Advancing Existing Assessment of Connecticut Marshes' Response to SLR

Final Report

September, 2016

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Northeast Regional Oceans Council

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NROC Report USF&W Grant Number F14AC01001

This project is supported in full by the
U.S. Fish and Wildlife Service:
Award # F14AC01001

Acknowledgements

Warren Pinnacle would like to thank the following individuals for their support during this project:

Sarah Hamm, Dewberry, LLC.

David Kozak, CT DEEP

Stephen Lloyd, The Nature Conservancy

Kevin O'Brien, CT DEEP

Nathan Vinhatiero, RPS

Thanks to the Association of United States Delegates
to the Gulf of Maine Council (USGOMA)
for their assistance

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Acronyms and Abbreviations List

CT	Connecticut
DEM	Digital Elevation Map
FEMA	US Federal Emergency Management Agency
GCM	General Climate Model
GIS	Geographic Information Systems
GT	Great Diurnal Tide Range
HTU	Half-Tide Units (highest tide each day minus the mean tide level)
in.	Inches
IFM	Irregularly-Flooded Marsh
LiDAR	Light Detection and Ranging– method to produce elevation data
LRR	Linear Regression Rate
m	Meters
MEM	Marsh Equilibrium Model
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
NED	USGS National Elevation Dataset
NLD	National Levee Database from the U.S. Army Corps of Engineers
NEIWPCC	New England Interstate Water Pollution Control Commission
NOAA	United States National Oceanic and Atmospheric Administration
NWI	National Wetlands Inventory
NYSERDA	New York State Energy Research and Development Authority
RFM	Regularly-Flooded Marsh
RIM	Rapid Ice Melt
RMSE	Root Mean Standard Error
SD	Standard Deviation
SLAMM	Sea-level Affecting Marshes Model
SLR	Sea-Level Rise
STORET	EPA Data Warehouse
SWEL	FEMA Stillwater Elevation
TSS	Total Suspended Solids
UConn	University of Connecticut
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
UTM	Universal Transverse Mercator (UTM) conformal projection
VDATUM	NOAA Product for converting vertical datums
WBE	Wetland Boundary Elevation (coastal-wetland to dry land boundary)
WPC	Warren Pinnacle Consulting, Inc.

1 Background

Effective conservation planning and management in coastal communities is complicated by multiple and often competing objectives. Changes in climatic and ecological conditions and development footprints further complicate meeting these objectives. For example, accelerating rates of sea-level-rise (SLR) require coastal managers to consider not only existing tidal-flooding conditions, but also potential changes to tidal-flooding within marsh systems and adjacent developed upland before adopting management strategies involving the restoration or redirection of tidal flow.

In 2013 and 2014, the New England Interstate Water Pollution Control Commission (NEIWPCC) and the state of Connecticut funded a marsh-habitat migration study for the entirety of coastal Connecticut. The goal of the project was to use the Sea Level Affecting Marshes Model (SLAMM) to identify potential responses of Connecticut's coastal marshes and adjacent upland areas to anticipated increases in mean-tide water level elevations in Long Island Sound (LIS) and Connecticut's estuarine embayments.

The current study used the previous project as a starting point with the goal of refining SLAMM projections and to use spatial analysis for identifying and characterizing potential marsh migration pathways. SLAMM simulations were updated to include:

- Accounting for road effects on marsh migration.
- New LiDAR data where available.
- Improvements of modeled spatial hydraulic connectivity by detailed hydrologic enforcement of elevation data.
- Improved modeling of tidal muting due to man-made barriers that restricts flow in specified areas.
- Marsh collapse that may occur during marsh transition.
- The effects of storm surge inundation on infrastructure.

In addition to providing data for environmental adaptation, the results of this study can benefit policymakers in the transportation, infrastructure, drinking water, and electrical utility sectors through:

1. Identification and characterization of the effect of increased sea-level on tidal flooding of roads and critical infrastructure. This information has been output by SLAMM and can be leveraged by CT DOT as well as other agencies.
2. Assessment of the combined effects of storm surge and SLR on infrastructure. Infrastructure risk was investigated given these additive effects.

3. Information sharing. Results and data are available to be shared with those most likely to use it to develop plans at the local, regional and state-wide level in a way that clearly and readily transfers the information to key tidal marsh and infrastructure managers.

The main deliverables of this project are SLAMM land cover prediction maps, land and infrastructure inundation maps. The general model setup, input parameter and data selection were described in the report of the previous project and downloadable at http://warrenpinnacle.com/prof/SLAMM/LISS/NEIWPCC_Final_CT_Report_Amended.pdf. The current report presents the updated methodologies included in these new simulations, new data inputs and amendments, and summarizes the primary project results with a focus on potential marsh migration pathways.

1.1 Model Summary

Changes in tidal marsh area and habitat type in response to sea-level rise were modeled using SLAMM 6. 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 (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; Titus et al. 1991).

The latest SLAMM capabilities being used in this project are summarized below. A detailed description of the general model processes, underlying assumptions, and equations can be found in the SLAMM 6.7 Technical Documentation (available at http://warrenpinnacle.com/prof/SLAMM6/).

Recently SLAMM has been updated to include infrastructure and marsh collapse. The new infrastructure code allows for the input of multiple point shapefiles representing the locations of critical infrastructure. Road and railroad input is required to be a line shapefile which is then divided into 5 m segments by SLAMM in order to characterize inundation on a segment-by-segment basis. Inundation for five inundation elevations (designated as "H1" to "H5") above Mean Tide Level (MTL) can be modeled. In the current model application the "H1" inundation was the 30-day inundation height, H2 the 60-day inundation height, H3 the 90-day inundation height, H4 the 10-year storm surge height, and H5 the 100-year storm surge height. SLAMM outputs inundation results for each type of infrastructure as GIS database attributes associated with each line or point shape.

Another SLAMM model update included is the accounting for marsh collapse, a process that represents the loss of elevation capital a marsh may undergo when transitioning from one marsh type to another. Through a collaboration with Dr. David Burdick at the University of New Hampshire, data were obtained to characterize this elevation loss that may occur when irregularly-flooded marsh is converted to regularly-flooded marsh and when regularly-flooded marsh is converted to tidal flat.

2 Methods

2.1 Study Area

The project study area was divided into 3 individual SLAMM projects, as shown in Figure 1:

- Area 1: Southwest Coast (1) and Housatonic river (2) watersheds
- Area 2: South Central Coast (3) and Connecticut river (4) watersheds
- Area 3: Southeast Coast (5), Thames (6) and Pawcatuck (7) rivers watersheds

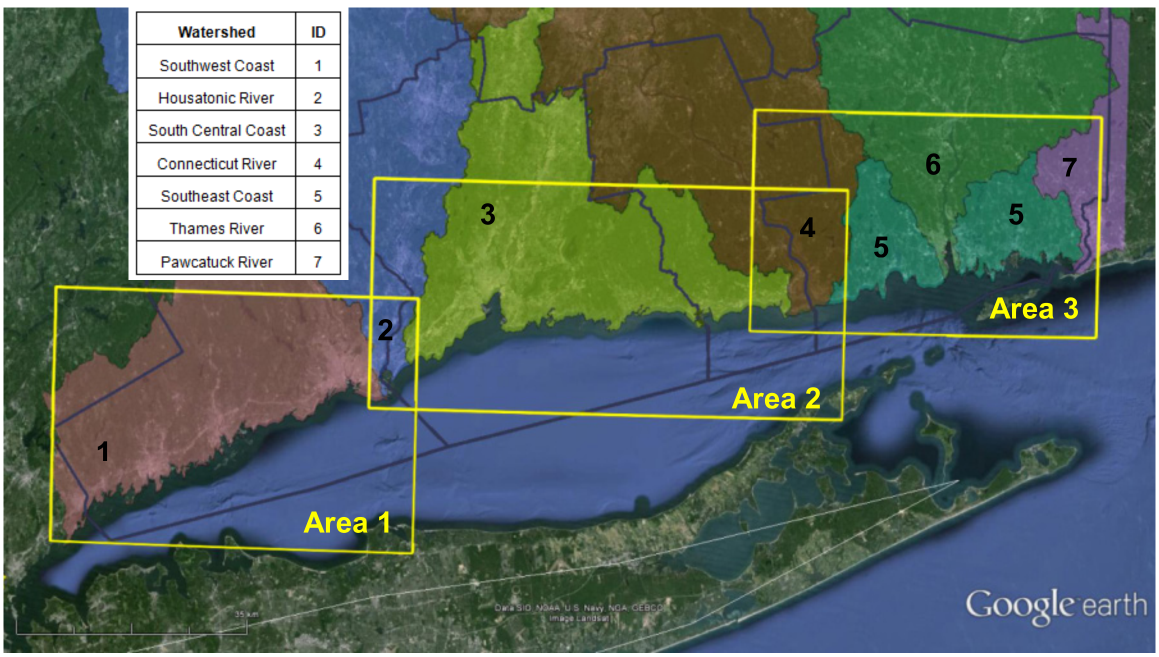

Figure 1. Project study area broken into the three individual SLAMM projects.
Colored areas are major watershed basins. Blue lines represent county boundaries.

SLAMM projections numerical results are summarized according to the major Connecticut watersheds.

2.2 Spatial Data

SLAMM is a raster-based model meaning that input cells are equally-sized squares arranged in a grid, like graph paper or a computer-based image. This section describes these critical 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

Compared to the previous project, some study areas have more recent elevation data available, in particular 2010 NRCS Eastern CT, 2011 USGS LiDAR and 2011 FEMA Quinnipiac River Watershed; while the rest of the study area is covered with same elevation data sources. These LiDAR sources and their native resolutions are shown in Table 1 and the extent of each LiDAR source is shown in Figure 2.

Table 1. Sources of CT LiDAR

Data Layer Name	Date	Nominal point spacing(*) (m)	Vertical Accuracy – RMSE (cm)	Source
Post-Sandy	2012	0.7	5	NOAA Digital Coast
USGS Lidar	2011	0.7	11	NOAA Digital Coast
Quinnipiac River Watershed	2011	0.5	15	NOAA Digital Coast
NRCS Eastern CT	2010	0.7	9	NOAA Digital Coast
FEMA CT	2006	1.25	10	NOAA Digital Coast
FEMA CT River	2004	0.6	15	NOAA Digital Coast
CT LiDAR	2000	3(**)	Unknown	UCONN
(*)Average point spacing of a LiDAR dataset typically acquired in a zig-zag pattern with variable point spacing along-track and cross-track.				
(**) 3 m x 3 m DEM resolution				

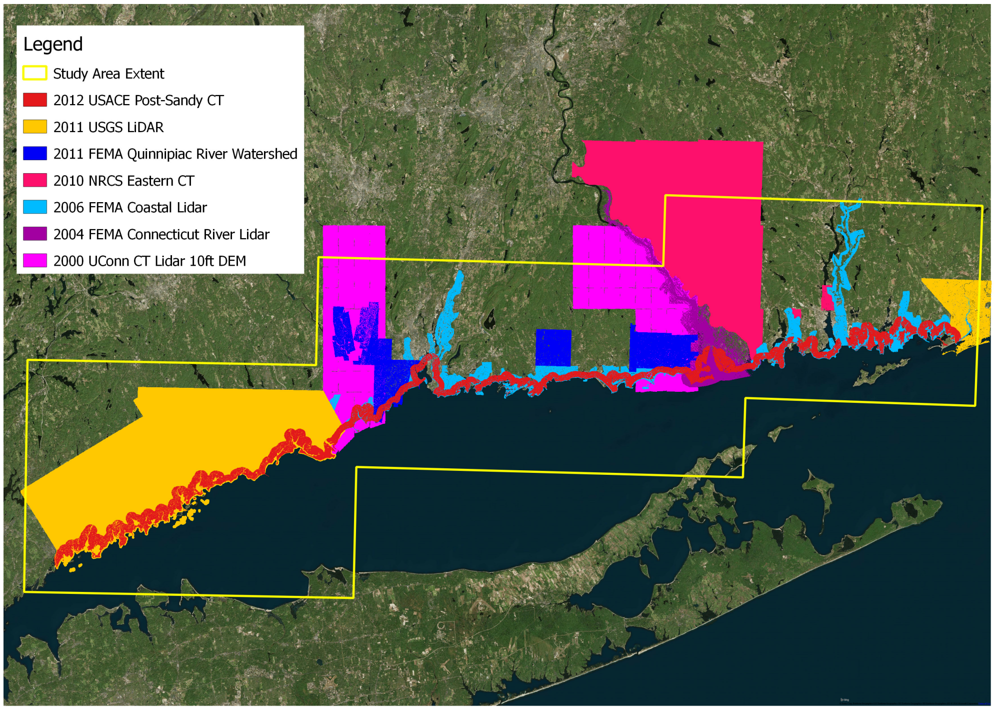

Figure 2. Elevation sources for Connecticut

These LiDAR data were combined and hydro-enforced (see Section 2.11.1 for more details) to create a 5m resolution Digital Elevation Model (DEM) maps for each study area.

2.2.2 Slope Layer

Accurate slopes of the marsh surface are an important SLAMM consideration as they are used in the calculation of the fraction of a wetland that is lost (transferred to the next class). Slope rasters were derived from the hydro-enforced DEMs using QGIS terrain models tool to create slope with output values in degrees.

2.2.3 Elevation transformation

The layers to convert elevation data from the NAVD88 vertical datum to Mean Tide Level (MTL), which is the vertical datum used in SLAMM, are identical to the previous project (see Appendix A).

2.2.4 Land coverage

The land cover layers are substantially the same as the ones used in previous project. However, under the suggestions of CTDEEP some changes were made to better reflect the actual observed land coverage. Table 2 shows the current land coverage for the entire study area contrasted with the input data used in the previous project. The different study-area total is mostly due to the fact that the current project includes areas of open water in the Long Island Sound and undeveloped dry land that previously was ignored as they did not have any effect on the land cover change dynamics. Other land cover changes are the suggested reclassification of some areas from estuarine beach to tidal flat.

Table 2. Land cover categories for entire Connecticut study area

Land cover type		Old Wetland Layer		Amended Wetland Layer	
		Area (acres)	**%**	**Area (acres)**	**%**
	Undeveloped Dry Land	196,599	45.1	199,076	41.5
	Estuarine Open Water	119,683	27.5	160,622	33.5
	Developed Dry Land	88,504	20.3	88,619	18.5
	Irreg.-Flooded Marsh	11,211	2.6	11,217	2.3
	Swamp	8,591	2.0	8,678	1.8
	Inland Open Water	4,561	1.0	4,632	1.0
	Estuarine Beach	2,457	0.6	1,629	0.3
	Regularly-Flooded Marsh	1,182	0.3	1,182	0.2
	Inland-Fresh Marsh	850	0.2	851	0.2
	Tidal-Fresh Marsh	743	0.2	762	0.2
	Tidal Swamp	667	0.2	671	0.1
	Riverine Tidal	452	0.1	642	0.1
	Transitional Salt Marsh	158	<0.1	159	0.0
	Inland Shore	120	<0.1	120	0.0
	Tidal Flat	98	<0.1	682	0.1
	Rocky Intertidal	62	<0.1	131	0.0
	Total (incl. water)	**435,938**	**100**	**479,670**	**100**

2.2.5 Dikes and Impoundments

The dike and impoundment layers are identical to the ones of previous project (See Appendix A).

2.2.6 Percent Impervious

These layers are from previous project without any modification (See Appendix A).

2.3 Model Timesteps

SLAMM simulations were run from the date of the initial wetland cover layer to 2100 with model-solution time steps of 2025, 2040, 2055, 2070, 2085 and 2100. Maps and numerical data were output for the years 2025, 2055, 2085, and 2100.

2.4 Sea Level Rise Scenarios

The accelerated sea-level rise (SLR) scenarios used in this analysis are different than those used in the previous project. The scenarios used previously were developed for a similar project undertaken in New York by the New York State Energy Research and Development Authority (NYSERDA) in conjunction with the project's advisory committee. The previously used scenarios corresponded to the maximum of the General Climate Model (GCM) and the minimum and maximum of the and Rapid Ice Melt (RIM) estimates as described in the New York State ClimAID report (Rosenzweig et al. 2011) as well as the intermediate scenario of 1 meter of SLR by 2100 (39.4 inches). The base year for these scenarios was 2002.

On January 1, 2016 the New York Governor's office released a new set of SLR scenarios for planning purposes. These scenarios are similar to those put forth in the ClimAID report and used in previous SLAMM simulations, as shown in Table 3 and Figure 3 SLR scenarios derived for New York City were assumed most relevant, and applied to the coast of CT. The most notable differences from the previous application are the two lower projections run for this project (the low and low-medium projections) that are lower than projections run previously.

Table 3. Sea Level Rise Scenarios applied

New York City/Lower Hudson Region					
Time Interval	Low Projection (mm)	Low-Medium Projection (mm)	Medium Projection (mm)	High-Medium Projection (mm)	High Projection (mm)
2002	0	0	0	0	0
2025	51	102	152	203	254
2055	203	279	406	533	762
2085	330	457	737	991	1473
2100	381	559	914	1270	1905

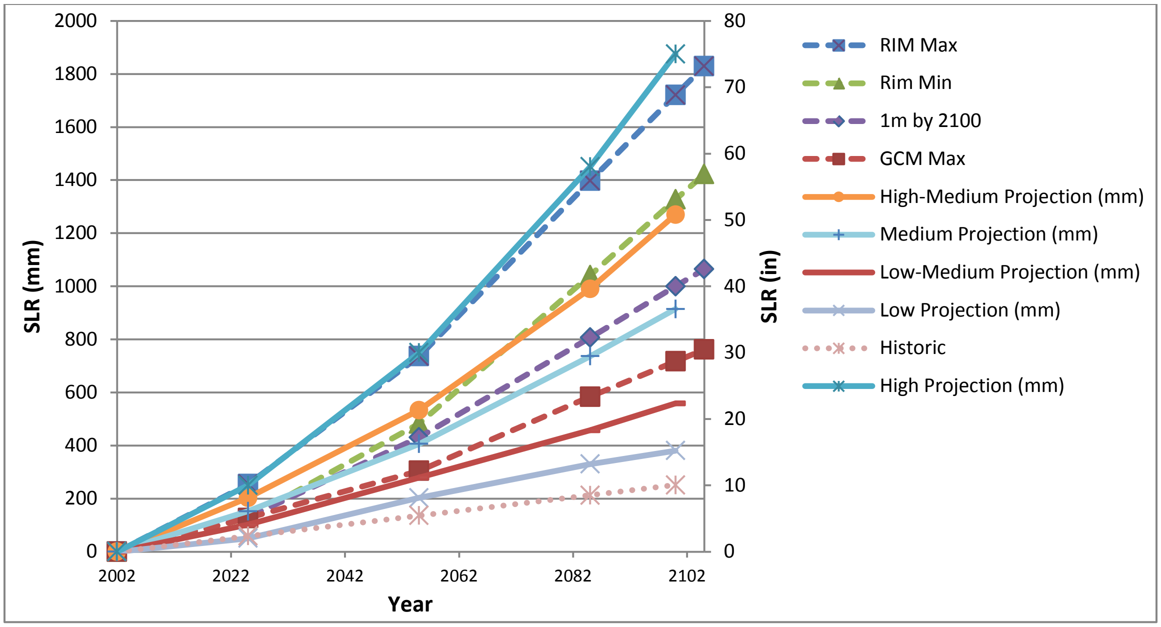

Figure 3. New accelerated SLR scenarios used in SLAMM simulations (solid lines).
The bottom dashed line shows the historic rate of SLR and the upper dashed lines show the scenarios run for the previous analysis (ClimAID scenarios).

According to NOAA gauges, historic sea level rise trends along the Connecticut coast range from 2.25 mm/yr at New London to 2.56 mm/yr. in Bridgeport. Each of the five scenarios simulated represents a significant acceleration of SLR from the local historical trend observed.

2.5 Tide Ranges

The general tidal regimes and their spatial variability are similar to the ones selected for the previous project. However, CT DEEP identified areas where existing structures such as culverts, bridges and ditches allow tidal flow, but the tidal amplitude is reduced as inflow and outflow are partially restricted. For these "tidally muted" areas, tidal regimes were modified to better reflect the current observed tidal ranges. A detailed description of the approach to derive the tidal ranges in muted-tidal areas is provided in Section 2.11.2.

2.5.1 Wetland Boundary Elevation

The wetland boundary elevation (WBE) parameter in SLAMM defines the boundary between coastal wetlands and dry lands (including non-tidal wetlands). These inundation parameters were obtained from daily water level data as described in Appendix A, and have remained generally the same except for the muted tidal areas described in Section 2.11.2.

2.6 Inundation Heights

Different inundation heights were considered to investigate the exposure of land and infrastructure to inundation.

2.6.1 30-day, 60-day, and 90-days inundation frequency

As discussed in more detail in Appendix A, the WBEs are estimated as the 30-day inundation heights (elevations that are statistically inundated once every 30 days) and these were determined using daily inundation data from the three locations in Connecticut with NOAA-verified water-level data available. One example that describes this statistic: if one year of data were available, the 30-day height would be the height that flooded for 12 days within that year (the 96.7 percentile daily-maximum water height.) Based on many SLAMM model application, we have found that this frequency of inundation is closely correlated with the wetland to dryland boundary defined within input wetland layers.

The 60 and 90 day periods were calculated in a similar way. Figure 4 shows the relationship between these inundation heights and the great diurnal tide ranges applied (GT) in meters. Essentially, the 60 and 90 day inundation heights are 7 and 7.4 cm higher than the 30 day inundation heights as one can see from Figure 5 and Figure 6.

