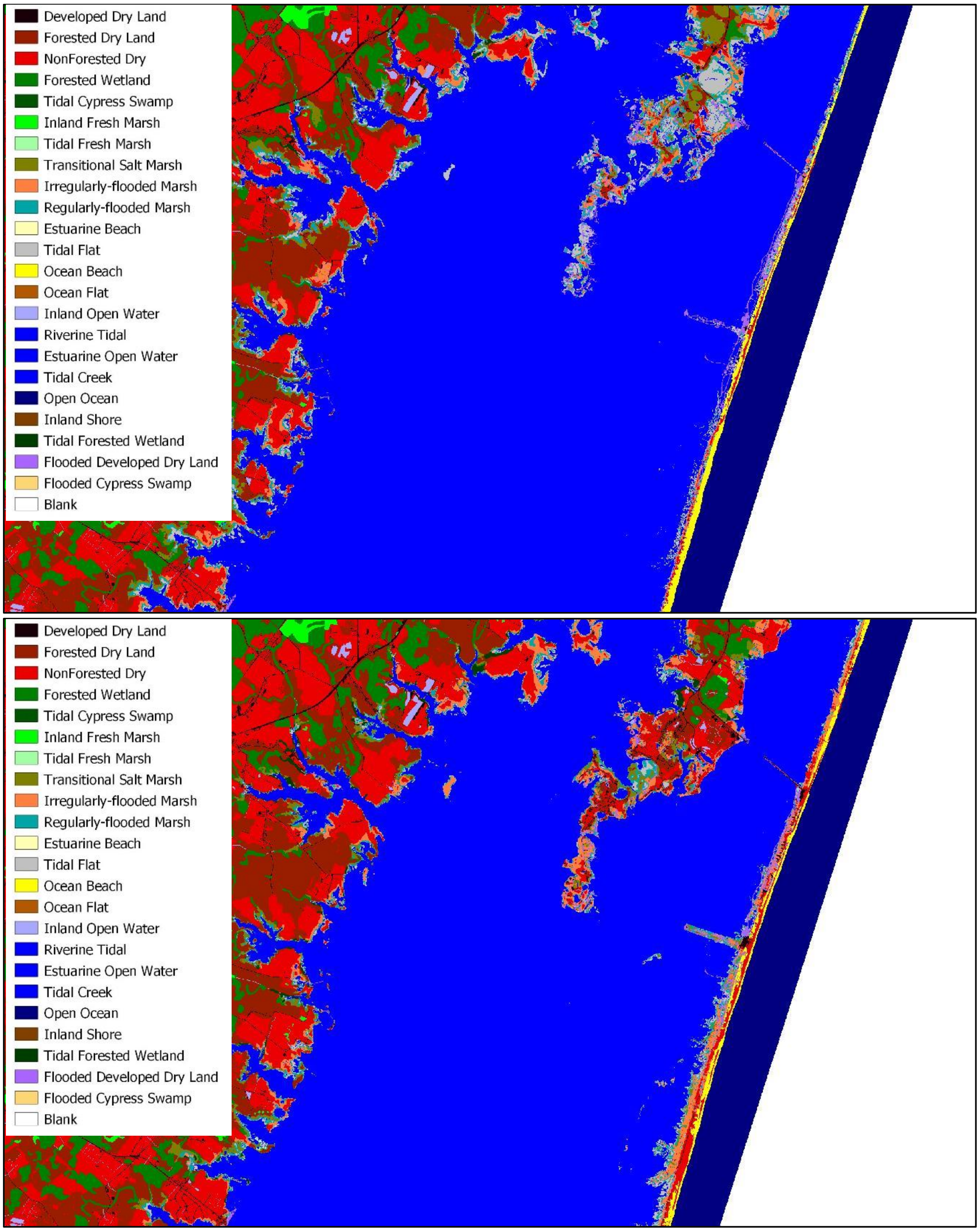


Figure 27 Assateague Island and surrounding regions in the year 2100 under two higher SLR scenarios. Top is 1.23 meters (Upper Limit of Likely Range); bottom is 1.98 meters (1% growing)

To enable the viewing of more specific locations, dates, and SLR scenarios, the full set of all model results are available as GeoTiff GIS files upon request, along with all other model inputs and outputs.