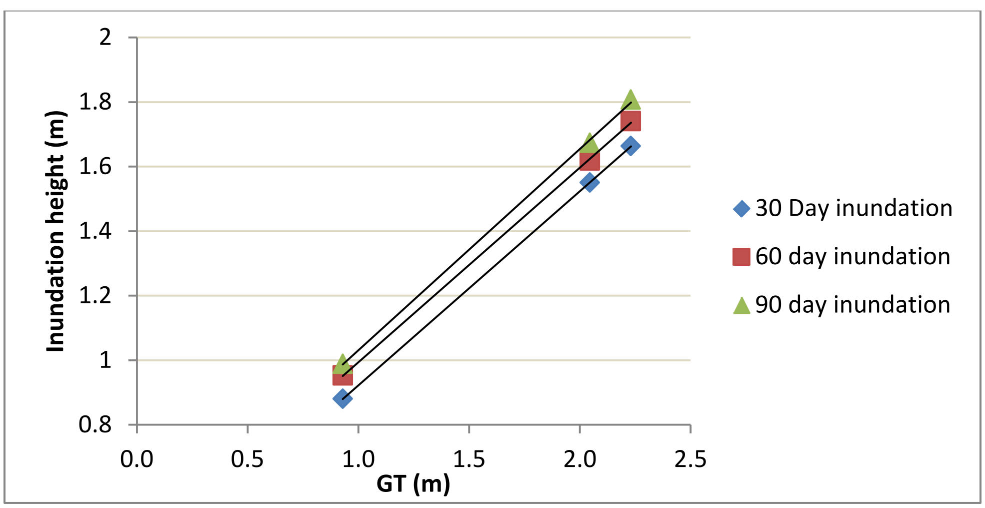

Figure 4. 30, 60 and 90 day inundation heights as a function of the Great Diurnal Tide Range (GT)

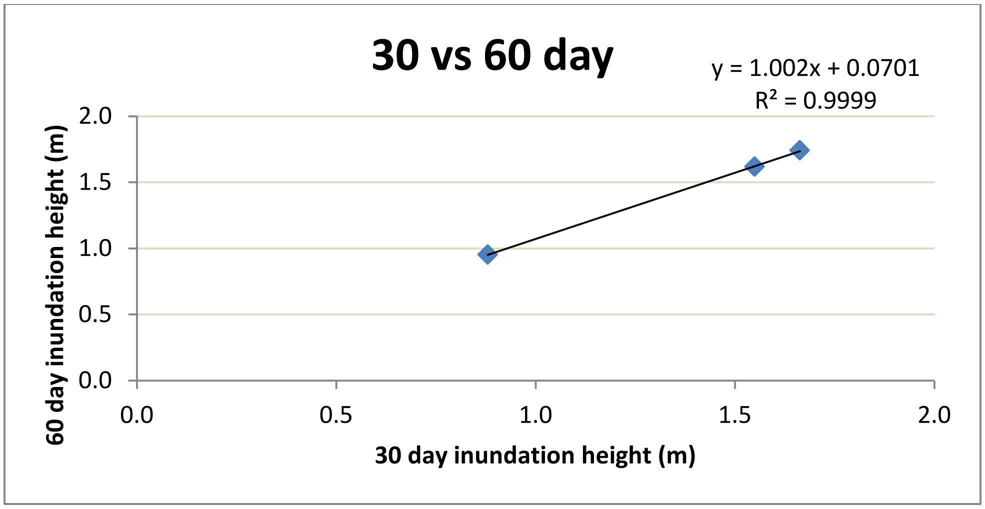

Figure 5. 30 day vs 60 day inundation height conversion

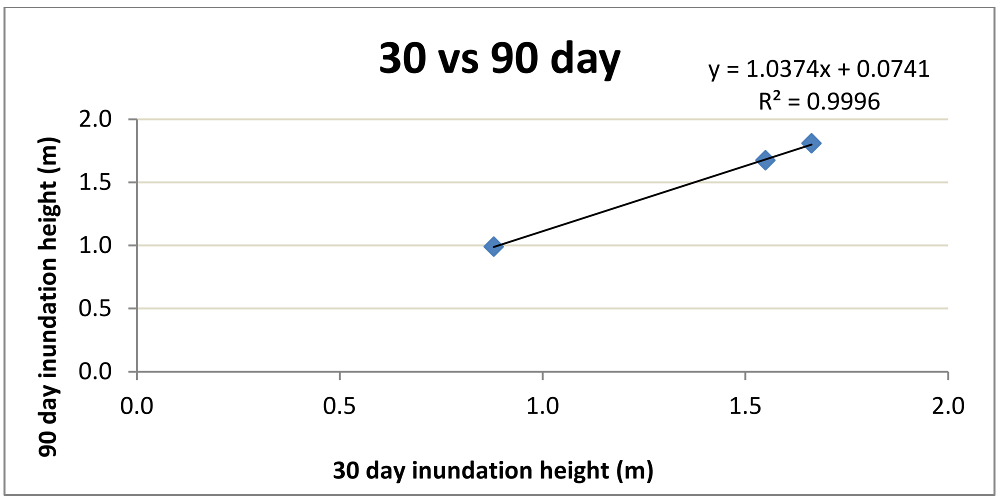

Figure 6. 30-day vs 90-day inundation height conversion

2.6.2 Storm Surge

This project builds on the previous application of SLAMM to Connecticut by including storm-surge heights for predicted 10- and 100-year storms. For comparison, it has been estimated that Hurricane Sandy's peak water level corresponded to a 103-year return period at the Battery in Lower Manhattan (Lopeman et al. 2015). The FEMA Stillwater Elevation (SWEL) transects were obtained from Dewberry, LLC. "The stillwater elevation is the elevation of the water due to the effects of the astronomic tides and storm surge on the water surface" (Federal Emergency Management Agency 2013). These transects were plotted along the CT coast, as shown in Figure 7 and Figure 8. Once the data were visualized, they were added to SLAMM as inundation heights (H4 and H5 inundation) using subsites with constant inundation height. Each subsite was chosen such that the inundation height variability within each subsite was less than 5 cm**.** Figure 7 and Figure 8 show the available data for 10 and 100 year storm, the green polygons in Figure 7 represent an example of derived SLAMM subsites over which storm surge was assumed to be uniform.

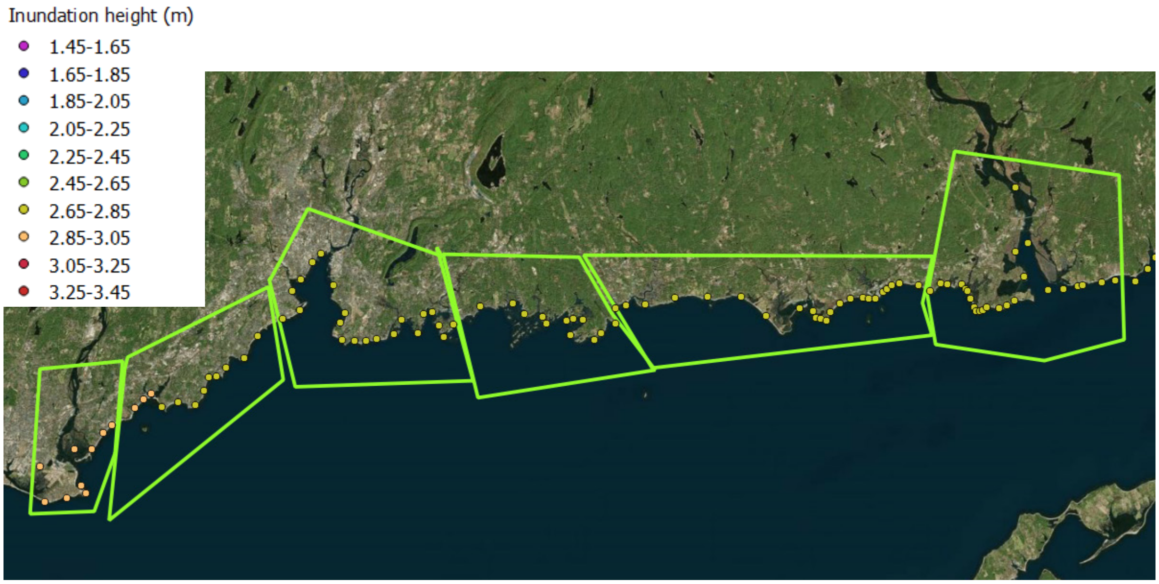

Figure 7. 1% SWEL transects

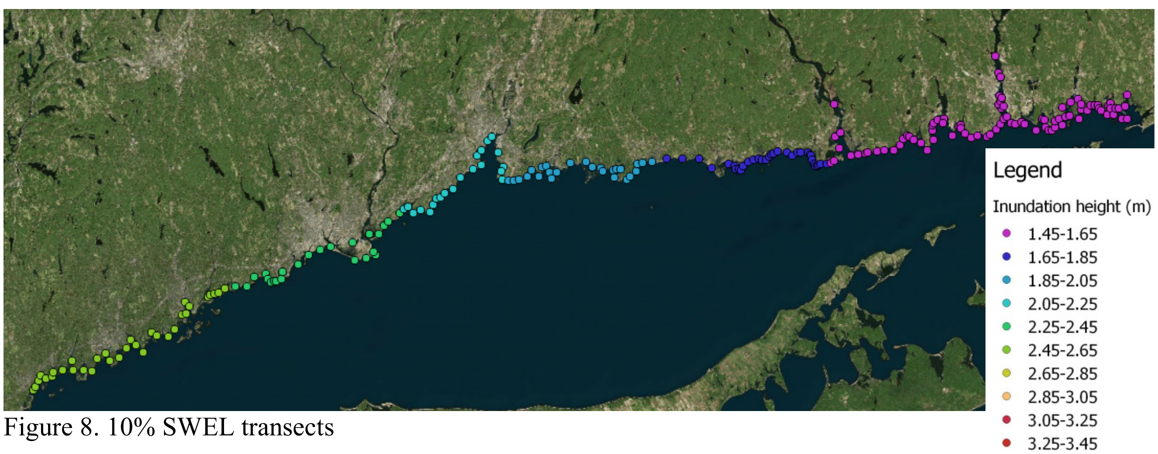

Figure 8. 10% SWEL transects

2.7 Accretion Rates

For all wetland classes, accretion rates and their modeled response to SLR (when applicable) have not been changed from previous project (see Appendix A).

2.8 Erosion Rates

Erosion rates have been assigned equal to the values defined in previous project. (see Appendix A).

2.9 Marsh Collapse Data

Recently, SLAMM has been updated to account for the loss of elevation capital that occurs when irregularly-flooded marsh is converted to regularly-flooded marsh and when regularly-flooded marsh is converted to tidal flat. This marsh collapse has been observed in many marsh systems when the above land-cover conversions occur.

Projections for this project include an implementation of this new model feature. Each transition includes a corresponding elevation loss based on data collected by Dr. David Burdick and his team at the University of New Hampshire (Burdick and Vincent 2015; Vincent et al. 2013). These data, collected in marshes in New Hampshire and Massachusetts, are summarized in Table 4. The weighted-average elevation losses were applied across the study areas and the standard deviation was used within the uncertainty analysis.

Table 4. Marsh Collapse Data

Transition Type	N	Weighted Average Elevation Loss (m)	Average Standard Deviation (m)
Irregularly-flooded Marsh to Regularly-flooded	70	0.07	0.02
Regularly-flooded Marsh to Tidal Flat	31	0.19	0.07

2.10 Infrastructure

The addition of infrastructure to the SLAMM simulations was the main improvement to model projections completed in this project. Roads, railroads, and point locations of critical infrastructure were added to simulations. An example map is presented in Figure 9.

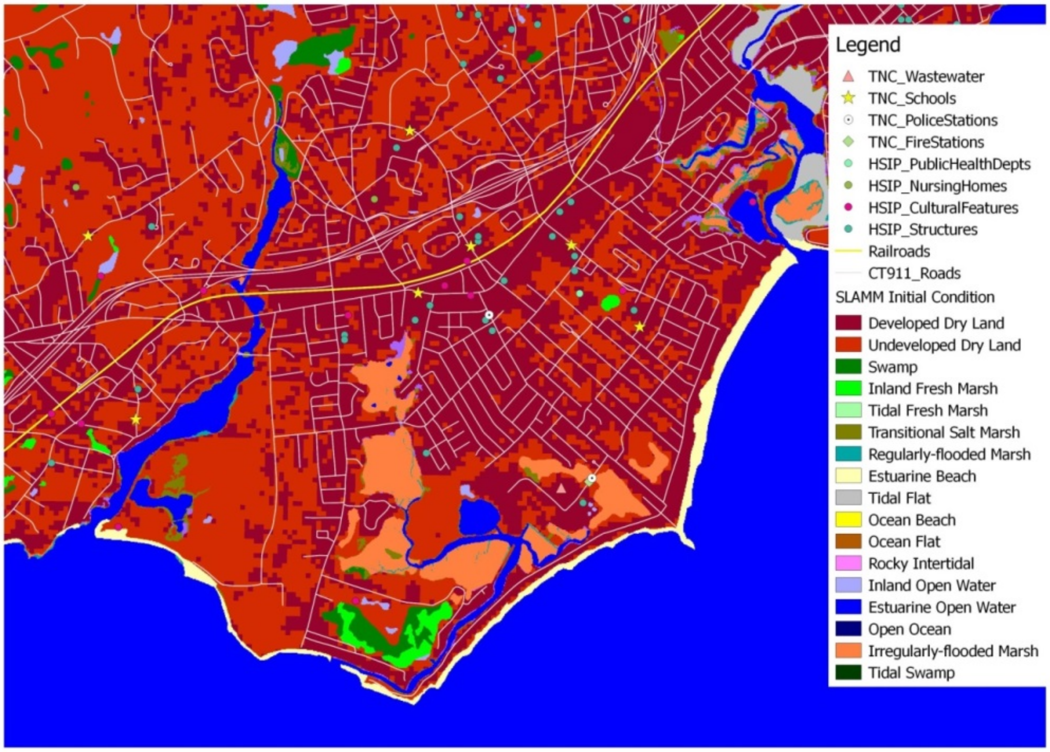

Figure 9. SLAMM land cover and infrastructure data example

As discussed in Section 2.10.1.1, detailed elevations of roads and railroads were included in the DEM in order to better account for the effects of this infrastructure on water flows and hydraulic connectivity, as well as to predict the approximate frequency of flooding of these resources given increased flooding due to a higher sea level.

In Connecticut, both public and restricted data layers were used to determine the locations of critical infrastructure. The Homeland Security Infrastructure Program provides a wealth of information. However, many of these datasets are For Official Use Only (FOUO). These datasets are marked as such in the following sections when used. It is important to note that these data are not all-inclusive. While the best available input data were used, there may be facilities that are not included.

2.10.1 Roads and Railroads

Data for roads in Connecticut were obtained from the CT Department of Emergency Services and Public Protection (DESPP_911CT_Roads). Railroad locations were determined from Homeland Security Infrastructure Program data (HSIP_Transground_Railroad.shp).

2.10.1.1 *Roads and railroads elevations*

The study area spatial layers are sampled at 5 m resolution. Although this resolution already provides quite an accurate description of the elevations spatial variabilities, the averaging of the elevation data within each 5 m x 5 m cells may decrease precision.

This is quite important when roads and railroads are considered. In fact this infrastructure often lies on a raised topography that acts as barrier to water flow. When considering a resolution of 5 m such elevation details may be lost and resulting elevation smoothed as the lower areas on the side of the road may be included in the cell average elevation calculation.

In order to include road and railroads elevations, several steps of data manipulation were necessary and are described below.

Once the infrastructure files with all the road and railroads lines were clipped to the study area extent, a 1 m buffer was added on both side of each transportation line.

A 1 m high-resolution elevation layer covering the entire study area was created from the LiDAR data described in Section 2.2.1 downloaded at their native resolution. For most of the study area this meant resampling elevation data whose initial native resolution was similar to 1 m and thus resulted in a minimal loss of spatial precision. The 2000 UConn CT LiDAR had the lowest native resolution at 3 meters.

Road and railroad elevations were extracted by selecting all elevations within the 2 m wide buffered lines. These elevations were then resampled at 5 m resolutions and assigned to each road and railroad broken down into 5 m segments. To model the impacts on water connectivity, the project DEM was also corrected using the updated elevations in the cells wherever roads and railroads are present.

2.10.2 Critical Infrastructure

Twenty-six individual infrastructure data layers were incorporated in the SLAMM simulation. These data were obtained from 3 different sources, as described below:

From the Connecticut Department of Energy and Environmental Protection (CTDEEP) :

- DESP_911_18N - ROADS
- Airports FAA
- Sewage Treatment Plants

From the Homeland Security Infrastructure Program:

- Amtrak Stations
- GNIS Cultural Features
- Fixed Guideway Transit Stations
- HSIP EPA FRS PowerPlants

- FBI Offices*
- Fire stations*
- GNIS Structures
- GNIS TransportationFeatures
- Hospitals
- NursingHomes
- PublicHealthDepts
- UrgentCareFacs

From The Nature Conservancy:

- Airports
- Electric Power Facilities
- Fire Stations
- Medical Facilities
- Police Stations
- Potable Water Facilities
- Schools
- Wastewater Facilities

Some of these data layers have usage constraints. Those layers marked with an asterisk (*) are For Official Use Only (FOUO) and therefore can only be distributed to Federal, State, local government and industry partners only. These data are not presented in this report but may be available on request from CTDEEP.

Infrastructure data were received as "point data" meaning that each piece of infrastructure is represented by a single lat.-long. location. The model assumes that when coastal water reaches the bare-earth DEM cell at the given point location that the infrastructure specified will be subject to flooding. While this method lacks some precision, it does give an overall accounting of relative vulnerability of infrastructure to tidal flooding and storm surge under SLR scenarios.

2.11 Model Calibration

In order to test the consistency of key SLAMM modeling inputs, such as current land cover, elevations, tide 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 swamp subject to regular saline tides, according to its elevation and tidal information, would be converted by SLAMM to a tidal swamp at time zero.

When time-zero results have significant land-cover changes additional investigation is required to determine if the current land cover of a particular area is better represented by time-zero conversion results rather than the initial wetland layer. If not, it may be necessary to calibrate data layers and model inputs to the actual observed conditions. The general rule of thumb is that if 95% of a major land cover category (one covering ≥ 5% of the study area) is not converted at time zero, then the model set-up is considered acceptable. However, land coverage conversion maps at time zero are always reviewed to identify any initial problems, and to make necessary adjustments to correct them. Model projections are reported from time-zero forward so that the projected land cover changes due only to SLR and not due to initial model and data inaccuracies.

Most of the model calibration was carried out in previous project with satisfactory result. Within the current project, the model was further calibrated to better account for water inundation paths.

2.11.1 Hydrologic Enforcement

Hydrologic enforcement refers to the process of correcting LiDAR land-surface elevations by modifying the elevations of artificial impediments, such as road fills or railroad grades, to simulate how man-made drainage structures, such as culverts or bridges, allow continuous downslope water flow (Poppenga et al. 2014). Without hydro-enforcement, downslope flow would be functionally dammed by the raised topography, creating false pooling on the upstream side (Poppenga et al. 2014) and tidal flow would be impeded to inundate upstream areas. Examples of model inconsistencies due to lack of hydrologic enforcement would be if an area classified as a tidal marsh does not get inundated because a bridge or culvert has not been hydro-enforced in the DEM. Similarly, areas identified as dry land could be regularly inundated because a tidal gate has not been properly accounted for.

Once initial model set up was completed, consistency between modeled inundation areas with land covers and elevations was closely analyzed. GIS analysis, along with correspondence with CTDEEP technical leads and examination of culvert databases, allowed our team to identify areas that were either inundated too frequently or not frequently enough. If water flow pathways did not accurately replicate current hydraulic conditions on the ground, the combined DEMs were edited by Warren Pinnacle Consulting by removing all elevation of impediments that were identified (e.g. adding missing culverts and/or removing bridges from the DEM). In practice this was achieved by adding a line of low elevation cells that would cut through the bridge or road that had impeded the water flow. An example is provided in Figure 10 where map (A) and (B) show the initial inundated areas in black with the irregularly-flooded marsh system not getting inundated. Investigation of aerial maps identified several bridges above water channels, in yellow in figure (C) that needed to be removed from the elevation layer. Finally in figure (D) the new inundations map covered all tidal-marsh systems.

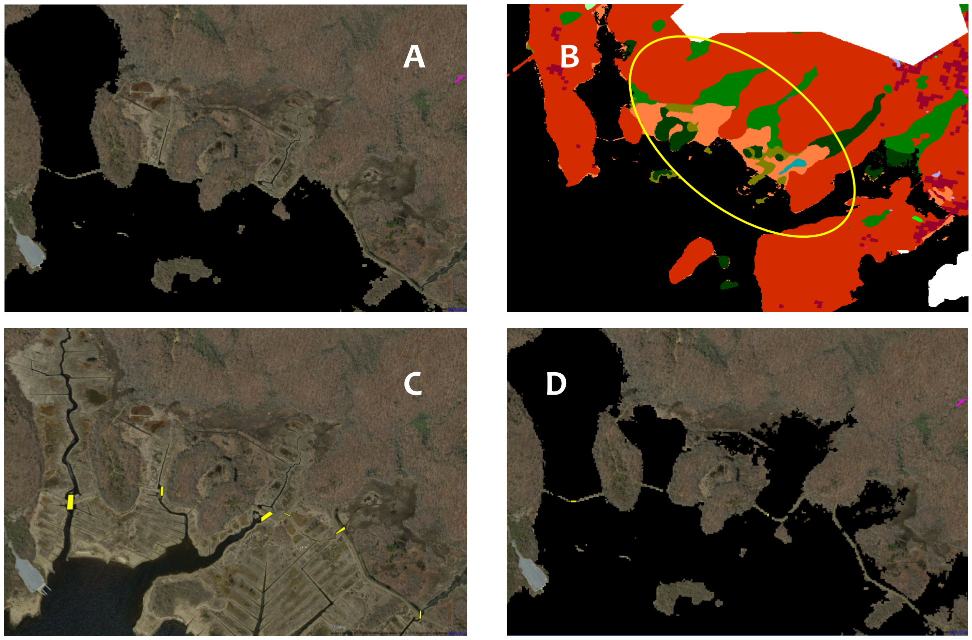

Figure 10. Hydro enforcement example at Barn Island, CT (Satellite Image: Google Maps).
(A) In black, initial inundation map, (B) Circled marsh are not getting inundated, (C) in yellow, polygons where elevations need to be lowered to remove artificial obstructions, and (D) new inundation map.

It is important to note that hydro-enforcement was not carried out only for current conditions, but also for future conditions where additional areas may become regularly inundated as a result of sea-level rise. As a result, this process identified several culverts whose current function is to allow drainage when excess water is accumulated in high-elevation areas upstream of road fills or railroad grades. In the future, these culverts may allow tidal water to regularly inundate these upstream areas.

2.11.2 Muted-Tidal Areas

Another model improvement was to consider effects when existing structures such as culverts, ridges and ditches allow tidal flow but tidal amplitude is reduced as inflow and outflow are partially restricted.

Adding muted-tidal areas was important for two main reasons. First, a better characterization of tide-inundation elevations improves the delineation of the wet to dry-land boundary. Second, wetlands in muted tidal areas may be more vulnerable to accelerated sea-level rise due to reduced sediment delivery and narrower wetland-elevation ranges. Both of these aspects are important for planning and management purposes in terms of planning for marsh expansion and also identifying marsh vulnerability. In some cases, to improve marsh viability, conservation efforts could be devoted in removing or replacing existing current man-made structures that are responsible for observed muted tides.

To assign the correct tidal amplitude, in the absence of available tidal data, land cover and elevation data were cross examined to manually identify the wetland boundary elevation (WBE). In practice, for each tidal muted area, we determined the approximate elevation in which land cover converts from irregularly-flooded marsh to dry land. This elevation was chosen as the WBE for the area. The great diurnal tide range (GT) was then derived using the general linear relationship between WBE and GT as described in Section 2.5.1. The selected muted GT and WBE were then applied to the muted tidal area and to the surrounding uplands that may become regularly inundate in the future because of sea level rise.

Generally, it is unclear if and how muted tides will change as a result of sea-level rise and it is unknown whether existing water-flow structures will be replaced. Therefore, within the model's uncertainty analysis, the tidal variability in these muted tidal areas was widened allowing maximum tides to extend up to the maximum tide ranges of unmuted adjacent regions and allowing minimum tides to be almost zero. The the "most likely" tide ranges remained close to the deterministic value assigned.

2.12 Model Setup

As noted above, the study area was divided into 3 individual SLAMM projects: Area 1: Fairfield County, Area 2: New Haven and Middlesex Counties, and Area 3: New London County. Within each of these areas project results were subdivided into seven watersheds, as shown in Figure 11 and summarized in Table 5

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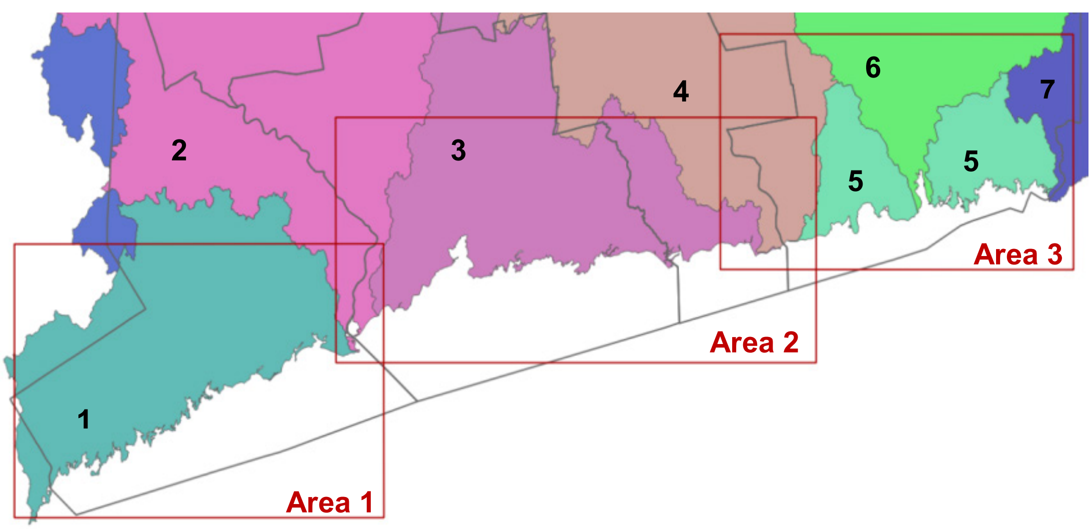


Figure 11. CT SLAMM project areas.

Table 5. Watersheds of coastal CT and the SLAMM project areas where represented

Watershed	Study Area
1 - Southwest Coast	1
2 – Housatonic River	1
3 - South Central Coast	2
4 - Connecticut River	2
5 - Southeast Coast	3
6 - Thames River	3
7 – Pawcatuck River	3

Project areas were also divided into subsites based on tide range and erosion parameters, as described in the following sections.

2.12.1 Area 1 - Fairfield County

Study Area 1, loosely referred to as Fairfield County, encompasses the Southwestern and Housatonic River watersheds. The coastal area of Southwest Coast watershed with elevations below 5 m above MTL is composed of 221,694 acres, of which nearly 76% is covered by dry land and 19% by estuarine open water. Swamp accounts for nearly 2% (4,423 acres) while the next most prevalent wetland category is irregularly-flooded marsh which makes up only 0.5 % of the study area (1,112 acres). The Housatonic watershed is comprised of 18,468 acres. Like The Southwest Coast, dry land and Estuarine open water dominate the landscape, followed by irregularly-flooded marsh which makes up 3.8% (710 acres) of the study area (Table 6).

It may be noted that the total areas of each of the watersheds in Area 1 (as well as those in areas 2 and 3) are less than those of the previous study. For example, The Southwest Coast watershed described in the previous project contained 237,676 acres as opposed to the 221,694 acres in the current study. These differences are mainly due to a reduction in the amount of Long Island Sound /Estuarine Open Water included in the watershed area. Additional small differences were also introduced when the wetland layers were amended based on input from CT DEEP (see section 2.2.4)

Table 6. Initial Wetland Coverage for the Southwest Coast watershed.

	Land cover type	Area (acres)	Percentage (%)
	Undeveloped Dry Land	120,487	54.3
	Developed Dry Land	47,710	21.5
	Estuarine Open Water	42,804	19.3
	Swamp	4,423	2.0
	Inland Open Water	3,482	1.6
	Irreg.-Flooded Marsh	1,112	0.5
	Estuarine Beach	617	0.3
	Inland-Fresh Marsh	342	0.2
	Regularly-Flooded Marsh	302	0.1
	Tidal Flat	195	0.1
	Inland Shore	119	0.1
	Riverine Tidal	27	< 0.1
	Rocky Intertidal	27	< 0.1
	Tidal Swamp	18	< 0.1
	Tidal-Fresh Marsh	15	< 0.1
	Trans. Salt Marsh	14	< 0.1
	Total (incl. water)	**221,694**	**100.0**

Table 7. Initial Wetland Coverage for the Housatonic River watershed.

	Land cover type	Area (acres)	Percentage (%)
	Developed Dry Land	6,582	35.6
	Undeveloped Dry Land	6,268	33.9
	Estuarine Open Water	3,885	21.0
	Irreg.-Flooded Marsh	710	3.8
	Swamp	315	1.7
	Regularly-Flooded Marsh	248	1.3
	Estuarine Beach	138	0.7
	Inland Open Water	115	0.6
	Tidal Flat	81	0.4
	Trans. Salt Marsh	44	0.2
	Inland-Fresh Marsh	38	0.2
	Tidal-Fresh Marsh	31	0.2
	Tidal Swamp	9	< 0.1
	Riverine Tidal	4	< 0.1
	Total (incl. water)	**18,468**	**100.0**

In order to account for spatially varying tide ranges, erosion rates, and storm surge inundation height, the Fairfield County project area was divided into six different input parametric subsites. Details for these study areas are shown in Table 8, while the boundaries of each subsite are shown in Figure 12. The tidal fresh marsh lower bound was set to 0.74 HTU and the Tidal Swamp boundary reduced to 0.77 HTU to reflect site-specific LiDAR data. Compared to previous project, new subsites were added to better describe the tidal regime moving upstream of Pine Creek and to reflect spatial variability of storm surge heights.

Table 8. Input subsites applied to Area 1

Subsite	**Description**	**Great Diurnal Tide Range - GT (m)**	**WBE (m above MTL)**	**Horizontal Erosion Rate (m/yr)**
Global	Area 1 not included in the subsites below	2.3	1.66	0
1	Erosion Zone - Stratford	2.3	1.66	0.06
2	Sikorsky Airport	1.2	1.02	0.06
3	Storm Surge 2*	2.3	1.66	0
4	Storm Surge 1*	2.3	1.66	0
5	Pine Creek	1.5	1.22	0
6	Pine Creek 2*	1.21	1.05	0

*New subsites added since the previous model application

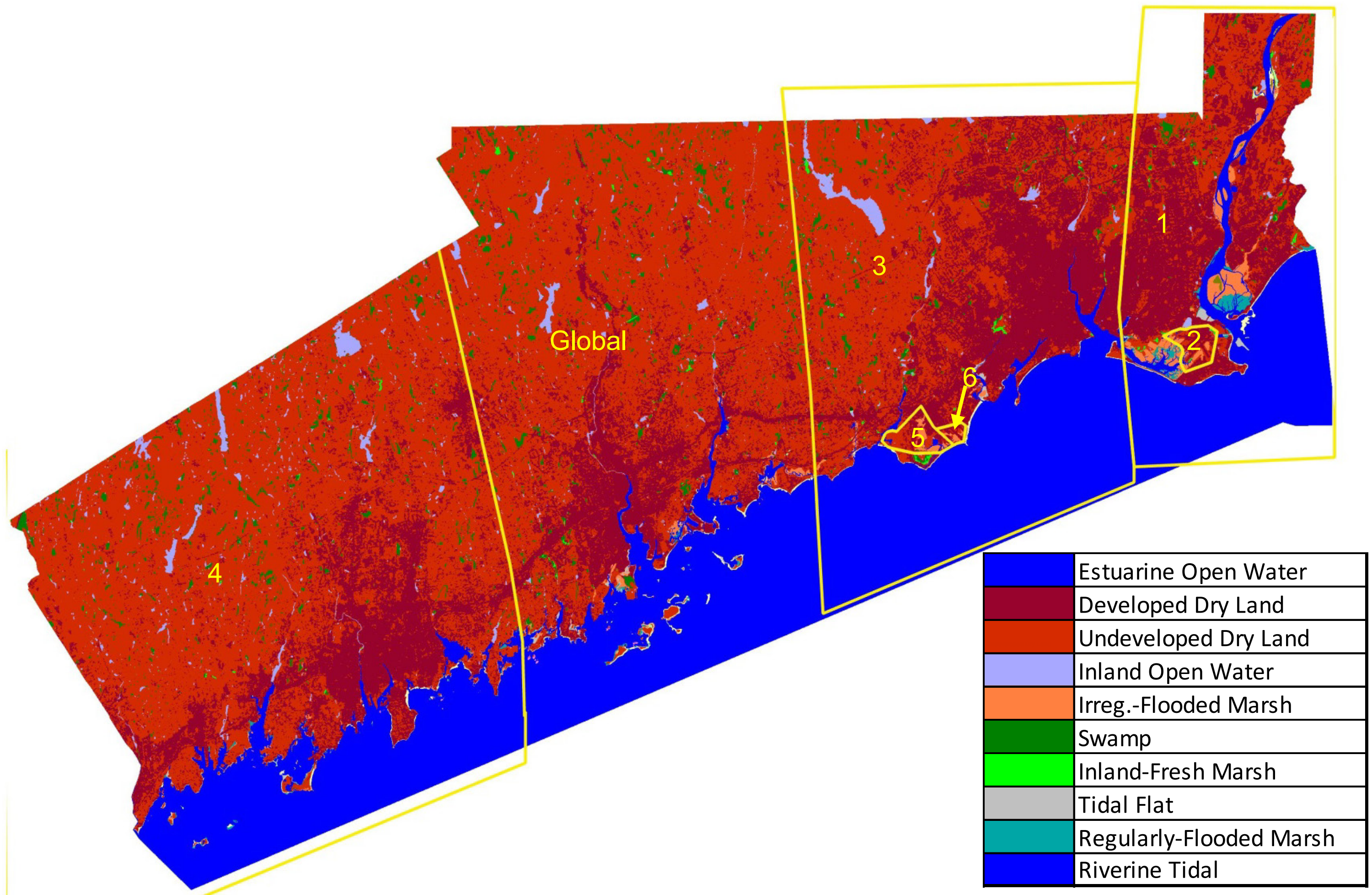


Figure 12. Current land coverage distribution for the Fairfield County Study Area.

Numbers correspond to subsites described in Table 8. The study area is limited to coastal zones with elevations below 5 m above MTL

Results of model calibration are presented in Table 9 for the Southwest Coast watershed and Table 10 for the Housatonic watershed. Both of these tables indicate there are conversions of greater than 5% of the initial wetland coverage in several categories. However, as discussed in section 2.10, these changes were accepted because these land cover categories had a small coverage, less than 2% of the study area and are explained by wetland layer corrections due to the high resolution of the elevation data.

Table 9. Southwest Coast Watershed Time-Zero Results (acres)

		Initial	2010	change in Acres	% change (- is loss)
	Undeveloped Dry Land	120,487	120,225	-263	-0.2
	Developed Dry Land	47,710	47,558	-152	-0.3
	Estuarine Open Water	42,804	42,817	13	0.0
	Swamp	4,423	4,410	-13	-0.3
	Inland Open Water	3,482	3,475	-7	-0.2
	Irreg.-Flooded Marsh	1,112	978	-134	-12.0
	Estuarine Beach	617	617	-1	-0.1
	Inland-Fresh Marsh	342	323	-19	-5.4
	Regularly-Flooded Marsh	302	430	127	42.1
	Tidal Flat	195	205	10	5.1
	Inland Shore	119	119	0	0.0
	Riverine Tidal	27	22	-5	-19.1
	Rocky Intertidal	27	27	0	0.0
	Tidal Swamp	18	18	0	-1.4
	Tidal-Fresh Marsh	15	14	0	-3.4
	Trans. Salt Marsh	14	305	291	2121.9
	Flooded Developed Dry Land	-	152	152	NA
	Total (incl. water)	**221,694**	**221,694**	0	0.0

Table 10. Housatonic River Watershed Time-Zero Results (acres)

		Initial	2010	change in Acres	% change (- is loss)
	Developed Dry Land	6,582	6,552	-30	-0.5
	Undeveloped Dry Land	6,268	6,202	-66	-1.1
	Estuarine Open Water	3,885	3,903	19	0.5
	Irreg.-Flooded Marsh	710	660	-50	-7.1
	Swamp	315	315	0	0.0
	Regularly-Flooded Marsh	248	295	46	18.7
	Estuarine Beach	138	138	0	0.0
	Inland Open Water	115	98	-17	-14.8
	Tidal Flat	81	92	11	13.9
	Trans. Salt Marsh	44	104	61	138.9
	Inland-Fresh Marsh	38	36	-2	-4.1
	Tidal-Fresh Marsh	31	31	-1	-1.9
	Tidal Swamp	9	9	0	-0.7
	Riverine Tidal	4	3	-1	-32.1
	Flooded Developed Dry Land	-	30	30	NA
	Total (incl. water)	**18,468**	**18,468**	0	0.0

2.12.2 Area 2 - New Haven and Middlesex Counties

The Area-2 project encompasses both New Haven and Middlesex counties which in turn make up the South Central Coast and Connecticut River watersheds.

Table 11 presents the wetland coverage of the South Central Coast watershed. The South Central Coast watershed is predominantly dry land, with irregularly-flooded marsh and swamp comprising the most dominant wetland types, covering 4.7% (5,486 acres) and 1.9% (2,223 acres) of the study area, respectively.

Table 11. Current land coverage distribution in South Central Coast watershed.

Land cover type	Area (acres)	Percentage (%)
Estuarine Open Water	57,759	49.9
Undeveloped Dry Land	26,627	23.0
Developed Dry Land	21,087	18.2
Irreg.-Flooded Marsh	5,486	4.7
Swamp	2,223	1.9
Estuarine Beach	651	0.6
Regularly-Flooded Marsh	507	0.4
Inland Open Water	474	0.4
Tidal Flat	330	0.3
Inland-Fresh Marsh	294	0.3
Tidal-Fresh Marsh	96	0.1
Rocky Intertidal	91	0.1
Tidal Swamp	82	0.1
Riverine Tidal	37	< 0.1
Trans. Salt Marsh	12	< 0.1
Inland Shore	1	< 0.1
Total (incl. water)	**115,758**	**100.0**

Like the South Central Watershed, the Connecticut River basin is predominantly dry land and Estuarine Open Water followed by irregularly-flooded marsh (comprising 6.9% of the watershed) and swamp (2.3% of the watershed). As shown in Table 12, other wetland types each make up less than 2% of the watershed areas according to this analysis.

Table 12. Current land coverage distribution in Connecticut River watershed.

Land cover type		Area (acres)	Percentage (%)
	Undeveloped Dry Land	23,020	62.8
	Estuarine Open Water	5,615	15.3
	Developed Dry Land	2,573	7.0
	Irreg.-Flooded Marsh	2,529	6.9
	Swamp	834	2.3
	Tidal-Fresh Marsh	598	1.6
	Riverine Tidal	567	1.5
	Tidal Swamp	374	1.0
	Inland Open Water	336	0.9
	Tidal Flat	65	0.2
	Regularly-Flooded Marsh	57	0.2
	Inland-Fresh Marsh	57	0.2
	Estuarine Beach	44	0.1
	Trans. Salt Marsh	6	< 0.1
	Total (incl. water)	**36,675**	**100.0**

In order to account for variations in tide ranges, erosion rates, storm surge variations, and wetland impoundments along the coast, thirty input subsites were utilized when setting up this project area. Table 13 presents the subsite areas with the GT, WBE, horizontal erosion rates and storm surge heights applied. Subsite areas are shown in Figure 13 and Figure 14. The "General Area 2," "CT River," and "Guilford" subsites are the largest input subsites and were used to represent the variation in GT (and WBE) that occurs moving from east to west in the Long Island Sound. The subsites representing the Hammock River, HVN Airport, Sybil Creek, and several areas of muted tide were added during the calibration process and through collaboration with CT DEEP. Two adjustments to the SLAMM elevation conceptual model were made: a reduction of the minimum boundary of Tidal Fresh Marsh to -0.18 HTU and Tidal Swamp to 0.4 HTU to reflect site-specific fresh-water flows and LiDAR data.

Table 13. SLAMM input subsites applied to Area 2

Subsite	**Description**	**Great Diurnal Tide Range - GT (m)**	**WBE (m above MTL)**	**Horizontal Erosion Rate (m/yr)**
Global Area 2	Area 2 not included below	2.1	1.1	0
1	CT river	1.1	0.94	0.12
2	Guilford	1.67	1	0.08
3	Housatonic	2.3	1.66	0.06
4	Hammock River	1	0.9	0.08
5	HVN airport	0.63	0.72	0
6	Storm surge 3	2.1	1.1	0
7	Sybil Creek	0.5	0.35	0
8	Muted Tide	0.88	0.7	0.12
9	Storm surge 1*	2.1	1.1	0
10	Storm surge 4*	1.67	1	0.08
11	Muted Tide 1*	0.8	0.8	0
12	Muted Tide 5*	0.46	0.6	0
13	Muted Tide 8*	0.96	0.9	0
14	Muted Tide 7*	0.8	0.8	0
15	Muted Tide 19*	0.8	0.8	0
16	Muted Tide 6*	0.63	0.7	0
17	Muted Tide 4*	0.46	0.6	0
18	Muted Tide 10*	0.46	0.6	0.08
19	Muted Tide 9*	1.13	1	0.08
20	Muted Tide 14*	0.63	0.7	0.08
21	Muted Tide 16*	0.96	0.9	0.08
22	Muted Tide 15*	0.96	0.9	0.08
23	Muted Tide 3*	0.3	0.5	0.08
24	Muted Tide 17*	0.63	0.7	0.08
25	Muted Tide 11*	0.8	0.8	0.08
26	Muted Tide 12*	0.8	0.8	0.12
27	Muted Tide 18*	0.63	0.7	0.12
28	Muted Tide 13*	0.63	0.7	0.12
29	Muted Tide 2*	0.46	0.6	0.12
30	TideGateGolf*	0.3	0.5	0

* New subsites added since the previous model application

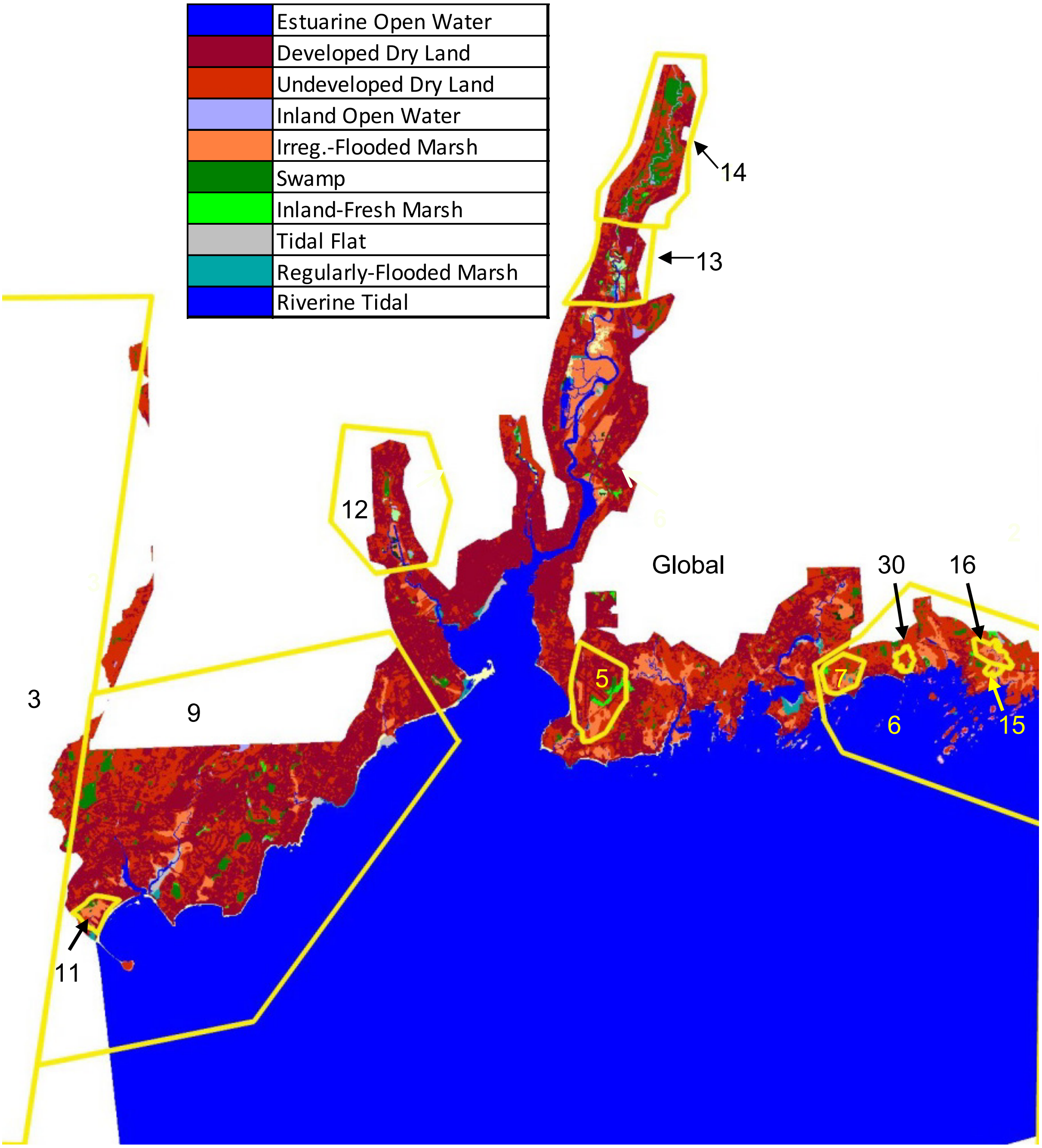


Figure 13. Current land coverage distribution for the Western half of the New Haven and Middlesex Counties Study Area. Numbers correspond to subsites described in Table 13.

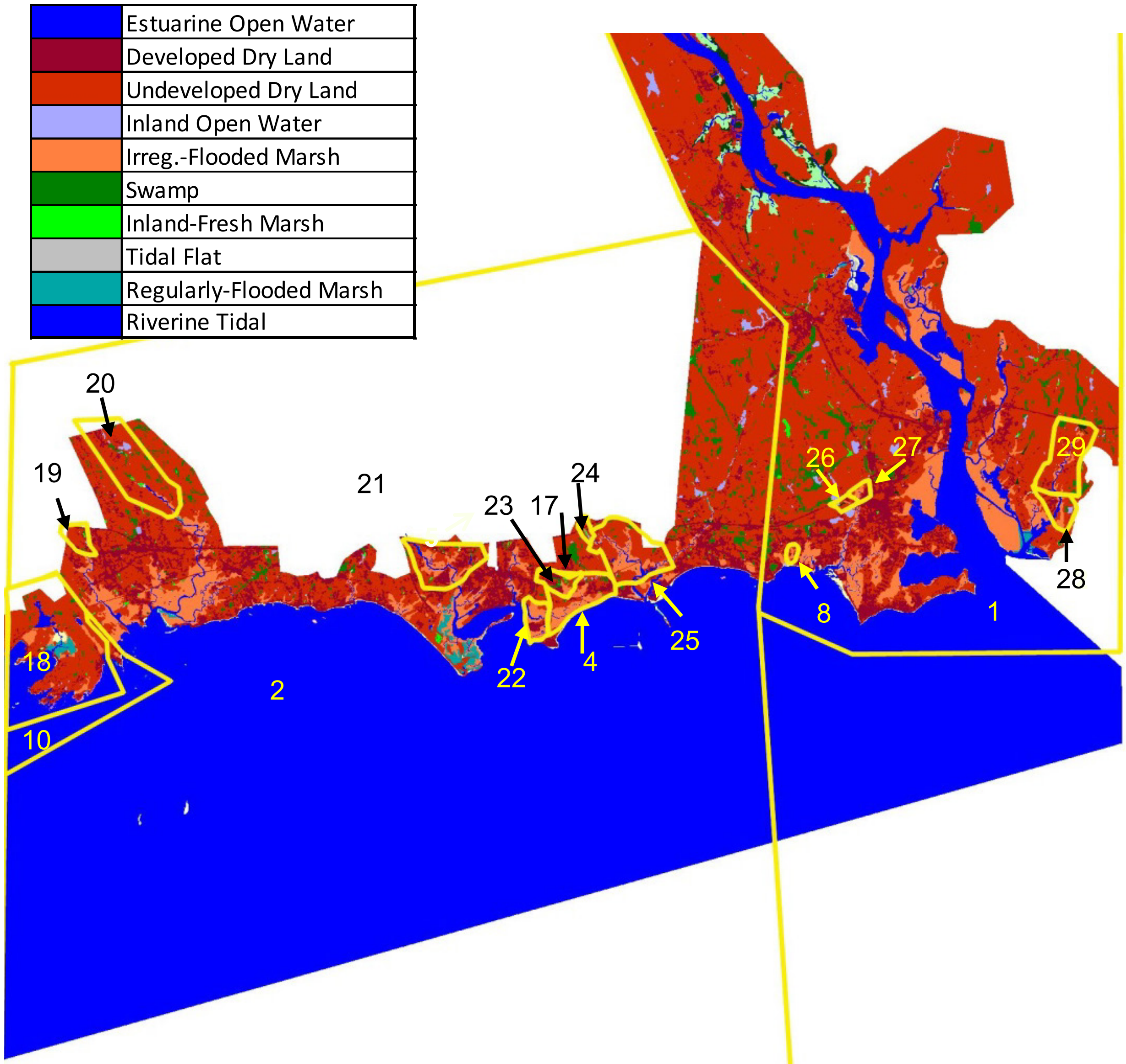


Figure 14. Current land coverage distribution for the Eastern half of the New Haven and Middlesex Counties Study Area. Numbers correspond to subsites described in Table 13.

Table 14 presents a comparison between the initial observed and time-zero wetland layers for The South Central Coast Watershed. Losses in undeveloped dry lands lead to gains in transitional marsh while losses in irregularly-flooded marshes resulted in increases in regularly flooded marsh. Within the 115,758 acre study area, approximately 377 acres of irregularly-flooded marsh converted (to regularly-flooded marsh) in the time-zero analysis. This represents 6.9% of the initial coverage of irregularly-flooded marsh and likely reflects the uncertainty in the elevation boundary between high and low marsh. The boundary between low and high marsh is a spatially variable buffer area more than a precise line; thus, wetland classification in this interface is affected by significant uncertainty. In addition, NWI marsh polygons do not map small low-lying marsh areas along drainage-ways and stream corridors, which are instead identified here using high resolution DEM (see Model Calibration section of previous report for more details).