4 Conclusions

SLAMM model results presented herein represent a significant step forward from previous large-scale SLAMM simulations produced for Chesapeake Bay. Current model results were run at a 10x10 meter resolution, incorporate Surface Elevation Table data to estimate feedbacks between rates of marsh elevation change and sea-level rise, and underwent calibration incorporating significant input from local scientists and stakeholders. Site-appropriate flow charts of wetland succession were derived, and dry lands were separated into forested and non-forested categories. Landcover data were refined from NWI using local datasets and local expertise. The elevation dataset driving these model simulations was updated with newer and higher-resolution LiDAR data.

As noted in the text above, model results do not take into account future anthropogenic activities such as building seawalls to protect dry lands or additional bulkhead construction to prevent erosion. Furthermore, assumptions about erosion and wetland elevation-change rates have been applied on a landscape rather than a site-specific basis, so the predictions for individual shoreline locations are subject to additional uncertainty.

Despite those caveats, these updated SLAMM results will provide useful information for policymakers to help address potential impacts of sea level on Maryland marshes. As part of the EESLR project, data from these simulations have been used to inform hydrodynamic ADCIRC simulations. Future land-cover and elevation predictions have been passed to that model to understand their potential impacts on water velocity and wave predictions. In another part of this project, the current SLAMM simulations have also been used to define potential habitat for submerged aquatic vegetation.

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Appendix A: NWI to SLAMM Code Classification for EESLR MD Project

		NWI code characters					
		First	Second	Third and fourth	Fifth	Sixth	Notes
SLAMM Code	Name	System	Subsystem	Class	Subclass	Water Regime	All modifiers (h* =Diked/ Impounded)
1	Developed Dry Land (upland)	U					Specified based on Maryland Land Use
2	Forested Dry Land (upland)	U					Specified based on Maryland Land Use
3	Non-Tidal Forested Wetland	P	NA	FO, SS	1, 3 to 7, None	A,B,C,E,F,G,H,J,K None or U	Palustrine Forested and Scrub-Shrub (living or dead)
4	Tidal Cypress Swamp *	P	NA	FO, SS	2	R	Needle-leaved Deciduous forest and Scrub-Shrub (living or dead)
5	Inland Fresh Marsh	P	NA	EM, f**	All None	A,B,C,E,F,G,H,J,K None or U	Palustrine Emergents; Lacustrine and Riverine Nonpersistent Emergents
		L	2	EM	2 None	E, F, G, H, K None or U	
		R	2, 3	EM	2 None	E, F, G, H, K None or U	
6	Tidal Fresh Marsh	R	1	EM	2, None	Fresh Tidal T	Riverine and Palustrine Freshwater Tidal Emergents
		P	NA	EM	All, None	Fresh Tidal S, R, T	
7	Transitional Marsh / Scrub Shrub	E	2	SS, FO	1, 2, 4 to 7,None	Tidal M, N, P None or U	Estuarine Intertidal, Scrub-shrub and Forested (ALL except 3 subclass)
8	Regularly Flooded Marsh (Saltmarsh)	E	2	EM	1 None	Tidal N None or U	Only regularly flooded tidal marsh No intermittently flooded "P" water Regime
9	Non-forested Dry Land	U					Specified based on Maryland Land Use
10	Estuarine Beach old code BB and FL = US	E	2	US	1,2 Important codes	Tidal N, P	Estuarine Intertidal Unconsolidated Shores
		E	**2**	**US**	None	Tidal N, P	**Only when shores (need images or base map)**
11	Unvegetated Mudflat	E	2	US	3,4 None	Tidal M, N None or U	Estuarine Intertidal Unconsolidated Shore (mud or organic) and Aquatic Bed; Marine Intertidal Aquatic Bed
	old code BB and FL = US	E	2	AB	All Except 1	Tidal M, N None or U	
		E	**2**	AB	1	P	**Specifically, for wind driven tides on the south coast of TX**
		M	2	AB	1, 3 None	Tidal M, N None or U	
12	Ocean Beach old code BB and FL = US	M	2	US	1,2 Important	Tidal N, P	Marine Intertidal Unconsolidated Shore, cobble-gravel, sand
		M	2	US	None	Tidal P	
13	Ocean Flat old code BB and FL = US	M	2	US	3,4 None	Tidal M, N None or U	Marine Intertidal Unconsolidated Shore, mud or organic, (low energy coastline)

* Within NWI layers, there remains uncertainty as to the extent of tidal-cypress land-cover. For this project, tidal-cypress extent was defined based on MD DNR data (Unpublished, Maryland DNR 2021).