Table 14. South Central Coast Watershed Time-Zero Results (acres)

		Initial	2010	change in Acres	% change (- is loss)
	Estuarine Open Water	57,759	57,793	33	0.1
	Undeveloped Dry Land	26,627	26,368	-259	-1.0
	Developed Dry Land	21,087	21,008	-80	-0.4
	Irreg.-Flooded Marsh	5,486	5,109	-377	-6.9
	Swamp	2,223	2,206	-17	-0.7
	Estuarine Beach	651	648	-3	-0.4
	Regularly-Flooded Marsh	507	863	356	70.3
	Inland Open Water	474	473	-2	-0.3
	Tidal Flat	330	345	16	4.8
	Inland-Fresh Marsh	294	285	-9	-3.2
	Tidal-Fresh Marsh	96	96	-1	-0.7
	Rocky Intertidal	91	84	-7	-7.7
	Tidal Swamp	82	77	-5	-5.7
	Riverine Tidal	37	32	-6	-15.3
	Trans. Salt Marsh	12	291	280	2356.9
	Inland Shore	1	1	0	0.0
	Flooded Developed Dry Land	-	80	80	NA
	Total (incl. water)	**115,758**	**115,758**	0	0.0

Time-zero calibration results for the Connecticut River watershed are reported in Table 15. Overall, there are not significant reclassifications of the major land cover types in the except for irregularly-flooded marsh that is converted by 7.2% due to the reasons discussed above.

Table 15. Connecticut River watershed Time-Zero Results (acres)

		Initial	2010	change in Acres	% change (- is loss)
	Undeveloped Dry Land	23,020	22,716	-304	-1.3
	Estuarine Open Water	5,615	5,691	76	1.4
	Developed Dry Land	2,573	2,565	-8	-0.3
	Irreg.-Flooded Marsh	2,529	2,347	-182	-7.2
	Swamp	834	829	-6	-0.7
	Tidal-Fresh Marsh	598	568	-30	-5.0
	Riverine Tidal	567	519	-48	-8.5
	Tidal Swamp	374	364	-10	-2.5
	Inland Open Water	336	336	0	0.0
	Tidal Flat	65	83	18	28.2
	Regularly-Flooded Marsh	57	256	199	349.8
	Inland-Fresh Marsh	57	57	0	-0.3
	Estuarine Beach	44	20	-24	-54.0
	Trans. Salt Marsh	6	315	309	5494.6
	Flooded Developed Dry Land	-	8	8	NA
	Total (incl. water)	**36,675**	**36,675**	0	0.0

2.12.3 Area 3 - New London County

This study area includes New London County in its entirety and covers the South East Coast, Thames River and Pawcatuck watersheds. Most of the marshes in this portion of the study area are located in the coastal area that includes Barn Island (a preferred location for marsh ecology studies). However, significant patches of marsh areas also exist along the coast in between.

Table 16 presents the wetland coverage for the Southeast Coast. This site is in fact made up of two different coastal areas divided by the Thames River, as shown in Figure 1. This study area is predominantly Estuarine Open Water and Dry Land, followed by Irregularly–Flooded Marsh (1.308 Acres or approximately 2% of the study area). The current wetland coverage for the Thames River watershed is presented in Table 17. Different from many of the other watersheds in this study, swamp is the dominant wetland type with 85 acres within the watershed. Landcover data for the smallest watershed in the New London study area, the Connecticut portion of the Pawcatuck River watershed, is shown in Table 18. Swamp is also the dominant wetland type in this watershed, with 54 acres (3.8 % of the study area) and 40 acres of irregularly-flooded marsh (2.8% of the study area).

Table 16. Current wetland coverage for the Southeast Coast watershed.

Land cover type		Area (acres)	Percentage (%)
	Estuarine Open Water	43,713	63.5
	Undeveloped Dry Land	15,799	23.0
	Developed Dry Land	6,456	9.4
	Irreg.-Flooded Marsh	1,308	1.9
	Swamp	742	1.1
	Tidal Swamp	181	0.3
	Inland Open Water	174	0.3
	Estuarine Beach	164	0.2
	Inland-Fresh Marsh	95	0.1
	Trans. Salt Marsh	81	0.1
	Regularly-Flooded Marsh	62	0.1
	Tidal-Fresh Marsh	21	< 0.1
	Rocky Intertidal	11	< 0.1
	Tidal Flat	8	< 0.1
	Total (incl. water)	**68,818**	**100.0**

Table 17. Current wetland coverage for the Thames River watershed.

Land cover type		Area (acres)	Percentage (%)
	Estuarine Open Water	6,552	39.0
	Undeveloped Dry Land	6,316	37.6
	Developed Dry Land	3,730	22.2
	Swamp	85	0.5
	Inland Open Water	47	0.3
	Irreg.-Flooded Marsh	30	0.2
	Inland-Fresh Marsh	24	0.1
	Estuarine Beach	14	0.1
	Tidal Swamp	7	< 0.1
	Regularly-Flooded Marsh	5	< 0.1
	Tidal Flat	4	< 0.1
	Rocky Intertidal	2	< 0.1
	Trans. Salt Marsh	1	< 0.1
	Tidal-Fresh Marsh	1	< 0.1
	Total (incl. water)	**16,819**	**100.0**

Table 18. Current wetland coverage for the Pawcatuck River watershed (CT portion only).

Land cover type		Area (acres)	Percentage (%)
	Undeveloped Dry Land	558	38.8
	Developed Dry Land	481	33.4
	Estuarine Open Water	294	20.4
	Swamp	54	3.8
	Irreg.-Flooded Marsh	40	2.8
	Riverine Tidal	6	0.4
	Inland Open Water	3	0.2
	Trans. Salt Marsh	1	0.1
	Inland-Fresh Marsh	1	< 0.1
	Tidal Swamp	0	< 0.1
	Total (incl. water)	**1,438**	**100.0**

In the initial analysis of Area 3, the site was divided into three subsites in order to accommodate spatial variations in tide ranges and erosion rates. During the second round of SLAMM application five additional subsites were added to capture differences in storm surge elevations and include additional areas of tidal muting. The input parameters assigned to corresponding subsite boundaries are shown in Table 19 and Figure 15.

Table 19. Tidal ranges and erosion rates for different SLAMM subsites in Area 3

Subsite	Description	Great Diurnal Tide Range - GT (m)	WBE (m above MTL)	Horizontal Erosion Rate (horz. m /yr)
Global Area 3	Area 3 not in the subsites below	0.92	0.84	0
1	Connecticut River	1.1	0.94	0.12
2	Erosion zone - Stonington	0.92	0.84	0.02
3	Storm surge 1*	0.92	0.84	0
4	Muted Tide 1*	0.71	0.75	0
5	Muted Tide 4*	0.8	0.8	0
6	Muted Tide 3*	0.7	0.7	0
7	Muted Tide 2*	0.7	0.7	0

* New subsites added since the previous model application

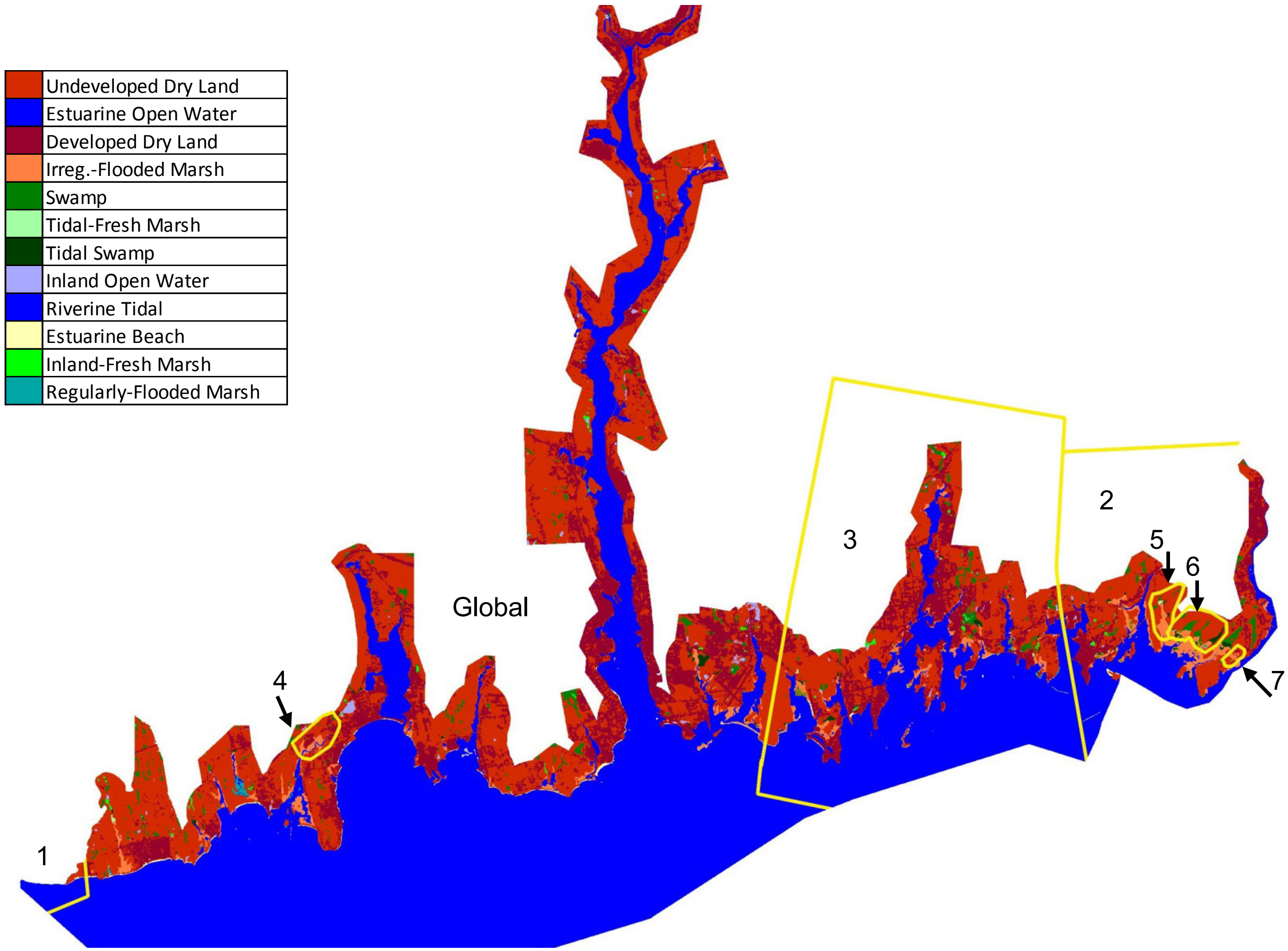


Figure 15. Current land coverage distribution for Area3 and SLAMM analysis subsites in black.
Numbers correspond to subsites described in Figure 15.

South East Coast watershed. Time-zero calibration results for this area are reported in Table 20 below. For this area, initial land cover changes are minimal indicating a good agreement between spatial data, parameters and tidal information. The change that may stand out the most is the large gain in regularly-flooded marsh. However, this result is somewhat expected as the boundary between low and high marsh is a spatially variable buffer area more than a precise line; thus, wetland classification in this interface is affected by significant uncertainty.

Table 20. South East Coast watershed Time-Zero Results (acres)

Land Cover		Initial	2010	change in Acres	% change (- is loss)
	Estuarine Open Water	43,713	43,716	3	0.0
	Undeveloped Dry Land	15,799	15,619	-180	-1.1
	Developed Dry Land	6,456	6,418	-39	-0.6
	Irreg.-Flooded Marsh	1,308	1,255	-53	-4.1
	Swamp	742	738	-4	-0.6
	Tidal Swamp	181	180	-1	-0.3
	Inland Open Water	174	174	0	0.0
	Estuarine Beach	164	167	2	1.4
	Inland-Fresh Marsh	95	94	-2	-1.7
	Trans. Salt Marsh	81	262	181	222.2
	Regularly-Flooded Marsh	62	113	51	81.7
	Tidal-Fresh Marsh	21	21	0	0.0
	Rocky Intertidal	11	11	0	-1.2
	Tidal Flat	8	11	3	42.5
	Flooded Developed Dry Land	-	39	39	NA
	Total (incl. water)	**68,818**	**68,818**	0	0.0

Thames River watershed. Time-zero calibration results for this area are reported in Table 21 below. There is a good agreement between the data and the model for this area.

Table 21. Thames River watershed Time-Zero Results (acres)

Land Cover	Initial	2010	change in Acres	% change (- is loss)
Estuarine Open Water	6,552	6,553	0	0.0
Undeveloped Dry Land	6,316	6,240	-76	-1.2
Developed Dry Land	3,730	3,716	-14	-0.4
Irreg.-Flooded Marsh	30	25	-5	-16.7
Swamp	85	85	0	0.0
Tidal Swamp	7	6	0	-5.0
Inland Open Water	47	47	0	-0.4
Estuarine Beach	14	14	0	0.2
Inland-Fresh Marsh	24	22	-2	-10.4
Trans. Salt Marsh	1	79	78	7804.9
Regularly-Flooded Marsh	5	11	6	109.1
Tidal-Fresh Marsh	1	1	0	-0.1
Rocky Intertidal	2	2	0	-0.7
Tidal Flat	4	4	0	0.1
Flooded Developed Dry Land	-	14	14	NA
Total (incl. water)	**16,819**	**16,819**	0	0.0

Pawcatuck River watershed. Time-zero calibration results for this area are reported in Table 22 below. For this area, there is also a strong agreement between the data and the model.

Table 22. Pawcatuck River watershed Time-Zero Results (acres)

Land Cover	Initial	2010	change in Acres	% change (- is loss)
Undeveloped Dry Land	558	549	-9	-1.6
Developed Dry Land	481	478	-3	-0.5
Estuarine Open Water	294	295	1	0.4
Swamp	54	54	0	-0.1
Irreg.-Flooded Marsh	40	39	-1	-3.1
Riverine Tidal	6	4	-1	-22.8
Inland Open Water	3	3	0	0.0
Trans. Salt Marsh	1	10	9	614.6
Inland-Fresh Marsh	1	1	0	0.0
Tidal Swamp	0.4	0.4	0	0.0
Regularly-Flooded Marsh	-	1	1	NA
Flooded Developed Dry Land	-	3	3	NA
Total (incl. water)	**1,438**	**1,438**	0	0.0

2.13 Uncertainty Analysis Setup

The base analyses (non-uncertainty-analysis runs, also called the "deterministic" model) consider a range of different possible SLR scenarios, but other model uncertainties such as variability in measured input parameters and spatial-data errors were not accounted for.

All of the site-specific data required by SLAMM, such as the spatial distribution of elevations, wetland coverages, tidal ranges, accretion and erosion rates, local sea-level rise and subsidence rates, may be affected by uncertainties that can propagate into the predicted outputs. The propagation of input-parameter uncertainty into model predictions cannot be derived analytically due to the non-linear spatiotemporal relationships that govern wetland conversion. The Monte Carlo uncertainty analysis module within SLAMM uses efficient Latin-Hypercube sampling of the input parameters (McKay et al. 1979). This module generates hundreds of prediction results that are then assembled into probability distributions of estimated wetland coverages. This module enhances the value of the results by providing confidence intervals, worst and best case scenarios, likelihoods of wetland conversion, and other statistical indicators useful to better characterize possible future outcomes and assist decision making. In addition, simplified maps showing the likelihood of wetland coverage in each location were produced for this project.

For each of the model input parameters, an uncertainty distribution was derived based on available site-specific data. Moreover, mechanistic considerations regarding the proper distributional family and the feasible bounds of the variable were considered. Distributions were derived reflecting the potential for measurement errors, uncertainty within measured central tendencies, and professional judgment (Firestone et al. 1997).

Because SLAMM calculates equilibrium effects of SLR based on relatively large time-steps, long-term erosion rates, accretion rates, and SLR rates were used to drive model predictions. Therefore, the uncertainty distributions described in the following section are based on long-term measurements rather than incorporating short-term variability within measurements. Cell-by-cell spatial variability has been considered for elevation data, but the majority of the input parameters have uncertainty distributions that vary on a subsite basis.

One important limitation that should be considered when interpreting these results is that the uncertainties of the general conceptual model in describing system behaviors are not taken into account (model framework uncertainty; Gaber et al. 2008). For example, within this uncertainty analysis, the flow chart of marsh succession is fixed. Low marshes must initially pass through a tidal flat category before becoming open water rather than directly converting to open water under any circumstance.

The next sections discuss each of the model's input parameters that are affected by uncertainties, and how they were handled within the uncertainty analysis for this project.

2.13.1 SLR by 2100

The SLR uncertainty distribution was not changed from the previous project. Sea level was assumed to vary between 0.35 m and 2.35 m by 2100 with a most-likely value of approximately 1 m. This analysis drew heavily on the recent NYC Panel on Climate Change (NPCC2) report (Rosenzweig and Solecki 2013) was used in addition to the ClimAID report (Rosenzweig et al. 2011).

2.13.2 Digital Elevation Map Uncertainty

Spatial elevation uncertainty was accounted for in the same manner as the previous project by applying to each cell a normal spatially correlated random field of elevation uncertainty with standard deviation of 0.1 m equal to the highest Root Mean Squared Error (RMSE) of the LiDAR data sources and a spatial correlation p-value of 0.2495.

2.13.3 Vertical Datum Correction

The uncertainty associated with the VDATUM correction was not modified from the previous project. NOAA characterizes the "maximum cumulative uncertainty" for each location in the documentation of the model (National Oceanic and Atmospheric Association 2010). Like the DEM uncertainty, the vertical-datum-correction uncertainty was also applied via spatially variable autocorrelated maps. The RMSE for the datum correction was set to 10 cm for the entire study area with the assumption of strong spatial autocorrelation with p-value of 0.2495 applied.

2.13.4 Great Diurnal Tide Range

Tide-range uncertainties determined in the previous project were applied here. In addition, the distributions derived for muted-tidal areas allowed their tide ranges to extend to the maximum of adjacent non-muted tidal amplitudes. This allowed the model to represent cases where tidal muting may not persist in the future.

2.13.5 Wetland Boundary Elevation

As in previous project, the potential variability of the WBE was estimated by considering the range between the 20-day and 40-day inundation elevations at the three tide stations that have this information. The maximum difference between 20/40-day and the 30-day inundation elevation was 5 cm. Uncertainty distributions for all WBEs were modeled as Gaussian distributions with a standard deviation equal to 5 cm.

2.13.6 Erosion

Marsh erosion was modeled using a uniform distribution ranging from 0 m/yr to 2.0 m/yr. Swamp and Tidal Flat erosion uncertainty were assigned to triangular distributions ranging between 0 m/yr and 2.0 m/yr with most likely rates varying spatially and equal to the values used in the base analysis. These distributions are the same as the ones used in the previous project.

2.13.7 Accretion

The accretion-rate response curve distributions determined in previous project were used here.

2.13.8 Marsh Collapse

Marsh-collapse uncertainty was estimated using the standard deviation data summarized in Table 4, and assuming a normal distribution for both irregularly- and regularly-flooded marsh collapse.

3 Results and Discussion

The primary model outputs for deterministic results are prediction maps of the entire study area in 5-meter resolution. One land-cover map is produced for each SLR Scenario and each year modeled.

Tables of results can also be instructive as they give a birds-eye view of overall trends over time. In the following sections, deterministic model results are presented for the entire study area. These results are also reported individually for each of the seven modeled watershed areas in Appendix D. Tables of land-cover acreage at each time step for each SLR scenario simulated are included, as well as summary tables showing the percentage loss and acreage gain for selected land-cover types. It is important to note that changes presented in the summary tables are calculated starting from the 2010 time-zero land cover conditions and thus represent projected land-cover changes as a result of sea-level rise only.

3.1 Entire Study Area

Within the coastal-Connecticut study area, irregularly-flooded marshes are the most vulnerable category to sea-level rise, with predicted losses ranging from approximately 500 acres to almost total loss by 2100 (Table 23). High marsh is also, by far, the most prevalent coastal wetland type in the Connecticut study area. These high marsh losses may be in part compensated by gains in transitional marsh establishing where land was initially dry and low marsh (regularly-flooded marsh) that is predicted to replace high marsh.

Other vulnerable habitats include tidal-swamps, tidal-fresh marshes, and estuarine beaches. In addition to these wetland losses, up to approximately 9,000 acres of developed dry land is predicted to fall below the WBE boundary and thus to become flooded at least once per month.

Table 23. Predicted change in land covers from 2010 to 2100 for the entire study area

Land cover category	Area in 2010 (acres)	Area changes from 2010 to 2100 for different SLR scenarios (acres)				
		NYC Low	NYC Low-Medium	NYC Medium	NYC High-Medium	NYC High
Undeveloped Dry Land	197,920	-1,321	-2,131	-4,020	-5,933	-9,115
Estuarine Open Water	160,768	948	1,258	2,015	4,203	11,025
Developed Dry Land	88,294	-666	-1,380	-3,437	-5,697	-9,520
Irreg.-Flooded Marsh	10,413	-545	-2,090	-8,486	-9,815	-10,200
Swamp	8,638	-73	-125	-297	-463	-745
Inland Open Water	4,606	-30	-60	-97	-139	-174
Regularly-Flooded Marsh	1,969	1,413	3,506	11,320	10,097	6,215
Estuarine Beach	1,604	-122	-176	-315	-462	-807
Trans. Salt Marsh	1,366	416	753	971	1,112	1,086
Inland-Fresh Marsh	817	-47	-90	-176	-224	-266
Tidal Flat	741	-156	-246	52	2,985	4,734
Tidal-Fresh Marsh	731	0	-13	-138	-402	-665
Tidal Swamp	655	-51	-135	-349	-456	-543
Riverine Tidal	580	-422	-438	-457	-469	-486
Flooded Developed Dry Land	324	666	1,380	3,437	5,697	9,520
Rocky Intertidal	123	-8	-13	-23	-33	-60
Inland Shore	120	0	0	0	0	0

A direct comparison to previous results cannot be made since the model has changed to some degree and, more importantly, different SLR scenarios are being considered. However, results show very similar trends to those observed previously. One difference is that additional open water is predicted to occur by 2100 overall. As expected, accounting for the marsh-collapse process reduces elevation capital when marsh is converted to another land cover, increasing overall land vulnerability to SLR. In addition, as discussed in more details below, muted tidal areas are more vulnerable to SLR.

3.2 Road-Inundation Results

The primary output product for road-inundation results are GIS shape-file layers for the entire study area at 5-meter resolution showing precisely which portions of which roads are subject to inundation given a combination of SLR and storm-surge (Figure 16). Results are available for 2008, 2025, 2040, 2055, 2070, 2085, 2100 under all five SLR Scenarios simulated.

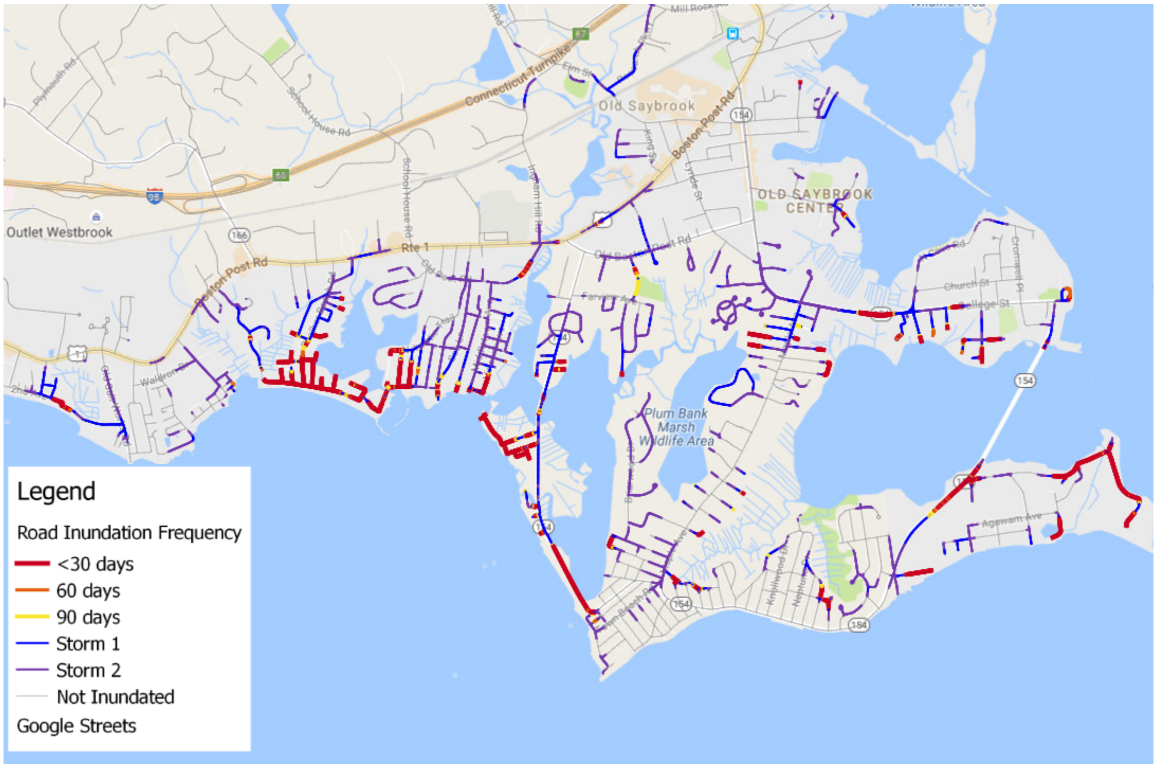


Figure 16. Example Roads Output: Roads at risk of inundation in the Old Saybrook area.
Map shows predictions of 2085 flooding under the medium-SLR scenario. (Maps data from Google Maps.)

Roads that are initially (at time-zero) predicted to be flooded every 30 days or less were removed from the analysis. This helped remove from the analysis bridges that did not have associated elevation data or elevated road surfaces that had been removed from bare-earth LiDAR coverages. This procedure ensures that predictions of flooded roads show incremental changes as a result of SLR rather than including initial data artifacts.

Road-inundation statistics by watershed are also available. Unlike marshes, which are assumed to undergo accretion over time, roads are not predicted to move vertically in this model. For this reason, a simple relationship of road-inundation frequency to sea-level rise is possible. Figure 17Figure 18shows that across Connecticut, the quantity of roads flooded every 30 days will increase to over 65 km given 1 meter of local SLR. Approximately 15% more roads (77 km total) will be subject to flooding every 90 days. Figure 18 suggests that currently just under 50 km of roads have the potential to be flooded by a 10-year storm. With 1 meter of SLR that quantity will rise to 140 km of roads predicted to be flooded each decade. These types of graphs can also be made available broken down by watershed.

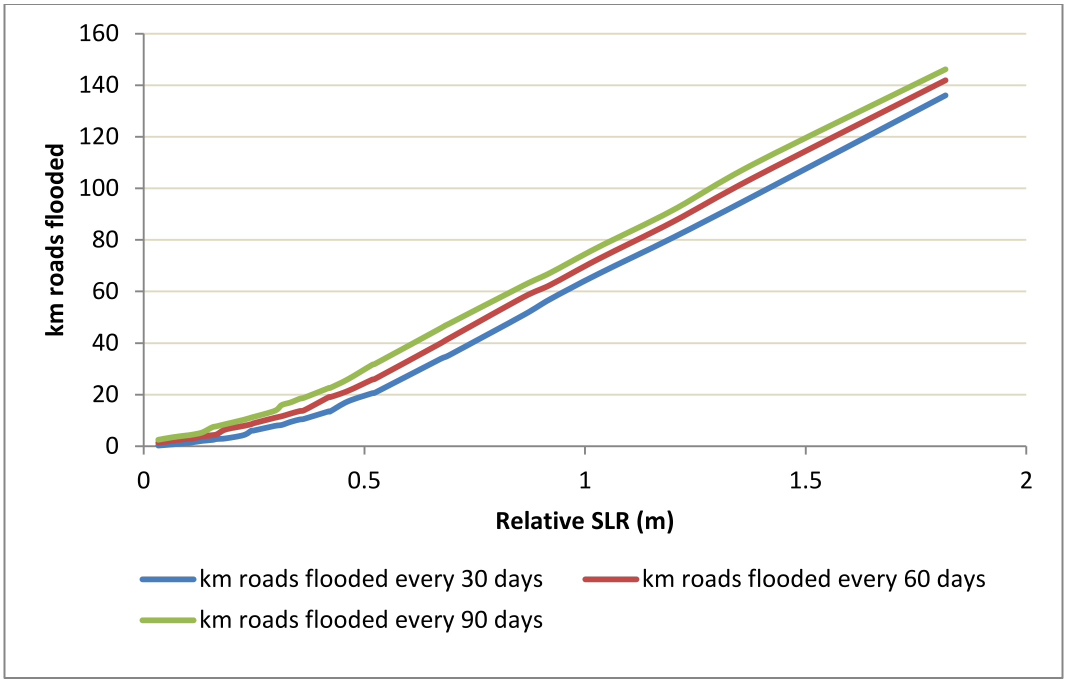


Figure 17. kilometers of coastal roads in Connecticut predicted to be regularly flooded under SLR scenarios up to 1.8 meters

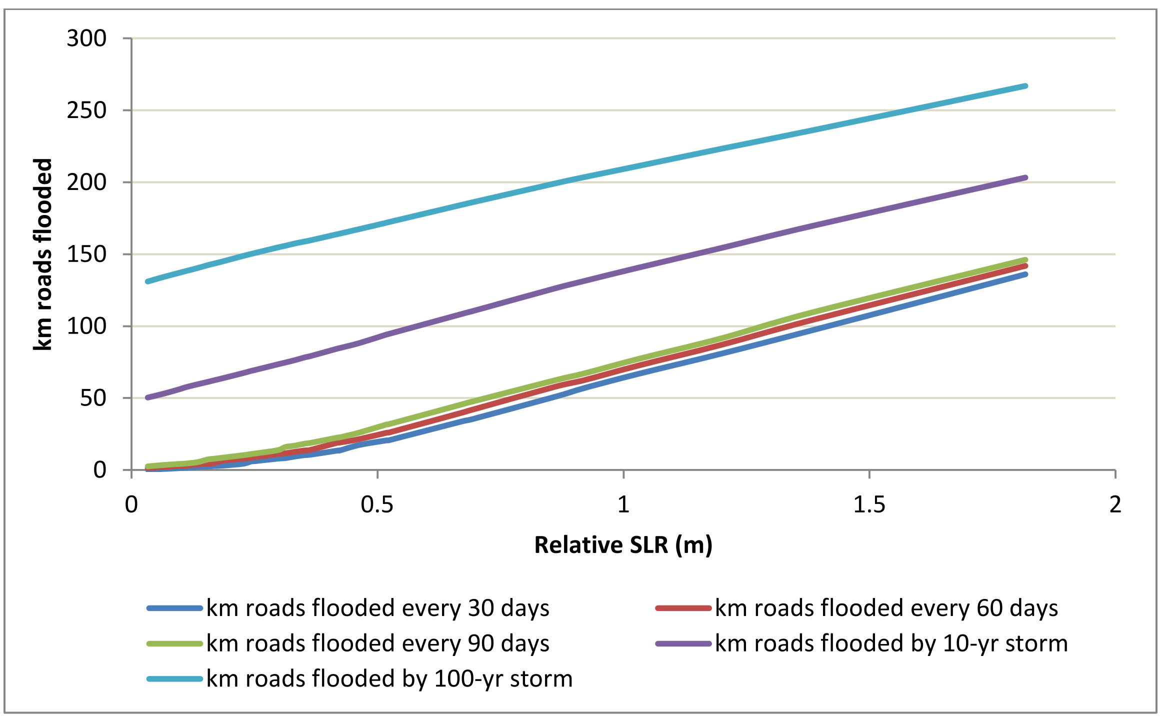


Figure 18. Length of coastal roads in Connecticut predicted to be regularly flooded given SLR and storms. SLR scenarios are shown up to 1.8 meters including roads impacted by 10 and 100-year storm scenarios

3.3 Infrastructure Results

The effects of accelerated SLR and storm surge on inundation frequency for the following categories of critical infrastructure were calculated:

- DEEP_Airports FAA
- DEEP_Sewage Treatment Plants
- HSIP_GNIS Cultural Features
- HSIP_Fixed Guideway Transit Stations
- HSIP_EPA FRS PowerPlants
- HSIP_FBI Offices*
- HSIP_Firestations*
- HSIP_GNIS Structures
- HSIP_GNIS TransportationFeatures
- HSIP_Hospitals
- HSIP_NursingHomes
- HSIP_PublicHealthDepts
- HSIP_UrgentCareFacs
- TNC_Airports
- TNC_Electric Power Facilities
- TNC_Fire Stations
- TNC_Medical Facilities
- TNC_Police Stations
- TNC_Potable Water Facilities
- TNC_Schools
- TNC_Wastewater Facilities

Layers marked with an asterisk (*) are For Official Use Only (FOUO) and are not presented in this report but are available on request from CTDEEP.

Section 2.10.2 provides details on the sources of these data. Following model simulations, duplicates were removed to ensure accurate accounting. Data were analyzed to determine the quantity and percentage of roads and infrastructure-facilities inundated and the frequency of this inundation. Infrastructure facilities affected by SLR were those predicted to be flooded once every 30, 60, or 90 days. Infrastructure flooding due to the 10-year and 100-year storm surge flooding are also presented to determine vulnerability to storm scenarios into the future. Estimates of vulnerability given both SLR and storm surge were also produced. Data were analyzed to determine the quantity and percentage of infrastructure points inundated and the frequency of this inundation. Where data areas overlap (e.g., HSIP_EPA FRS Power Plants and TNC Electric Power Facilities) efforts were made to combine the data sets for ease of interpretation.

Each of these infrastructure data points was represented by a single lat-long location within the dataset. When a model cell containing the data point was predicted to be regularly flooded, that facility was also assumed to be flooded. Results for specific infrastructure should be interpreted carefully, therefore. If the lat-long location provided represents a “low point” next to the infrastructure, for example, the structure’s vulnerability may be overstated. Similarly, vulnerability may be understated if the lat-long is located on a high-elevation location.

The results of these analyses uncover areas of vulnerability as well as resilience. Facilities with simple results are summarized in the bulleted-list below, otherwise a dedicated section is provided in the body of the report or in Appendix C. (Schools and Power Plants are included in the main body of the report, and then Appendix C of this report includes detailed graphs and tables of results for most infrastructure categories modeled.)

- None of the 8 HSIP_Hospital or 11 of the TNC Medical Facilities were predicted to be impacted and only 1 of the 10 urgent care facilities is predicted to be flooded due to SLR or storm surge (“Concentra Urgent Care – Stratford”).
- None of the three **potable water facilities** included in the analysis were predicted to flood due to SLR or storm surge based on simulations carried out.
- Half of all **Amtrak stations** analyzed are predicted to flood due to SLR under the High scenario by 2100
- None of the **airport/heliport facilities** (from a combined analysis of DEEP_Airports_FAA and TNC_Airports) are predicted to flood due to SLR alone until the Low-Medium scenario at 2100. With storm surge and SLR up to 43% of the facilities examined are predicted to flood (12 locations) by 2100 under the High SLR scenario.
- None of the four **fixed guideway stations** (with Amtrak stations removed) are predicted to be inundated by SLR under the scenario studied, However the 10-year and 100 –year storm surge combined with High SLR are predicted to affect 50% of the stations by 2055.
- No effects of SLR predicted until 2085 under the Medium-High scenario, maximum of 5 **Wastewater Treatment Plants** predicted to be affects by SLR at 2100 under the High SLR scenario. Under the Low SLR scenario 9% (3 facilities) are predicted to be inundated by the 100-year storm in 2025. A maximum of 41% of facilities (14 locations) are predicted to be inundated due to SLR and the 100-year storm by 2100 under the High SLR scenario.
- Of the 58 **fire stations** in The Nature Conservancy’s database for CT, a maximum of 10 facilities (17.2%) are predicted to be inundated by SLR and the 100-year storm by 2100 under the high SLR scenario. SLR alone is not predicted to affect any stations until the year 2100 under the Medium-High scenario.
- More than 1000 facilities were included in the GNIS_**Structures** database used. However, there is some double-counting as the facilities include Schools, Hospitals, Airports and Fire Station facilities that are also included in other layers. Of the 1064 facilities 6% (87) are predicted to flood due to SLR alone under the High scenario at 2100. With High SLR and the 100-year storm, 13% (69 facilities) are predicted to be inundated in 2100. Under the lowest SLR scenario, 5% (55 facilities) are predicted to be inundated by the 100-year storm in 2025
- The GNIS_**Transportation** features were analyzed without including bridges due to uncertainty in their elevations. SLR alone is predicted to cause flooding at up to 5 of the 99 facilities studied by 2100 under the High SLR scenario. More importantly, two facilities are predicted to be regularly inundated by 2055 under the low SLR scenario: Interchanges 67 and 69 in Middlesex County.

- SLR alone was predicted to affect **law enforcement locations** beginning in 2085 under the Medium SLR scenario. A maximum of 14% of the 44 facilities (5 locations) studied are predicted to be affect by High SLR and the 100-year storm in 2100.
- Of the 101 **nursing homes** included in the analysis, only 6% were predicted to be affected by SLR and the 100-year storm surge under the High scenario at 2100. Only 1 facility may be affected by SLR alone, and that is not predicted to occur until 2100 under the high scenario.
- One of the **21 public health department** buildings studied is predicted to be affected by High SLR at 2100, while under the same scenario 3 are predicted to be affect by the 100-year storm.
- The 669 **cultural features** analyzed include shopping centers, transit stations, historic sites and cemeteries. Docks, marinas, dams, lighthouses, and yacht clubs are also included in this layer and 100 of these sites were predicted to be inundated at the time zero step, indicating these are built over water. Of those features not inundated at time-zero, a maximum of 11% of culture features (73 locations) included in this analysis are predicted to flood by 2100 under the High SLR scenario. SLR alone does not appear to affect many cultural features until the medium SLR in 2085. The 100-year storm is predicted to cause inundation even under the low SLR scenario: a minimum of 9% (35 locations) are inundated under the 100-year storm with Low SLR at 2025 to a max on 17% at 2100 under the High SLR scenario.

3.3.1 Schools

Of the several categories of infrastructure examined in this analysis, schools may be one of the most critical. As they often serve as emergency shelters in addition to their primary function, the resilience or vulnerability of these locations should not be overlooked. According to SLAMM analysis, which included 356 schools throughout the study area, SLR alone is predicted to cause inundation at 11 schools (3.1% of facilities studied) under the High SLR scenario at 2100. One school is predicted to be regularly inundated due to SLR by 2055 under the Low SLR scenario (the Roger Fuller School in Fairfield). A maximum of 35 schools are predicted to flood under the worst case scenario of SLR and storm surge at 2100.

Table 24. Schools

SLR Scenario	Year	sites inundated due to SLR	sites inundated due to SLR & 10 year storm surge	sites inundated due to SLR & 100 year storm surge
Low	2025	0	3	8
	2055	1	3	8
	2085	1	6	10
	2100	1	6	11
Low-Medium	2025	0	3	8
	2055	1	4	8
	2085	1	6	11
	2100	1	6	12
Medium	2025	0	3	8
	2055	1	6	11
	2085	3	8	14
	2100	4	8	15
Medium-High	2025	0	3	8
	2055	1	6	12
	2085	5	8	17
	2100	7	12	22
High	2025	1	3	8
	2055	3	8	14
	2085	7	13	25
	2100	11	19	35

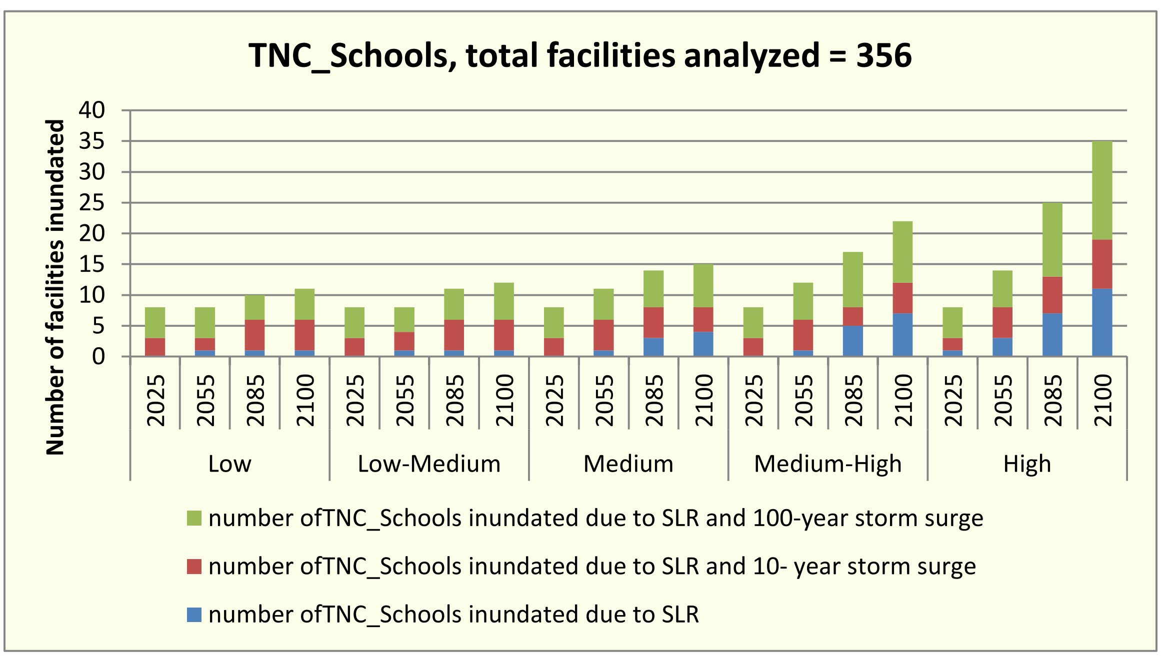


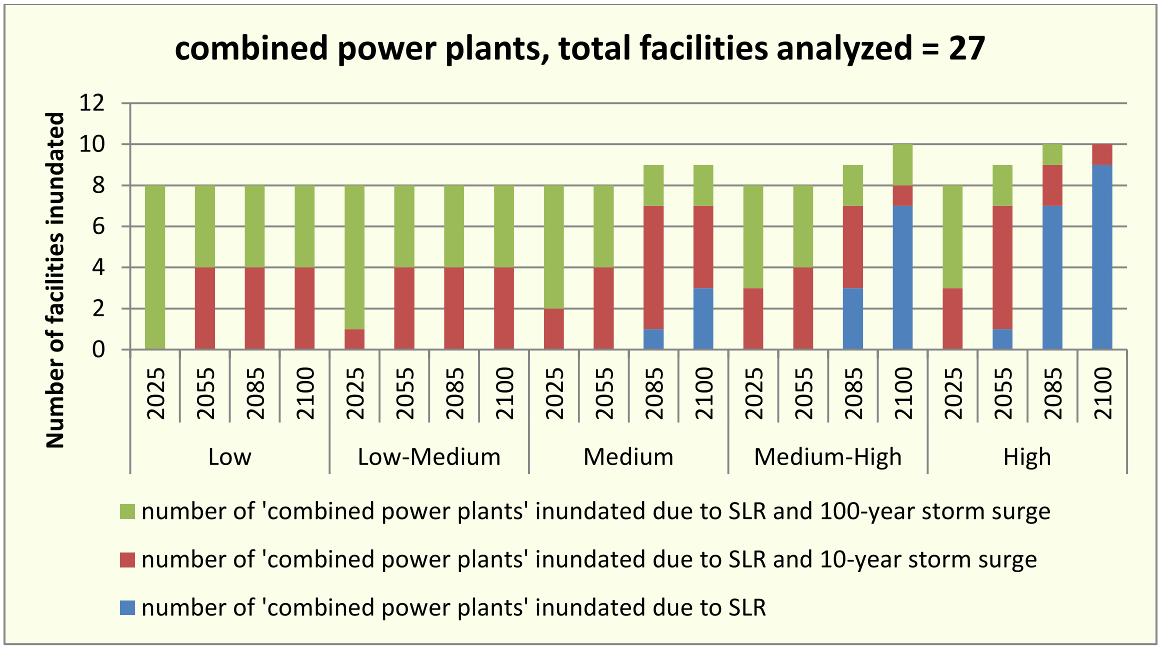
Figure 19. Predicted number of schools inundated under various SLR and storm surge conditions.

3.3.2 Power Plants

A combined analysis of the HSIP_EPA FRS PowerPlants and TNC_Electric Power Facilities indicated that of 27 sites analyzed, a maximum of 10 (37%) are predicted to be impacted by SLR and storm surge by 2100. This does not include the NRG Norwalk Harbor Power Station in New Haven that is predicted at time zero due to the point marker for this facility being placed on the shoreline rather than over the main body of the plant. Under the low SLR scenario 15% of facilities (4) are predicted to flood due to the 10-year storm and 30% of facilities (8) are predicted to flood due to the 100-year storm by 2055. 33% of facilities (9) are predicted to flood due to SLR alone under the High scenario at 2100.

Table 25. Power Plants

SLR Scenario	Year	sites inundated due to SLR	sites inundated due to SLR & 10 year storm surge	sites inundated due to SLR & 100 year storm surge
Low	2025	0	0	8
	2055	0	4	8
	2085	0	4	8
	2100	0	4	8
Low-Medium	2025	0	1	8
	2055	0	4	8
	2085	0	4	8
	2100	0	4	8
Medium	2025	0	2	8
	2055	0	4	8
	2085	1	7	9
	2100	3	7	9
Medium-High	2025	0	3	8
	2055	0	4	8
	2085	3	7	9
	2100	7	8	10
High	2025	0	3	8
	2055	1	7	9
	2085	7	9	10
	2100	9	10	10



3.4 Effects of road elevation on marsh inundation

As previously discussed, the current project explicitly accounts for road and railroad elevations in order to better characterize marsh migration. A comparison with previous SLAMM projects and inundation maps shows that, on a larger scale, land cover predictions, were not significantly affected by this more detailed description of the terrain elevation. However, localized effects may be possible.

Overall, our analysis of model results suggests that the 5-meter cell resolution was fine enough to provide an elevation layer with sufficient details to describe water paths. Increasing the model resolution (to the width of road obstructions) may have some marginal benefits but did not significantly modify model predictions.

We further suggest that, when working at this resolution, a high-quality hydro-enforced map is more important than a specific accounting of road obstructions. With regards to hydro-enforcement, it is important to note that not only should the elevation data be hydro-enforced for today's conditions but also for future sea levels. Overall, adding culverts and ditches and removing other artificial obstructions to water flows proved to be key steps in determining inundation paths and thus future land-cover conversion under SLR.

3.5 Areas with muted tides

An important model improvement over the previous project is a better description of the muted-tidal regimes-- areas connected to the main water body but subject to restrictions such as culverts, bridges and ditches. Simulations results for these areas show an increased vulnerability to SLR. An example is reported in Figure 20. Map A shows land cover predictions at 2100 under Medium-High SLR scenario when tides are not muted while map B shows the projection when tidal regime is modelled with tidal muting included. In the second case marsh is predicted to be more vulnerable to SLR with a significant conversion of land to tidal flat and open water.

These results, which were generally observed throughout the study area, are consistent with previous model results and the literature (Kirwan et al. 2010; Stevenson and Kearney 2009 chap. 10). There are several reasons for the increased vulnerability of micro-tidal marshes. Primarily, a marsh living in an area with a small tidal range colonizes a smaller elevation range than a marsh in a macrotidal regime. Therefore, when accretion rates are not high enough, less SLR is required for a marsh to become inundated. (For example, a marsh that loses elevation at a rate of 1 cm/yr. in a tidal regime of 10 cm has at the most 10 years before becoming subtidal. On the other hand, a marsh losing elevation at the same rate within a 1-meter tide range might require 100 years before becoming subtidal.)

Another reason for increased vulnerability within muted tide regions is that marshes with muted tides are often associated with limited nutrient and sediment supply. This reduced sediment supply can make the marsh systems even more vulnerable to SLR since accretion rates (accumulation of sediment) will be generally lower. This affect is accounted for within SLAMM to some degree because accretion curves are estimated as a function of the tide range (See Figure 33 in Appendix A, for example.) An area with a higher tide ranges will be able to maintain high accretion rates over a larger range of elevations and thus would be less vulnerable to SLR effects.