		NWI code characters					
		First	Second	Third and fourth	Fifth	Sixth	Remaining
SLAMM Code	Name	System	Subsystem	Class	Subclass	Water Regime	Special modifiers ANY (h =Diked/ Impounded)
14	Rocky Intertidal	M	2	RS	All None	Tidal M, N, P None or U	Marine and Estuarine Intertidal Rocky Shore and Reef
		E	2	RS	All None	Tidal M ,N, P None or U	
		E	2	RF	2, 3 None	Tidal M, N, P None or U	
		E	2	AB	1	Tidal M, N None or U	
15	Inland Open Water	R	2	UB, AB	All, None	All, None	Riverine, Lacustrine, and Palustrine Unconsolidated Bottom, and Aquatic Beds
		R	3	UB, AB, RB	All, None	All, None	
	old code OW = UB	L	1, 2	UB, AB, RB	All, None	All, None	
		P	NA	UB, AB, RB	All, None	All, None	
		R	5	UB	All	Only U	
16	Riverine Tidal Open Water old code OW = UB	R	1	All	All None	Fresh Tidal S, R, T, V	Riverine Tidal Open water
				except EM	Except 2		**R1EM2 falls under SLAMM Category 6**
17	Estuarine Open Water (no h for diked / impounded) old code OW=UB	E	1	All	All None	Tidal L, M, N, P	Estuarine subtidal
18	Tidal Creek	E	2	SB	All, None	Tidal M, N, P Fresh Tidal R, S	Estuarine Intertidal Streambed
19	Open Ocean old coed OW = UB	M	1	All	All	Tidal L, M, N, P	Marine Subtidal and Marine Intertidal Aquatic Bed and Reef
		M	2	RF	1,3, None	Tidal M, N, P None or U	
20	Irregularly Flooded Marsh	E	2	EM	1, 5 None	P	Irregularly Flooded Estuarine Intertidal Emergent marsh
		E	**2**	US	2, 3, 4 None	P	**Only when these salt pans are associated with E2EMN or P**
22	Inland Shore old code BB and FL = US	L	2	US, RS	All	All Nontidal None or U	Shoreline not pre-processed using Tidal Range Elevations
		P	NA	US	All, None	All Nontidal None or U	
		R	2, 3	US, RS	All, None	All Nontidal None or U	
		R	4	SB	All, None	All Nontidal None or U	
23	Tidal Forested Wetland	P	NA	SS, FO	All, None	Fresh Tidal R, S, T	Tidally influenced swamp
24	Blank	No-Data					
25	Flooded Developed Dry Land						
26	Flooded Cypress Swamp						

***** h=Diked/Impounded - When it is desirable to model the protective effects of dikes, an additional raster layer must be specified.

****** Farmed wetlands are coded Pf
All: valid components or none listed
None: no Subclass or Water regime listed
U: Unknown water regime
NA: Not applicable

Water Regimes	
Nontidal	A, B, C, E, F,G, J, K
Saltwater Tidal	L, M, N, P
Fresh Tidal	R, S,T, V

Note: We will run into illegal codes and have to categorize by intent.
Old codes BB, FL = US
Old Code OW = UB

Appendix B: SLAMM GIS Codes

GIS Code	Color	Name
1		Developed Dry Land
2		Forested Dry Land
3		Forested Wetland
4		Tidal Cypress Swamp
5		Inland Fresh Marsh
6		Tidal Fresh Marsh
7		Transitional Salt Marsh
8		Regularly-flooded Marsh
9		NonForested Dry
10		Estuarine Beach
11		Tidal Flat
12		Ocean Beach
13		Ocean Flat
14		Rocky Intertidal
15		Inland Open Water
16		Riverine Tidal
17		Estuarine Open Water
18		Tidal Creek
19		Open Ocean
20		Irregularly-flooded Marsh
22		Inland Shore
23		Tidal Forested Wetland
24		Blank
25		Flooded Developed Dry Land
26		Flooded Cypress Swamp