From a planning perspective, model results suggest that removing barriers to water flow to eliminate or reduce tidal muting effects could be beneficial for the resilience of marsh systems.

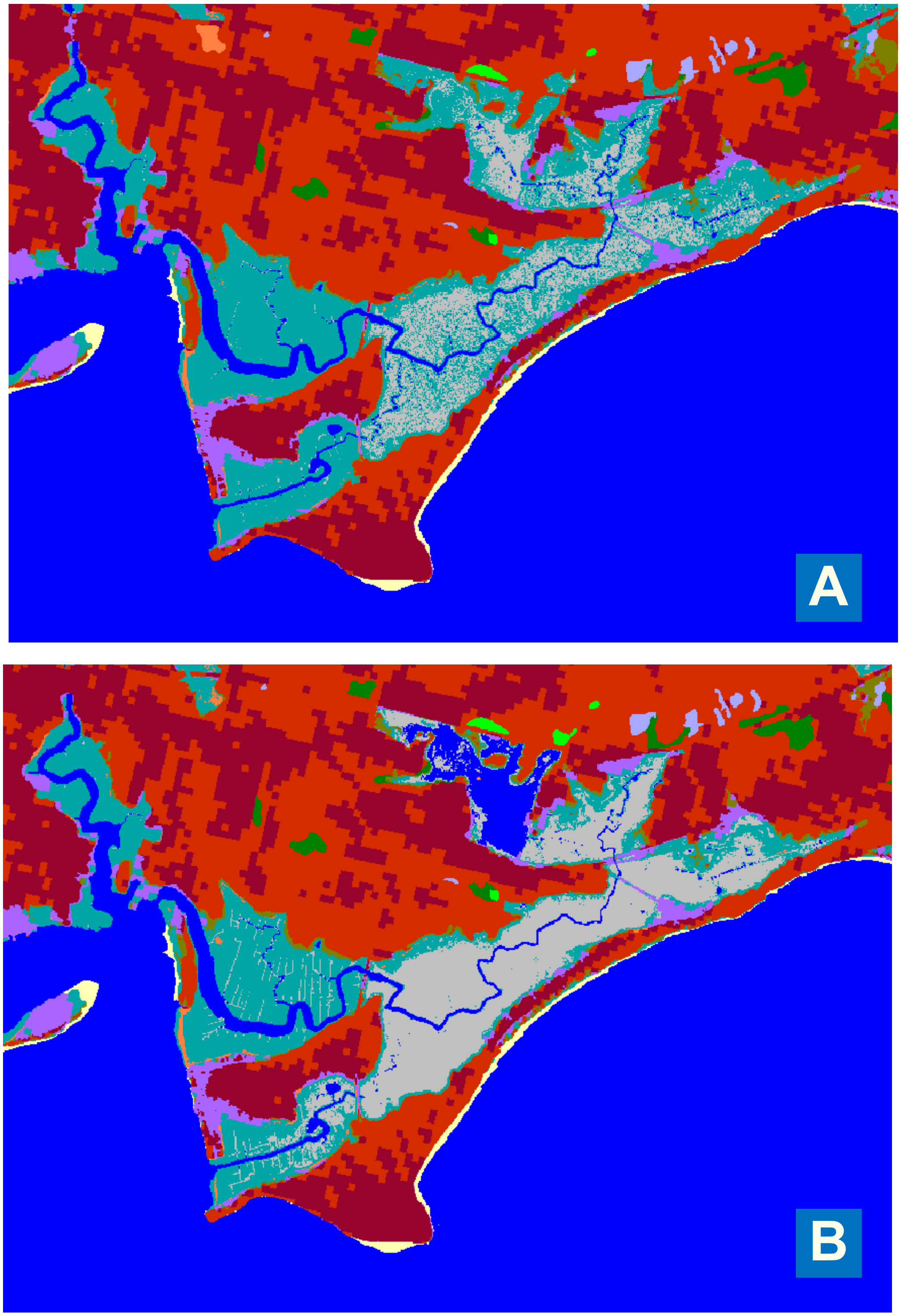


Figure 20. Land cover predictions at 2100 for a marsh system south of Clinton, CT under the High-Medium SLR scenario. In map A oceanic tide is applied to the marsh areas. In map B muted tides are accounted for.

3.6 Marsh migration

Marshes may adapt to SLR by migrating to adjacent areas that today are high and dry but in the future may become regularly inundated. This project provides maps defining potential new marsh areas along with the probability that marsh will colonize these regions considering uncertainties in model parameters and driving variables. As noted below, the most significant model uncertainty tends to be the extent of future SLR predicted.

One example marsh-migration map is provided in Figure 18. This map shows several opportunities for existing marsh to colonize currently dry land south of Old Saybrook in Middlesex County, CT. As might be expected, the probability of becoming a marsh decreases as one moves away from the marsh into higher grounds.

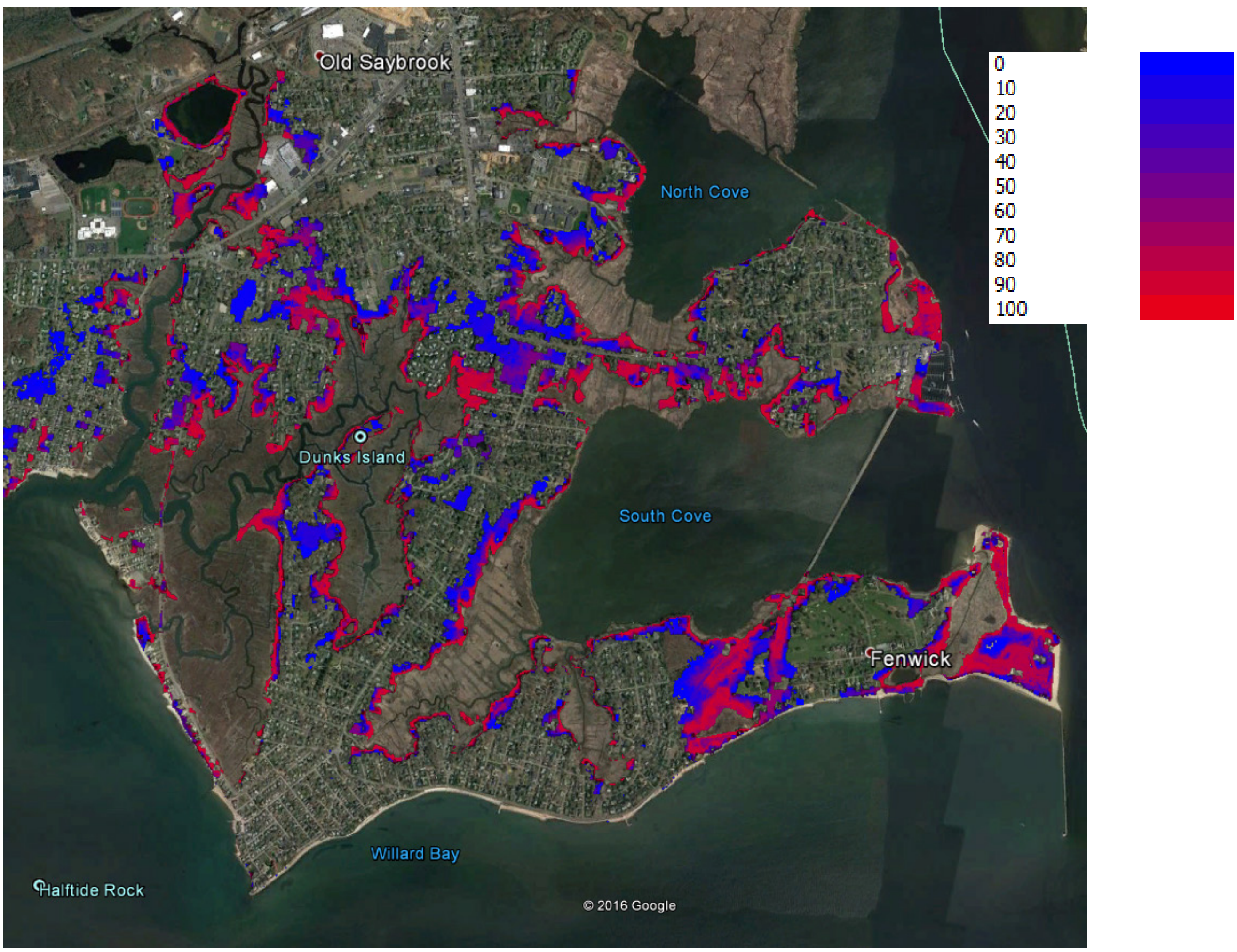


Figure 21. Land areas where marshes are predicted to migrate south of Old Saybrook in Middlesex County, CT. Colors indicate probability.

The provided marsh-migration maps predict that marshes will exclusively colonize currently-undeveloped areas. While regular water inundation may also occur in developed areas (for example roads and parking lots close to water) the establishment of marsh would probably require some "restoration" or "retreat" decisions that were not considered in this project. Therefore developed areas are excluded in this analysis as land suitable for marsh migration. For planning purposes, the marsh migration maps can provide spatial information to evaluate land acquisition and/or protective measures for specific parcels of interest.

Table 26 shows average predicted areas of coastal marsh (regularly- and irregularly-flooded) broken down by watershed. These maps were obtained by weighting each model cell with its probability of being a marsh (a basic calculation of expected value). Overall, existing marsh systems are predicted to lose land coverage by converting to subtidal systems or open water under SLR conditions. However, new marsh areas may offset part of the losses experienced by current systems and in some cases have the potential to provide a net gain of coastal marsh coverage (for example in the Southwest Coast watershed). This general analysis shows that there are opportunities for upland migration to counter losses of existing marshes to SLR if land is sufficiently protected from development. Further opportunities for upland migration may also be possible if developed areas are returned to undeveloped, though that is not accounted for in this analysis.

Table 26. Average predicted coastal marsh area by 2100 and watershed.

		Average predicted coastal marsh area coverage (acres)		
Watershed	**Current (2010)**	**Still covered by marsh at 2100**	**New marsh area at 2100**	**Total area at 2100**
Housatonic	1,059	542	236	778
Southwest Coast	1,713	1,217	1,466	2,683
Connecticut	2,918	1,907	803	2,710
South Central Coast	6,263	5,130	2,030	7,161
Southeast Coast	1,630	747	1,084	1,831
Thames	115	46	127	173
Pawcatuck	50	24	56	80
Entire coastal Connecticut	13,748	9,614	5,802	15,416

3.7 Water connectivity

A series of SLAMM simulations was performed to investigate whether additional marsh migration pathways may exist beyond the ones ‘identified above. In particular the analysis identified areas that are not connected to tidal water but, that could potentially accommodate tidal-marsh establishment if connected, for example by using hydraulic structures as culverts or by creating ditches. One basic requirement for a suitable area is that elevations have to fall in the intertidal zone-- above MTL and below the wetland boundary elevation (WBE). This is the range of elevations in which dry land can convert to tidal marsh if connected to tidal water. To identify these areas, SLAMM was run without its “connectivity component” turned on. This type of model run allows land cover conversion whether or not estuarine or oceanic water can actually reach that cell through a connected hydraulic pathway. Low areas are always treated “as if” they are connected to tidal water. By comparing these model results with previous model results (that include connectivity), the new marsh areas identify the potential marsh colonization for unconnected regions.

An example map is displayed as Figure 22. The blue and green colored area is currently occupied by non-tidal-fresh marsh and there appears to be a culvert draining excess water to the tidal marsh on the north. This analysis predicts that that low and transitional marsh could establish this area if the drainage culvert connecting to the marsh on the north is lowered and sized appropriately to allow tidal water flow without muting.

Other similar opportunities are identified along the entire coast of Connecticut. (A full set of maps of “NotConnected” maps has been delivered in GEOTIFF format.) However, given hydrodynamic complexities, and potential changes in sediment transport under hydraulic connectivity, it is likely that not all identified areas would become a marsh if connected. Additional engineering studies would certainly be warranted prior to changing hydraulic structures. It is also possible that some of these areas are already well connected to coastal waters but this information was not available for these model runs. If this is the case, these identified areas remain interesting because they may have a muted tide range and actions may still be required to improve the tidal flow.

Overall these maps can be an important tool for identifying potential areas for marsh migration and can direct further analysis for the implementation of or improvement of water-connectivity paths that could favor future marsh migration.

Figure 22. Marsh migration potential example, east of Milford, CT.

3.8 Uncertainty results

For uncertainty simulations, 200 unique model realizations were run for each of the three study areas. The number of uncertainty iterations performed in this analysis was relatively small due to CPU-time restrictions. However, as in the previous analysis, this limitation was accounted for by conservatively widening confidence intervals in time-series graphs and tables of output.

The primary sets of outputs from the uncertainty analysis are a delivered set of raster GIS maps in which results are broken down on a cell-by-cell basis. The list of maps that were specifically derived for this project are:

- **"Habitat Change":** Percent Likelihood of Habitat Change. For each cell in the study area, the percent likelihood that this cell has changed category since the start of the simulation.
- **"Is Coastal Marsh":** Probability that the cell is a coastal marsh. This map can assist in identifying potential locations for "marsh migration." A coastal marsh is defined as a cell that is flooded by tidal waters including low marsh (regularly flooded marsh), high marsh (irregularly flooded marsh), dry land recently converted to marsh (transitional marsh), and tidal-fresh marshes.
- **"Is Low Marsh":** Probability that the cell is a regularly-flooded marsh.
- **"Is High Marsh":** Probability that the cell is an irregularly-flooded /transitional marsh .
- **"Is Flood Dev."** Probability that the cell contains flooded-developed land. Likelihood a developed cell in initial layers will be regularly flooded at the map date.
- **"Land To Open Water":** Probability that a land category has converted to open water. Likelihood a cell that is not water at low tide (MLLW) will become open water at that tide at the map date.
- **"Is Beach":** Probability that a cell contains an estuarine beach or ocean beach category.
- **"Is Coastal Wetland":** Probability that a cell has either a coastal marsh or beach cell within it, as defined above.
- **"New Flood Dev."** Probability that the cell contains flooded-developed land, and this land was not predicted to flood at "time zero."

In addition, two additional sets of uncertainty maps were produced to examine hydraulic connectivity given tide-range uncertainty, and marsh migration potential under uncertainty.

- **"Below WBE"** The probability that the given cell lies below the predicted 30-day inundation level.
- **"New Coastal Marsh"** The probability that the given cell is predicted to have new coastal marsh that migrated onto the cell (the cell was not a coastal marsh at the start of the simulation.)

Uncertainty maps are all available as GEOTIFF GIS layers with a 5-m resolution allowing for close inspection of model results for individual locations.

An example of these maps is presented below for the Southwest Coast and Housatonic Watershed study area (Stratford detail). Figure 23 suggests that there is a moderate-to-low percent likelihood of habitat change in the Southwest Coast and Housatonic Watershed study area by 2055. Figure 24 suggests a much higher percent likelihood of habitat change by 2100 in many locations. In these maps, "habitat change" includes dry lands converted to marsh, high marsh converting to low marsh, and even developed dry land becoming regularly flooded. These maps do not consider the possible effects of building seawalls or other defenses against rising seas, however.

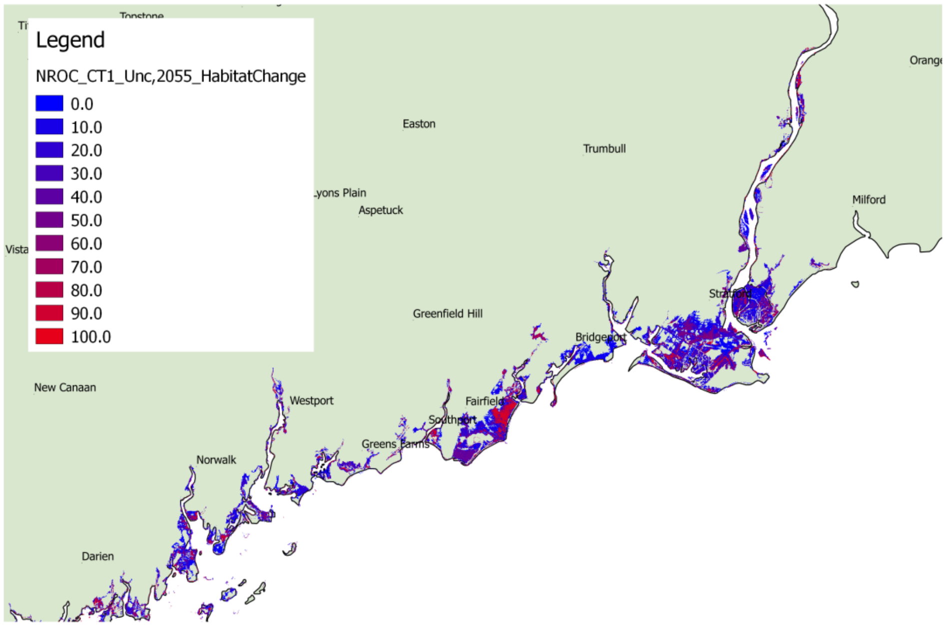


Figure 23. Area 1 -Southwest Coast and Housatonic Percent Likelihood of habitat change by 2055

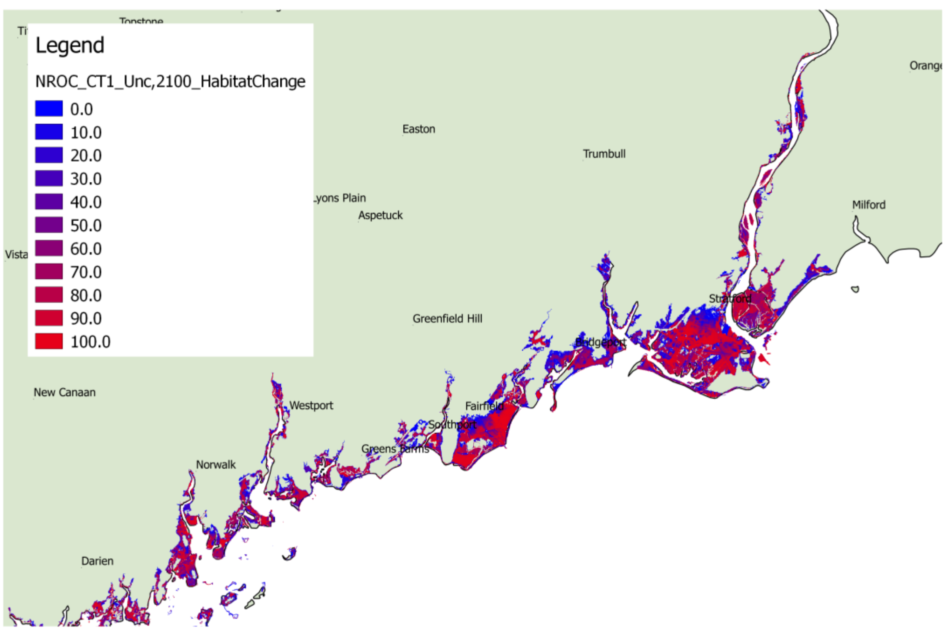


Figure 24. Area 1 -Southwest Coast and Housatonic Percent Likelihood of habitat change by 2100

Two additional summaries of uncertainty results have also been produced: tabular summaries and time-series graphs with confidence intervals.

Tables of results present minimum and maximum values and, more importantly, confidence intervals based on the 5th to 95th percentile. The standard deviation presented in these tables, with units of acres, gives a sense of the relative uncertainty for each model category. For example, Table 27, summarizing the Southwest Coast watershed, suggests that, by 2055, developed dry land has the highest uncertainty range, with a confidence interval ranging from 45,856 acres to 47,389 acres. This table also shows that regularly-flooded marsh is the wetland category with the highest uncertainty (it has the highest standard deviation). Table 28 presents results for the Southwest Coast watershed for the year 2100. Tables of uncertainty results did not change dramatically from the previous LISS project as many model differences have produced local results that get lost in landscape-scale statistics. However, uncertainty tables for all watersheds are available, and have been delivered in Excel format.

Time-series graphs are also available to visualize model results with confidence intervals for individual wetland types. Figure 25 and Figure 26 present the results for irregularly-flooded marsh and swamp. The 5th and 95th percentile estimates are shown in black lines, presenting a confidence interval for predictions in each category. These results illustrate the increasing uncertainty in model results the further into the future projections run. To help clarify the data behind these figures, Figure 27 shows all of the model's uncertainty iterations for irregularly-flooded marsh for the Southeast Coast watershed along with derived confidence intervals and deterministic model results.

The uncertainty-analysis results presented in this section represent uncertainty in all model parameters and driving variables including sea-level rise. While the model is sensitive to many parameters, particularly accretion rates (Chu-Agor et al. 2010), sea-level rise is often the most important driver of model uncertainty. When presenting time series of confidence intervals in this report, we also plot results from the four highest deterministic SLR scenarios. These deterministic results help to add context of how much the overall uncertainty interval is driven by future SLR as opposed to other parameter choices. For example, in Figure 26, the vast majority of uncertainty in high-marsh predictions can be explained by the uncertainty in SLR with the lowest scenario (NYC low-medium) resulting in a prediction very close to the top of the confidence interval and the highest SLR scenario (NYC high) resulting in a value nearly identical to the bottom of the confidence interval.