Appendix C: Great Diurnal Tide Ranges in Study Area (m)

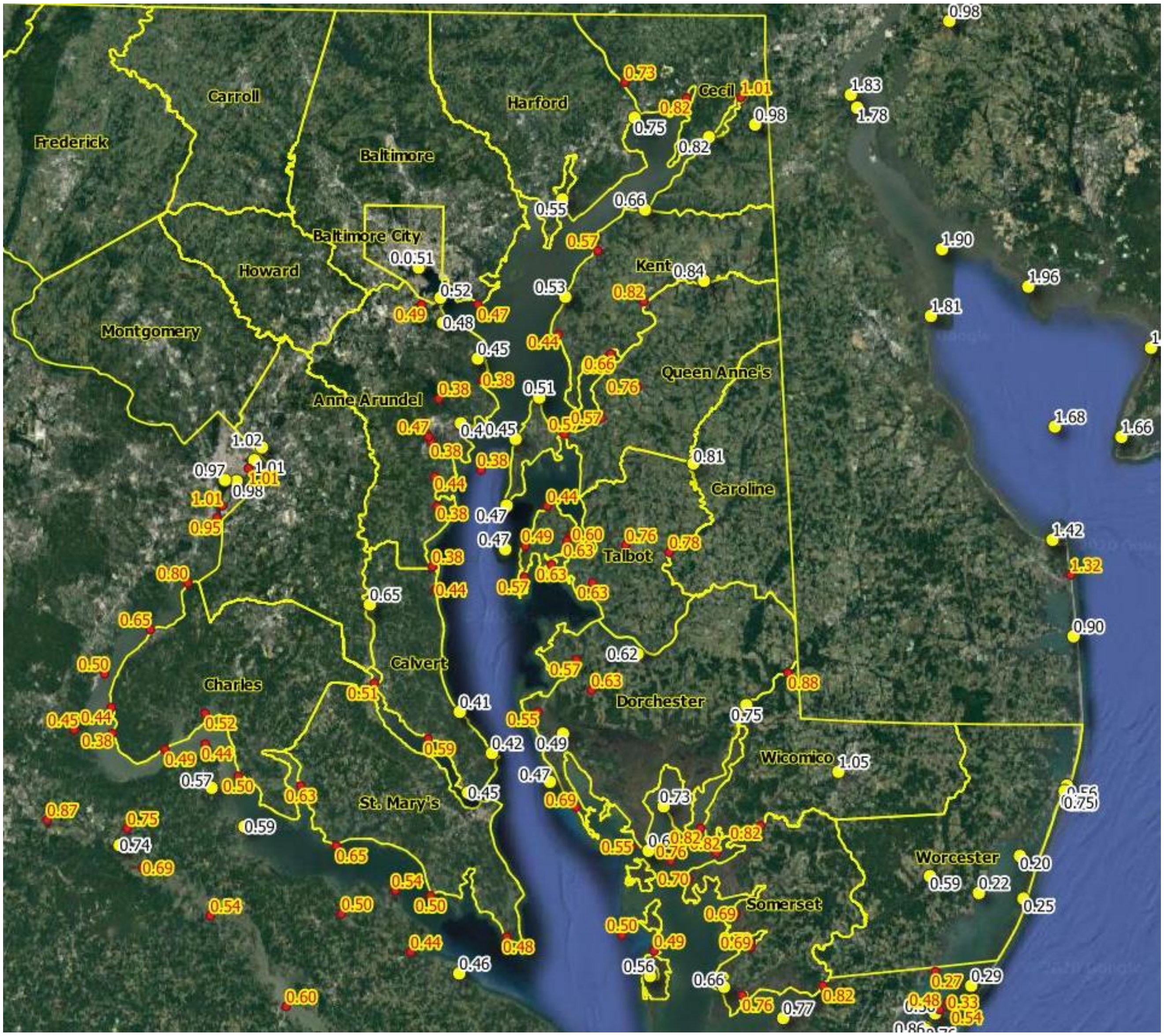

Figure 28. Great diurnal tide ranges (m) from NOAA gauges (black text) and estimated from tide tables (red text)