Table 27. Uncertainty Results for Southwest Coast Watershed by Landcover (acres, 2055)

Landcover Type	Min	5th Percentile	Mean	95th Percentile	Max	Std. Dev.
Undeveloped Dry Land	118,937	119,087	119,541	119,832	119,944	197
Developed Dry Land	45,456	45,856	46,827	47,389	47,475	422
Swamp	4,332	4,337	4,384	4,409	4,411	21
Inland Open Water	3,415	3,418	3,446	3,468	3,473	15
Estuarine Open Water	1,146	1,150	1,189	1,249	1,281	27
Regularly-Flooded Marsh	313	367	648	1,245	1,372	237
Irreg.-Flooded Marsh	300	359	712	870	893	141
Inland-Fresh Marsh	272	275	295	318	324	14
Estuarine Beach	234	238	245	251	251	3
Trans. Salt Marsh	190	271	472	721	843	125
Flooded Developed Dry	166	251	813	1,785	2,184	422
Inland Shore	119	119	119	119	119	0
Tidal Flat	70	75	86	99	107	6
Tidal Swamp	14	15	16	17	17	1
Tidal-Fresh Marsh	7	7	8	9	9	0

Table 28. Uncertainty Results for Southwest Coast Watershed by Landcover (acres, 2100)

Landcover Type	Min	5th Percentile	Mean	95th Percentile	Max	Std. Dev.
Undeveloped Dry Land	117,616	117,727	118,636	119,493	119,779	484
Developed Dry Land	42,342	42,621	44,719	46,694	47,261	1,142
Swamp	4,293	4,296	4,327	4,382	4,406	24
Inland Open Water	3,395	3,399	3,411	3,451	3,461	11
Estuarine Open Water	1,175	1,206	1,369	1,833	2,051	156
Regularly-Flooded Marsh	381	566	1,716	2,389	2,456	542
Flooded Developed Dry	379	947	2,921	5,020	5,299	1,142
Trans. Salt Marsh	323	488	676	821	856	87
Inland-Fresh Marsh	264	265	272	284	312	7
Estuarine Beach	168	191	221	245	247	14
Inland Shore	119	119	119	119	119	0
Tidal Flat	56	58	153	498	654	119
Irreg.-Flooded Marsh	18	21	244	789	870	237
Tidal Swamp	10	10	13	17	17	2
Tidal-Fresh Marsh	3	3	7	9	9	2

Figure 25. Time series for Irregularly-flooded marsh area coverage in the Southwest Coast Watershed, CT

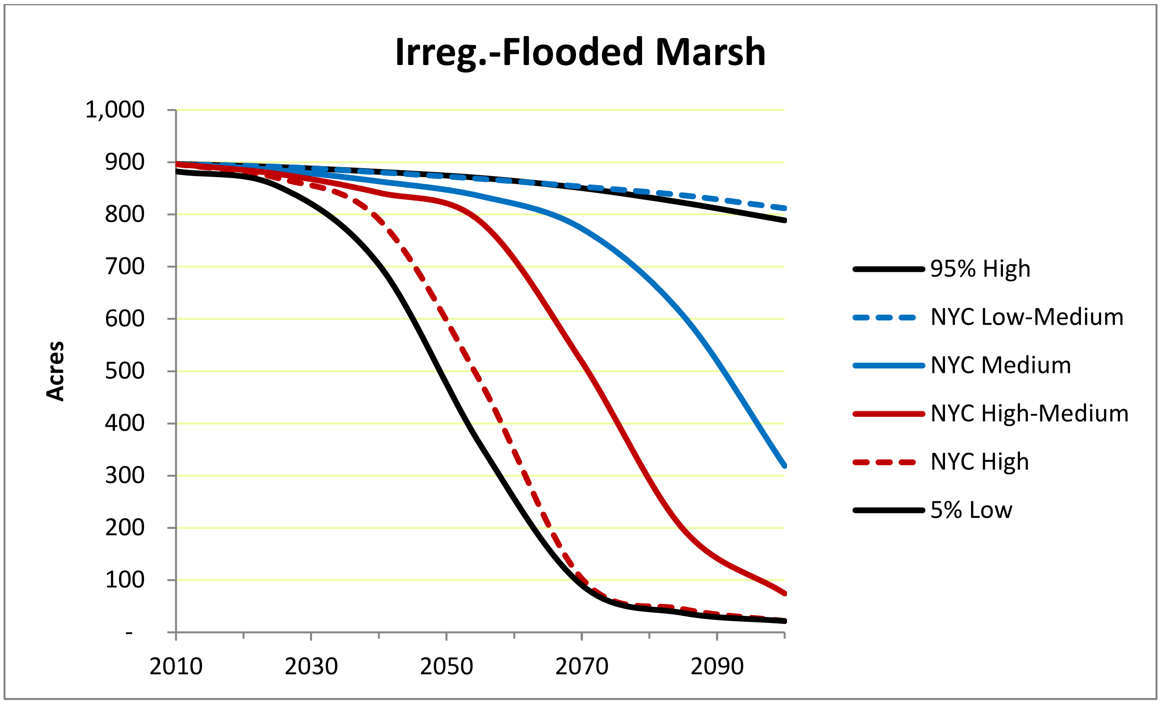
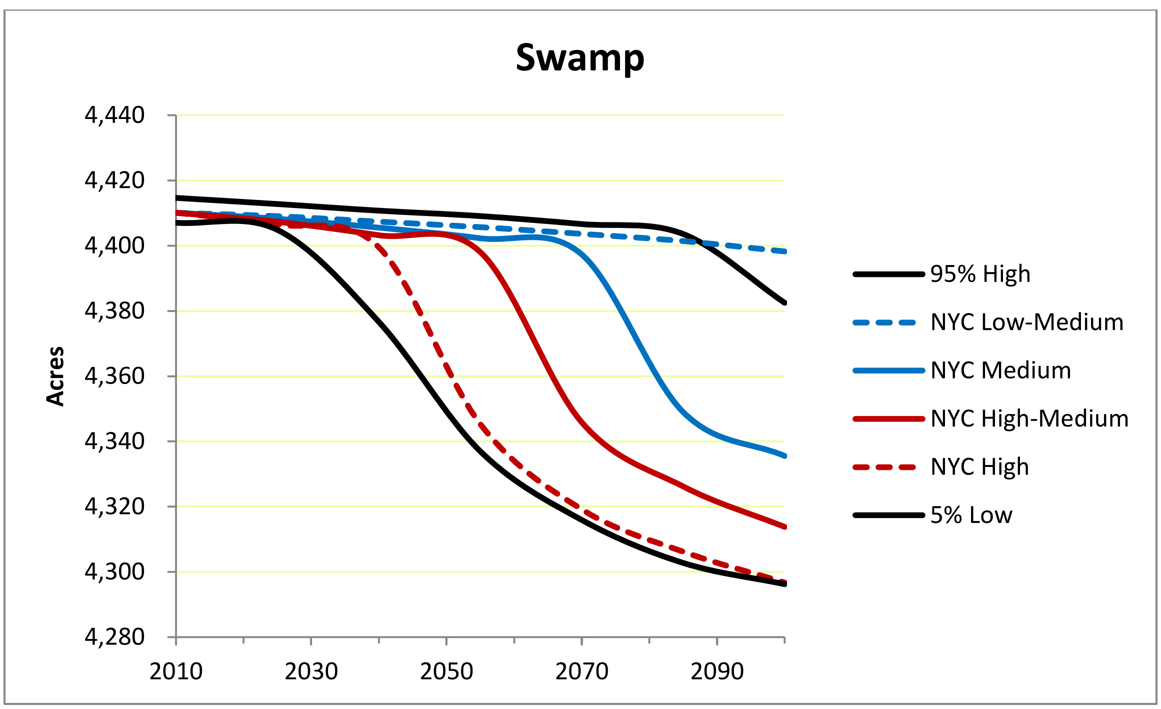


Figure 26. Time series for Swamp area coverage in the Southwest Coast Watershed, CT



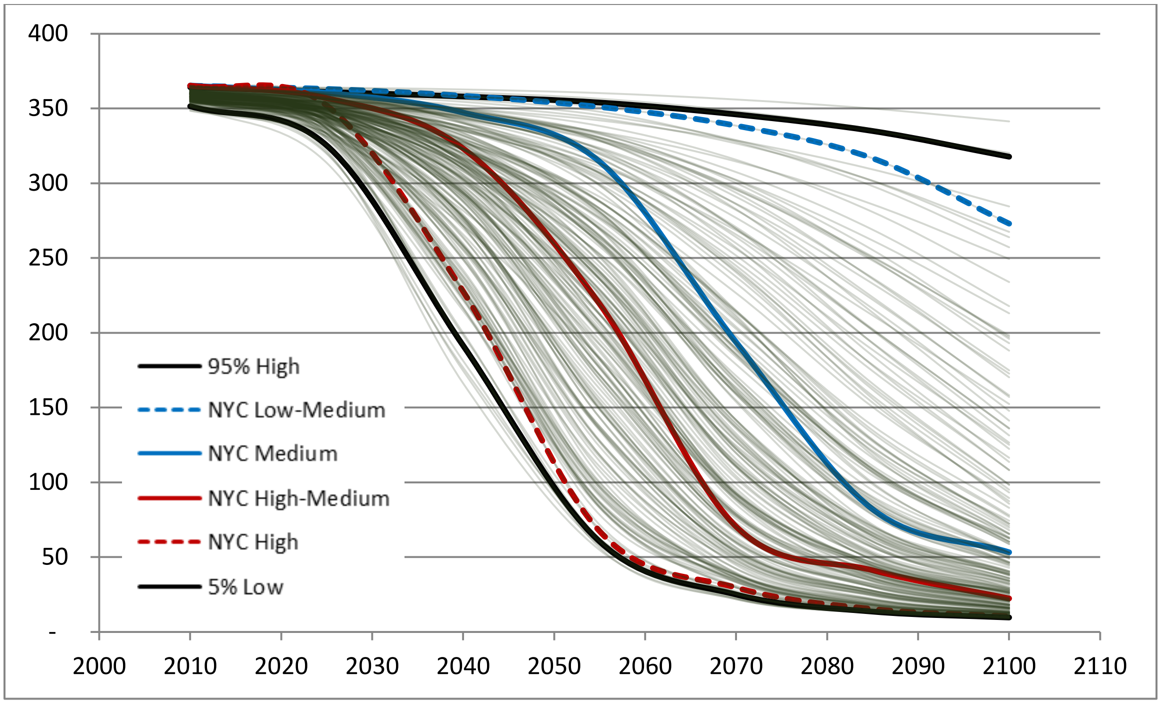


Figure 27. All uncertainty-run model iterations for irregularly-flooded marsh for Southeast Coast Watershed

4 Conclusions (Lessons Learned)

This application of the Sea-Level Affecting Marshes Model was funded by the Northeast Regional Ocean Council (NROC) with the goal of refining existing SLAMM projections for coastal Connecticut[1]. Refinements included accounting for road and infrastructure effects and the use of spatial analysis to identify and characterize marsh-migration pathways. High resolution maps of roads sections that may be vulnerable to a combination of SLR and storm-surges were produced. Spatial data layers were also produced that show which infrastructure could be regularly flooded by SLR, or that could be vulnerable to the combined effects of SLR and storm surge.

For this project, a significant effort was devoted to producing digital elevation maps that are well hydro-enforced for current sea-level conditions. Updated hydro enforcement also accounted for culverts and openings that could allow tidal-water flow as sea level increases. In practice this was achieved by

[1] This study focused on coastal regions of the entire state of Connecticut with elevations of below five meters (NAVD88) and examines sea-level-rise effects through the year 2100.

modifying the DEM with a line of low elevation cells that would cut through the bridge or road that had impeded the water flow. A better description of current and future inundation zones has also been attained by including effects of tidal muting (due to the presence of restrictions or distance upriver) for many marsh systems throughout the study area. In the absence of actual tidal data available for these areas, land cover and elevation data were examined to approximately define the boundary between dry and wet areas. As this boundary is related to the tidal amplitude, the great diurnal tide range was estimated using general relationships determined from gauge station data.

SLAMM projections delivered by this project also account for the loss of elevation capital that occurs when a marsh is converted to a lower tidal or subtidal system. This “marsh collapse” has been observed in marsh systems when land-cover conversions occur (Burdick and Vincent 2015).

While significant differences in model results were observed in some local marsh systems, overall tables of results show similar trends to those observed previously. One change in study-wide results is likely due to the marsh-collapse process that increases overall land vulnerability to SLR. As a result more area is predicted to be covered with tidal flat and open water.

Generally, existing marshes in Connecticut are predicted to be capable of keeping up with moderate SLR. Since current SLR is relatively small, this result suggests that, similar to other non-subsiding marsh areas in the US, marsh losses observed in the last 40 years may be due to reasons beyond SLR-- mostly local anthropogenic reasons, such as nutrient load, boat traffic, or development.

In addition, spatial analysis of model results shows that there are opportunities for upland migration to counter losses of existing marshes to SLR if land is sufficiently protected from development. It is also possible that some low lying areas, if properly connected to tidal water in the future, could provide additional land for marsh colonization. Specific map products have been delivered that delineate where new marshes may migrate as well as defining non-hydraulically-connected areas that could support future marsh migration.

Our analysis of model results suggests that the 5-meter cell resolution is fine enough to provide an elevation layer that effectively describes water paths. Increasing elevation-data resolution, by adding road center lines, did not have a significant effect on model predictions. In fact, roads are typically wide from 18 to 30 feet (5.4 to 9.2 m). Therefore, a 5m resolution DEM created by sampling native Lidar data with 1 m point spacing appears to be accurate enough to characterize road elevations and their effects on hydrology.

This study found that the quality of hydrologic enforcement for current and future conditions had a far more significant effect on model results than accounting for center-line road elevations. In the future, efforts focused on characterizing culverts and other hydrologic openings could provide valuable information for planning purposes and future modeling efforts.

Current and previous model results show that when moving from west to east along the coast, marsh systems are increasingly susceptible to SLR. One possible explanation is that the tidal amplitude is reduced moving eastward. Coastal marshes are known to be more susceptible to sea-level rise when tide ranges are smaller (Kirwan et al. 2010; Stevenson and Kearney 2009). In addition, a comparison of land-cover predictions in tidally muted areas with previous results where muting was not considered, indicate that tidally-muted marshes are at greater risk. Where possible, reducing restrictions to restore tidal flow could be beneficial for the resiliency of marsh systems. This type of change both increases the elevation range that marshes can inhabit and also can increase sediment supply as a result of increased inundation.

Another significant project conclusion pertains to the updated uncertainty-analysis results. Of the many input parameters and data uncertainties within the model, future SLR seems to be the most important driving variable for land-cover projections. This result has also been encountered in other geographically similar study areas (Clough et al. 2016). This observation can be important when considering resource allocation when data gathering for models. In particular, allocating great efforts to reduce the uncertainty of spatial data, or the uncertainty in future erosion and accretion rates may significantly improve model predictions only if the uncertainty of future SLR can also be reduced. Given current uncertainty in future SLR, models should continue to examine alternative futures, either through examination of alternative SLR scenarios as performed in this project, or via a comprehensive uncertainty estimation as also completed here.

From this project, several general lessons were learned in regards to applying SLAMM regionally. First of all, a precise water-inundation map is a key input to predict the fate of current marsh systems and the colonization of future marsh areas. Therefore, efforts should not only be devoted to reducing SLR-scenario uncertainty, but also to describing current and future hydraulic conditions and hydraulic pathways. Secondly, tide ranges and tidal muting do make a difference in model results. Low-tide-range and muted-tide marshes are more vulnerable to future SLR. Third, properly accounting for marsh collapse had local effects, but did not significantly affect landscape-level model predictions. This seems to be because high marshes that collapse are subject to higher sedimentation rates which partially make up for the elevation-capital loss. Finally, if a fine resolution elevation map is used (five by five meter cell size or lower) a precise accounting of road center-line elevations will have little effect on model results.

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Appendix A: Previous SLAMM Application and GIS Methods

Elevation transformation

VDATUM version 3.2 (NOS 2013) was utilized to convert elevation data from the NAVD88 vertical datum to Mean Tide Level (MTL), which is the vertical datum used in SLAMM. This is required as coastal wetlands inhabit elevation ranges in terms of tide ranges as opposed to geodetic datums (McKee and Patrick 1988). VDATUM does not provide vertical corrections over dry land; dry-land elevations were corrected using the VDATUM correction from the nearest open water. Corrections in the study areas do not vary significantly, ranging from approximately -0.12 m to 0.05 m. A spatial map of corrections is shown in Figure 28.

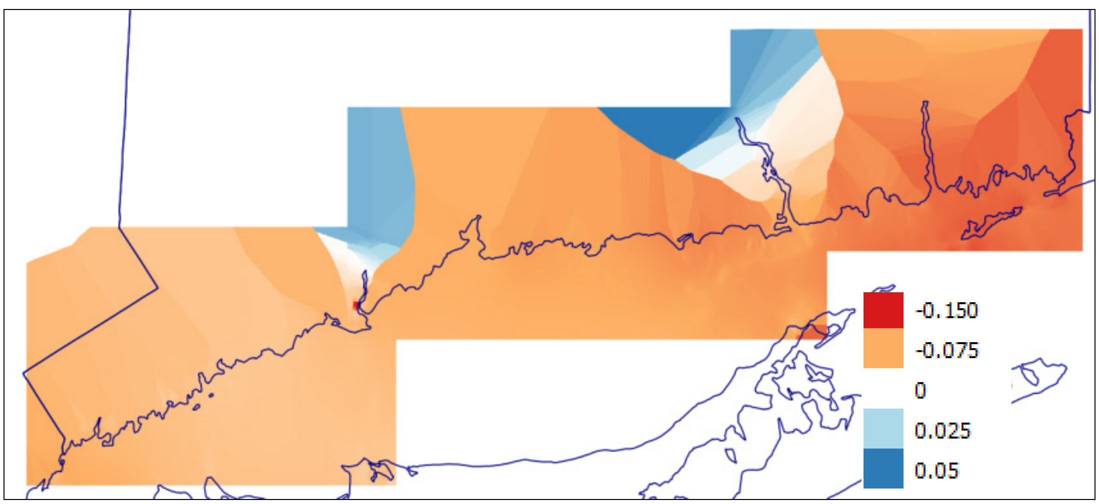

Figure 28. VDATUM-derived correction values (meters)

Wetland Layers and translation to SLAMM

Wetland rasters were created from a National Wetlands Inventory (NWI) survey dated 2010 for the entire study area. NWI land coverage codes were translated to SLAMM codes using Table 4 of the SLAMM Technical Documentation as produced with assistance from Bill Wilen of the National Wetlands Inventory (Clough et al. 2012).

Since dry land (developed or undeveloped) is not classified by NWI, SLAMM classified cells as dry land if they were initially blank but had an elevation assigned. 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.

Dikes and Impoundments

Dike rasters were created using different data sources:

- NWI data. 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.
- 2013 FEMA Flood Hazard Layers using the attribute of dams. These data were inspected to make sure each feature consisted of a single line drawn on top of the dam structure.
- Connecticut Dams database which consists of point data representing the general location of a dam. A new line feature class was created for each dam feature that could be found within a 500' area surrounding each point.
- National Levee Database (NLD). The U.S. Army Corps of Engineers National Levee Database (2014) (http://nld.usace.army.mil/) was accessed and any additional levees in the study area not included in the NWI, FEMA, and Connecticut Dams database but represented in the NLD were added manually, based on dimensions shown in the on-line mapping interface. Dikes in locations above five meters in elevation were not digitized.

Line and polygon data from the first three datasets listed above were mosaicked together into a final dikes and dams raster with a 5 meter cell size. Raster data were checked visually to make sure the projection information was correct, layers had a consistent number of rows and columns, and that the data captured all features within the source data. NLD data were then manually added through the SLAMM interface using SLAMM wetland layers laid over satellite imagery to ensure locations were digitized as precisely as possible[2].

In Stamford CT, the dike system has a flood gate that may be closed when necessary. Therefore the open water behind this gate was classified as diked. Because of this, SLAMM projections assume that SLR will not occur behind this gate (the gate will be maintained and improved in the event of SLR).

A significant amount of the Connecticut coastline is protected by seawalls. However, if these structures were uniformly designated as "diked" by SLAMM it would be equivalent to having them continually

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[2] Dikes were manually added in the following locations: Stonington CT, 41.371465°, -71.833078°; New London CT, 41.349526° -72.101089°;

armored against sea-level rise. There will likely be some changes to the structures over time, but there is no reliable way to assess which structures may be altered. In these simulations, current seawalls were generally accounted for only by their current elevation (provided by the LiDAR data) and were allowed to be overtopped when sea levels become high enough. In a few cases where seawalls were visible on satellite imagery and time-zero flooding was predicted, a few cells were designated as "diked" to protect against immediate flooding[3].

Historic sea level rise rates

The SLR scenarios shown in the table and figure above are "relative" sea-level rise estimates. Therefore, SLAMM scenarios do not need to be corrected for differentials between local (or relative) SLR and global (or eustatic) SLR trends. For this reason, within the model, the historic SLR was set to zero (to model relative sea level rise rather than eustatic SLR).

According to NOAA, historic sea level rise trends along the Connecticut coast range from 2.25 mm/yr at New London to 2.56 mm/yr in Bridgeport. Each of the four scenarios simulated represents a significant acceleration of SLR from the local historical trend observed.

Tide Ranges

Tide range data were collected from NOAA tidal data and tide prediction tables for 2011. SLAMM requires the great diurnal tide range (GT)[4] as an input. The GT, along with several other tidal data, are provided directly by the NOAA Tides & Currents website (www.tidesandcurrents.noaa.gov). However, these data provide the mean tide range (MN)[5] of the area in question. Therefore, GT was extrapolated from MN by considering the average ratio between GT/MN measured at the NOAA tidal datum stations.

Overall, GT values in the project area varied from a maximum of 2.5 m at Cos Cobb Harbor to 0.88 m in New London. As discussed in the results section below, a smaller GT tends to make marshes more vulnerable to SLR in the eastern portion of the study area. A map of GT data throughout the study area is provided in Appendix B.

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[3] Some seawalls cells were manually set to "diked" in the following locations: Spruce Swamp Pond 41.087893° -73.394471° ; Rocky Point Club 41.016840° -73.558618°; In front of a pond shown as "impounded" in the NWI Layer 41.021223° -73.577665° .

[4] GT - Difference between the mean higher high (MHHW) and mean lower low water (MLLW) levels.

[5] MN - Difference in height between mean high (MHW) and mean low water (MLW) levels.

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 29. Because of this, 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).
- For example, consider a marsh with an elevation 1 m above MTL, with a tide range (GT) of 1.5 m. The height of the marsh in HTU is equal to 1/(1.5/2)=1.33 HTU.
- 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 absolute value of the tide.

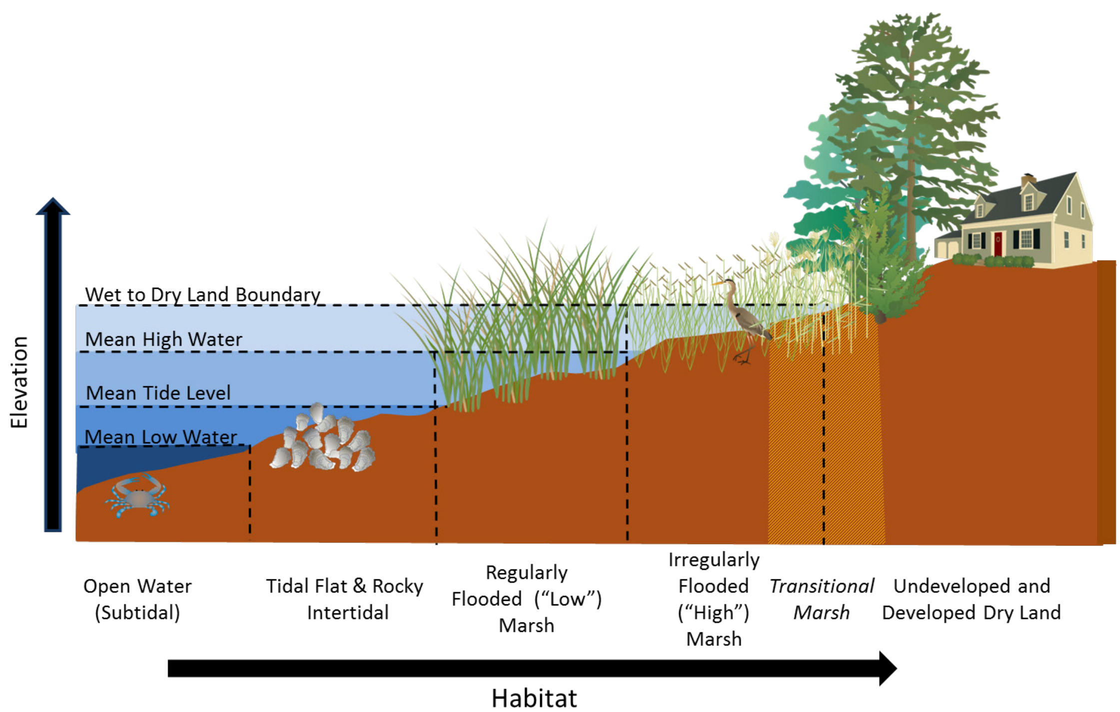


Figure 29. Relationship between tides, wetlands, and reference elevations for an example estuarine shore profile.

Wetland Boundary Elevation

The wetland boundary elevation (WBE) parameter in SLAMM 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 in NOAA tide records. In practice, we have found that the elevation that differentiates coastal wetlands and dry lands is approximately the height inundated once every 30 days.

Therefore, the 30-day inundation level was determined for the three locations in Connecticut with NOAA verified water-level data available: Bridgeport, New Haven and New London. Five years of data were analyzed in order to characterize this relationship in each location. Although relatively few data points were available spatially, a linear relationship was determined between the calculated WBEs versus the great diurnal tide ranges for the entire study area (WBE = 0.6015 · GT + 0.3205; see Figure 30). This relationship was used to derive site-specific WBEs based on the available local measured GT applied.

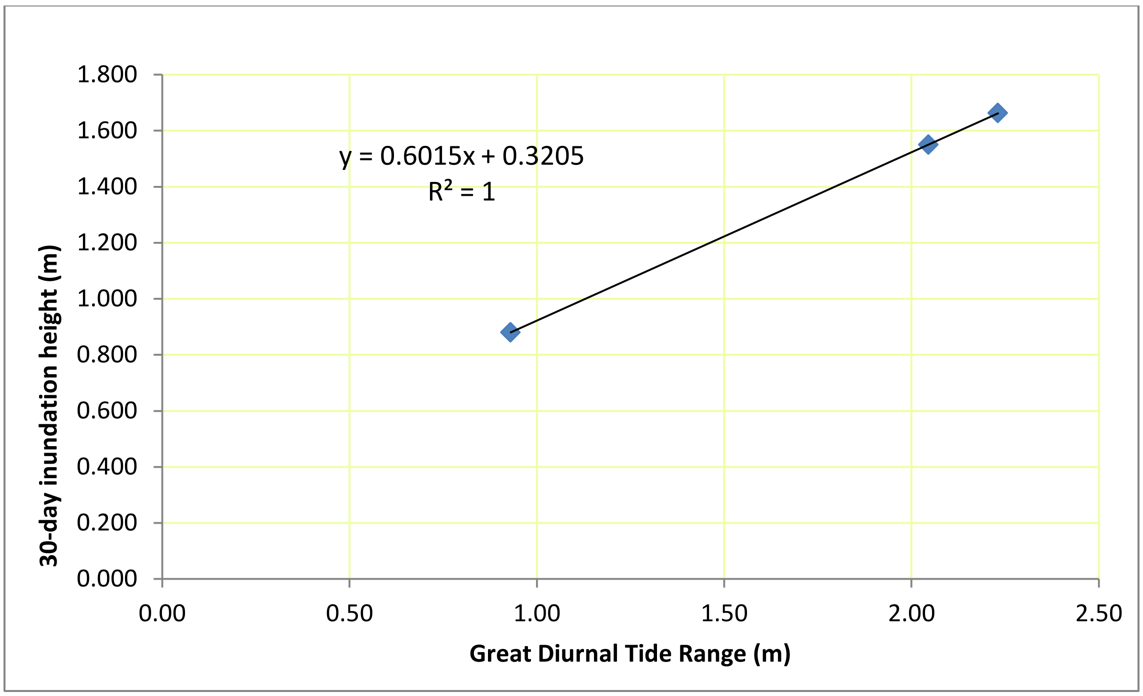


Figure 30. Great Diurnal Tide Range to 30-Day Inundation Height/Wetland Boundary Elevation relationship derived from NOAA

Accretion Rates

A full literature search was conducted to collect relevant accretion rates. In addition, unpublished data from members of the project advisory committee were used to determine the accretion rates for the study area.

Accretion in Tidal Salt Marsh

The current SLAMM application attempts to account for what are potentially critical feedbacks between tidal-marsh accretion 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).

In this project, such feedback relationships were investigated using observed accretion rates as compared to DEM-derived marsh platform elevations. Elevations relative to accretion rates were derived by comparing the location provided in the citations to the corresponding project area DEM. There is significant uncertainty in terms of assigning elevations to these marsh platforms, especially when data from wetland cores were used to derive accretion rates[6].

When sources did not define the type of marsh being studied, data for regularly-flooded marsh (RFM) vs. irregularly-flooded marsh (IFM) were discerned using the NWI wetland layer. Qualitatively, RFM includes low to mid marshes, while IFM includes high marshes. The persistence of these marshes and the decision tree that SLAMM uses when converting them to another land-cover class in the event of inundation are as follows:

- RFM may occupy a region if its platform is between [-0.4, 1.2] HTU (McKee and Patrick 1988). This interval of existence can be adjusted to address local observations. When the marsh platform falls below the minimum elevation, then the land cover is assumed converted to tidal flat.
- IFM may occupy areas that are higher, typically between 0.5 HTU and the wetland boundary elevation. As above, this interval can be adjusted to address local observations. When the marsh platform falls below the minimum elevation, then the land cover is converted to RFM.

All available accretion data are summarized in Table 3. Data with known sampling locations are shown with colored backgrounds in Table 3, and these locations are illustrated in Figure 31.

[6] With core data, assuming that the marsh has maintained a constant equilibrium elevation relative to sea levels, accretion rate best estimate is the average value over the historical period of the core (in the order of hundred years) while the marsh platform elevation (relative to sea level) best estimate is the current elevation. These accretion rate and marsh platform elevation uncertainties should be accounted for in an accretion rate uncertainty analysis.

Figure 31. Locations of Available Accretion Data in Coastal CT. (yellow dots)

Table 29. Accretion database for Connecticut. Shading indicates regions – Red = Fairfield, Green = New Haven, Orange = Barn Island, White = precise locations unknown.

Location	Marsh Type	Accretion (red) or Elevation change (mm/yr)	Accretion (red) or Elevation change Std. Dev. (mm/yr)	elev (m, from LiDAR) NAVD88	GT (m)	Source
Sherwood	RFM	*3.5*		1.55	2.3	Anisfeld 2014
Hoadley	RFM	*3.9*		0.8065	1.9	Anisfeld 2014
Jarvis	RFM	*10.3*		0.337	1.9	Anisfeld 2014
Guilford CT	IFM	*2.5*	*1.4*	1.3692	1.9	Anisfeld et al. (1999)
BP1	IFM	3.2	0.1	0.505	0.85	Barrett and Warren (2014)
BP2	IFM	2.7	0.1	0.4189	0.85	Barrett and Warren (2014)
WC1	IFM	2.3	0.2	0.5	0.85	Barrett and Warren (2014)
HQ1	IFM	1.62	0.07	0.36	0.85	Barrett and Warren (2014)
HQ3	IFM	3.07	0.09	0.68	0.85	Barrett and Warren (2014)
HQ2	IFM	2.4	0.1	0.36	0.85	Barrett and Warren (2014)
IP1	IFM	1.4	0.2	0.4	0.85	Barrett and Warren (2014)
IP2	IFM	1.3	0.4	0.4	0.85	Barrett and Warren (2014)
IP3	IFM	2.8	0.3	0.4	0.85	Barrett and Warren (2014)
CT	IFM	*3.3*		0.39	0.85	Orson, Warren and Niering (1998)
CT	IFM	*2*		0.5	0.85	Orson, Warren and Niering (1998)
CT	IFM	*1.8*		0.455	0.85	Orson, Warren and Niering (1998)
Barn Island		2				Harrison and Bloom, 1977
Great Island		3.8				Harrison and Bloom, 1977
Hammock River marsh, CT		3.6				Harrison and Bloom, 1977
Stony Creek marsh, CT		6.6				Harrison and Bloom, 1977
Nells Island, CT		6				Harrison and Bloom, 1977
Pataguanset		1.1				Orson et al., 1987
Headquarter, CT		1.125				Warren et al., 1993
Wequetequock Cove, CT		2.25				Warren et al., 1993

Irregularly-flooded marsh

The accretion data sampled from locations identified as irregularly-flooded marsh were analyzed to determine if they exhibit spatial trends or underlying feedback relationships with elevations. However, the distribution of the available accretion data as a function of the elevation suggests that there is not a strong relationship between elevation and accretion for this type of marsh, as shown in Figure 32. This may be expected since irregularly-flooded marshes are subject to less frequent flooding and therefore less sedimentation. These high marshes can therefore be assumed to be less sensitive to their vertical elevations. The average of the available measured accretion data is 2.42 mm/year. Because observed irregularly-flooded marsh accretion data suggest no strong relationship between marsh surface elevation and accretion rates, the average accretion rate was uniformly applied for all irregularly-flooded marshes across the entire study area. However, the forthcoming uncertainty analysis will explore the effects of other possible accretion-rate relationships by varying maximum and minimum accretion rates based on regional minimum and maximum observed data.

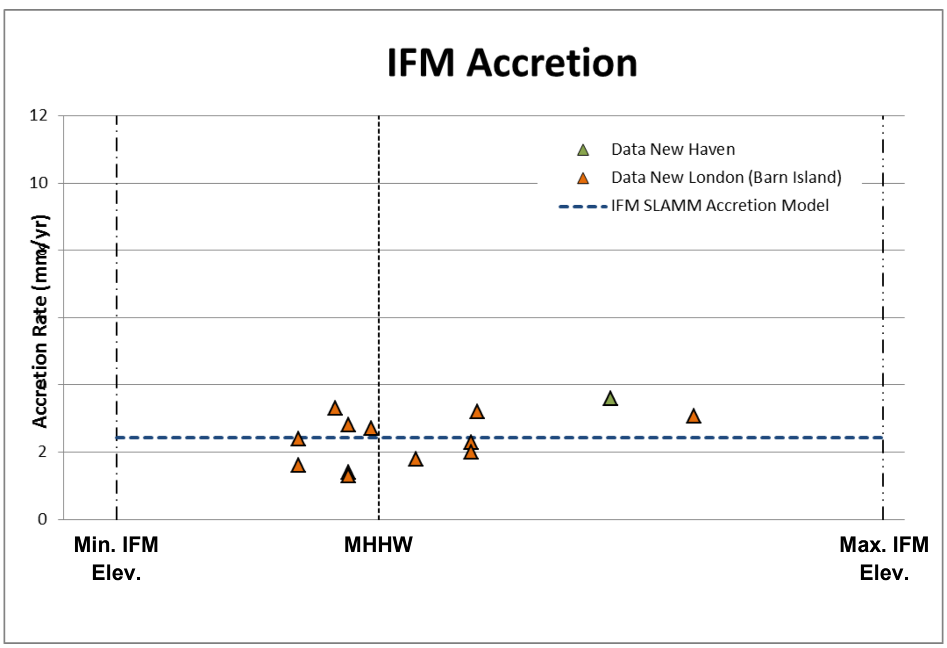


Figure 32. Irregularly-flooded marsh data and models for CT

Regularly-flooded Marsh

For Connecticut low marshes, accretion rates and their relationship with elevation were derived by calibrating the Marsh Equilibrium Model (MEM) (Morris 2013; Morris et al. 2002, 2012) to site-specific data. The MEM model was chosen for several reasons. MEM describes feedbacks in marsh accretion rates, it is backed up by existing data, and it accounts for physical and biological processes that cause these feedbacks. An alternative approach could be to fit available accretion data with a simple mathematical function. However, as described below, available accretion data often do not span a wide enough set of elevations to be able to derive the required curve. Furthermore, using a mechanistic model such as MEM helps explain the causes for feedbacks between accretion rates and elevation and therefore can tell a more compelling story. Another important reason to use MEM is that results from this model can be extrapolated to other geographic areas where there are no accretion data available, but when other physical/biological parameters *are* available (e.g. suspended sediment concentrations or tidal regimes). The model can also be extrapolated to vertical positions in the tidal frame where data do not exist. This is often required in areas where there is little marsh low in the tidal frame due to historically low rates of SLR.

The key physical input parameters of the MEM model are tide ranges, suspended sediment concentrations, initial sea-level and marsh platform elevations, and the elevation defining the domain of marsh existence within the tidal frame. Biological input parameters are the peak concentration density of standing biomass at the optimum elevation, organic matter decay rates, and parameters determining the contribution to accretion from belowground biomass. However, several input parameters are not always known (e.g. partition between organic and inorganic components to accretion, peak biomass, settling velocities, trapping coefficients, organic matter decay rate, below ground turnover rate and others). The approach taken was to estimate MEM input parameters based on observations when available and fit the unknown model parameters using observed accretion rates measured in Connecticut (listed in the first four rows of Table 29).

The sections below discuss the regional physical and biological input parameters for developing MEM within Connecticut.

Suspended Sediment. Suspended sediment data (in the form of total suspended solids or TSS) were collected from the US EPA STORET Data Warehouse (U.S. Environmental Protection Agency 2013). Table 30 presents the averages obtained when the TSS data were analyzed by region.

Table 30. Average TSS by Study area

	Fairfield	New Haven and Middlesex	New London
Average (mg/L)	10	17	8
St.Dev. (mg/L)	13	17	7
N – Sample size	56	45	15

Statistical analyses of the TSS data (Kolmogorov Smirnoff tests) show that the New Haven/Middlesex data set is distinct from the other two data sets, but the Fairfield and New London data sets are not statistically different. Despite this, we have produced three different MEM curves applied to each study region since New London and Fairfield counties are not spatially adjacent and have different tidal range.

Marsh biomass. Relatively few studies on marsh biomass are available within the study area. Anisfeld and Hill (2012) measured a maximum "net aboveground primary production" in a *Spartina alterniflora* marsh in Guilford, CT (Area 2) of 250 g of Carbon/m^2/year. This can be converted into a biomass basis given that aboveground organic carbon content of *Spartina alterniflora* is generally between 39 to 44%. Assuming that this ratio is 39.2% (Middelburg et al. 1997), the peak biomass for the Guilford Marsh can be estimated to be around 625 g/m^2. Hartig et al. (2002) measured biomass of *Spartina alterniflora* ranging 700-1450 g/m^2 in Jamaica Bay.

More recently, values between 700-1000 g/m^2 have been measured at Hoadley and Jarvis marshes in New Haven County, CT (Area 2) and Sherwood marsh in Fairfield County, CT (Area 1) by Shimon Anisfeld (2014). These values, that are more recent and consistent with other regional observations, were used as input parameters for the MEM models developed for the different study areas (Table 31). A peak biomass of 700 g/m^2 was chosen across the study area except for in New Haven and Middlesex counties where available data suggested a higher value.

Table 31. Peak biomass applied to the MEM models in CT

	Fairfield (Area 1)	New Haven and Middlesex (Area 2)	New London (Area 3)
Peak biomass (g/m^2)	700	995	700

MEM Calibration Results. When building MEM for the study areas, model input parameters such as tide ranges, peak biomasses, and total suspended solids were set to the local specific values discussed above while input parameters determining the partition between inorganic and organic contribution to accretion were calibrated to fit the available Connecticut accretion data. The final set of RFM marsh accretion models plotted against data is shown in Figure 33.

Although MEM was used to generate accretion rates for regularly-flooded marshes, Figure 33 also reports irregularly-flooded marsh data (depicted as triangles). This was done because accretion rates for regularly-flooded marshes located high in the tidal frame (near MHHW), are believed to be similar to those for irregularly-flooded marshes. While there is some uncertainty in the National Wetland Inventory between the spatial domains of regularly and irregularly-flooded marshes, overall model uncertainty is reduced as both marshes have very similar accretion rates at their boundaries.

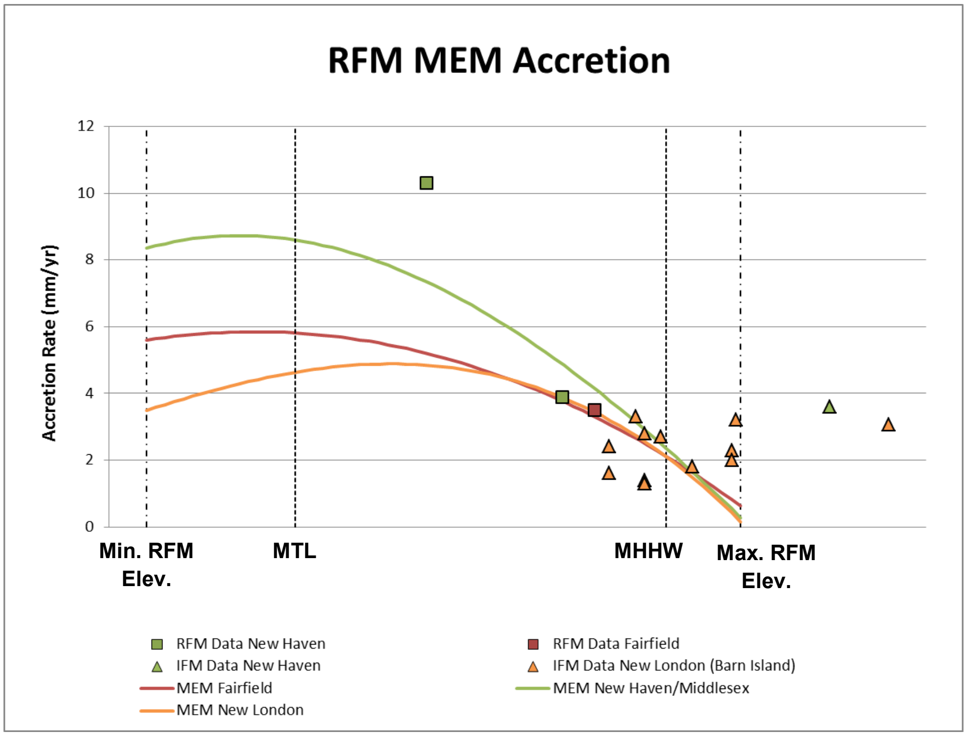


Figure 33. Regularly-flooded marsh accretion models plotted against available data

There is no doubt that the RFM accretion models shown above are somewhat conjectural as there are few site-specific RFM accretion data available to compare our model against, especially when estimating accretion response at low elevations. However, this is one of the main benefit of using MEM – to extrapolate models based on physical relationships into spatial regions (both moving horizontally or vertically) where data are limited or nonexistent.

Overall, at higher elevations, these RFM accretion curves not only reasonably fit the Anisfeld data (Table 29), but they also fit available Barn Island high-marsh data (IFM in Table 29) for marshes at the high-marsh/low marsh boundary. The general curve is also describing a feedback that increases with increasing inundation which is reasonable when considering the qualitative marsh response to sea level rise. As expected, the maximum accretion rate is predicted in New Haven/Middlesex counties due to the high TSS in the area. However, accretion rates predicted in Fairfield county are not too different because, although TSS are lower, the MEM model suggests that the increased average tidal range (GT=2.4 m vs. GT=1.7 m) results in a higher sedimentation rate. On the other hand, for New London, due to the low TSS (half of New Haven) and lower tide range the predicted accretion rate model does not exceed 4.9 mm/yr. However, maximum accretion rates in Fairfield and New London are not so different from measured accretion rates in the north shore of Long Island which make sense when considering the regional area.

Accretion Rates of Other Wetlands

The Inland-fresh Marsh accretion 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. Tidal Fresh Marsh accretion was set to 5 mm/yr based on data presented by Neubauer (Neubauer 2008; Neubauer et al. 2002). Tidal-fresh marsh accounts for only one half of one percent of coastal wetlands in the study area. Accretion feedbacks were not used for tidal-fresh marshes due to a lack of site-specific data. Lacking site-specific data, values of 1.6 mm/yr and 1.1 mm/yr were assigned for swamp and tidal swamp accretion, 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.

Erosion Rates

In SLAMM average erosion rates are entered for marshes, swamps and beaches. SLAMM models erosion as additive to inundation and this is considered the effects of wave action. Horizontal erosion is only applied when the wetland type in question is exposed to open water and where a 9 km fetch[7] is possible. In general, SLAMM has been shown to be less sensitive to the marsh erosion parameters than accretion parameters (Chu-Agor et al. 2010).

In order to parameterize the erosion rates required by SLAMM, we relied on recent shoreline change statistics derived for the CT coast by Barrett and Coworkers (2014). This work characterized transects along the entire coast of CT to determine both long (1880 - 2006) and short-term (1983-2006) shoreline change rates. Long term rates were used to calculate the Linear Regression Rate (LRR) by fitting a least-squares regression line to all shoreline points for a particular transect (Barrett et al. 2014). In several cases the LRR showed positive shoreline movement, indicating aggradation. In these areas erosion rates were set to zero. In areas where shorelines had negative LRRs, the rate derived was applied equally to marsh, swamp, and beach categories, though erosion only applies in open-water to wetland boundaries. Specific rates applied, ranging from 0.02 to 0.12 meters per year, are described in the individual model calibration

[7] "Fetch" is the distance traveled by waves over open water, calculated by the model based on current land-cover predictions.

sections below. These rates are lower than the 1 m/year observed by Fagherazzi (2013) and applied to the NYSERDA-funded SLAMM modeling of the entire Long Island and New York City coastlines.

Initial GIS Methods

DEM Preparation:

Multiple steps were used to produce a hydro-enforced DEM for the Connecticut coastal project area. The 2011 and 2012 LiDAR dataset ground points were converted to DEMs with 5m cell resolution. The earlier NED and UConn DEM data were resampled to a 5m cell resolution. The DEMs were mosaicked together. The Post Sandy DEM elevation data were used wherever cells overlapped with the other datasets. The other datasets were used to fill in gaps in the Post Sandy data, or to extend coverage inland (i.e., 2011 USGS LiDAR data), to islands along the coast (NED), and along the Housatonic River (UConn DEM). The mosaicked DEM was reclassified to create the hydro-enforcement extent, which is limited to elevated areas at or below 5.5 m above mean tide level.

Pre-processing. The LiDAR datasets were downloaded in laz format. The files were extracted and re-projected from geographic to UTM coordinate systems. Post Sandy heights are referenced to ellipsoidal heights using Geoid12a. USGS LiDAR heights are referenced to ellipsoidal heights using Geoid09. The NED data were downloaded and reprojected from geographic to UTM coordinate systems. NED heights are referenced to NAVD88. The 10ft UConn DEM was downloaded and reprojected from State Plane US_ft to UTM meters coordinate systems. There is no height information for the 10ft UConn DEM. The FEMA Structures database was used as the primary source of data to locate all bridges and culverts in the project area. If a bridge or culvert existed, the LiDAR data and publicly available orthoimagery (i.e., ESRI online imagery) was used as reference data to digitize a line through the bridge or culvert. If the stream was greater than 5m wide then a polygon was digitized through the bridge or culvert along with a centerline. All lines were digitized in the downstream direction. Elevation values were then conflated to the end points of the lines using the hybrid elevation dataset. A custom ArcGIS tool was used to verify the start point of each artificial path was higher than or the same elevation of the endpoint. Vertices were edited as needed to ensure a downstream constraint. The vertices of each line and polygon were then densified to 5m spacing. Another custom tool conflated elevation values to the interior vertices of all lines using the start point and end point elevations. If the start point and end point had the same elevation value then all interior vertices will have the same elevation value. If the start point and end point had different elevation values then the value of each interior vertex was calculated using a linear algorithm based on the values of the two endpoints. We used the LP360 Flatten River Polygon tool to conflate the elevation values of each artificial path to each vertex of the polygons that were digitized at each bridge/culvert location, resulting in 3d polygon breaklines that cut through every culvert/bridge location in the study area.

DEM Hydroenforcement: The mosaicked DEM was converted to a multipoint feature class. Points were then erased from the multipoint feature class that fell inside the bridge/culvert polygons. Multipoint feature class and polygon breaklines were then used to create an ESRI terrain dataset. The terrain dataset was converted to a raster DEM with a 5m cell resolution. The breakline polygon areas were inspected to make sure they were represented in the final DEM. For bridges/culverts represented by lines only, the vertices of the lines were converted to points. Points were converted to raster and mosaicked onto the DEM that was converted from the ESRI terrain.

Wetland-Layer Preparation:

The preparation for all wetland layers required the following steps:

- The projection for each data source was checked/converted to NAD83 UTM Zone 18N.
- ESRI's ArcGIS Union tool was used to join each wetland data layer in order of priority.
- The attributes for the priority layer were updated with each subsequent join operation.
- This process was repeated until all the data sources were combined in the order of priority.
- ESRI's Dissolve tool was used to merge adjacent polygons with the same attribute.
- The wetland polygons for individual project areas were merged together into one single dataset representing the full extent of the project using ESRI's Merge tool.
- ESRI's Conversion tool was used to convert the polygon data to raster format with 5 m cell resolution.
- Each project area was then extracted from the full extent raster using the ESRI's Spatial Analyst tool "Extract by Mask".

Initial Model Calibration

Fairfield County Site Calibration and Parameters

Several rounds of calibration were run for the Fairfield County study area. These iterations focused mostly on refining the time zero results for the Pine Creek marsh and around Sikorsky Airport where the initial site parameters led to excessive flooding not consistent with the current land cover survey of the areas. This initial model calibration effort suggested that the tide ranges in these areas are lower when compared to the rest of the study area. A study of wetland delineation around the Sikorsky Airport confirmed that the tides are restricted by man-made structures and provided the information of the area affected by this reduced tidal regime (Fitzgerald & Halliday, Inc. 2013). Pine Creek Marsh was investigated by Roman and coworkers and that study, as well as data available from the town of Fairfield, provided insight for the probable extent and tide range of the subsite there (Roman et al. 1984; Town of Fairfield CT, 2014). For the rest of the study area, NOAA gauge stations measure GTs varying between 2.2 m at the mouth of the Housatonic River to 2.4 m at Cos Cob Harbor, CT and Rye Beach, NY. Therefore, an average GT=2.3 m was set.

New Haven and Middlesex Counties Site Calibration

Several calibration iterations were carried out in order to adjust tide ranges and wetland boundary elevations within the New Haven and Middlesex study area. Adjustments were made to the WBE in all the large input subsites (General Area 2, CT River, and Guilford), revising them to match the current wetland conditions. Smaller subsites (Hammock River, HVN Airport, Sybil Creek, and muted tide areas) were added during calibration to reflect muted tidal ranges due to tide gates and culverts and to minimize flooding in residential areas. Muted tide ranges were determined based on literature review (Bjerklie et al. 2013; Roman et al. 1984; Rozsa 1995) , examination of marsh elevation profiles using SLAMM, and through collaboration with CT DEEP. Calibration of this site also included additional hydroenforcement of marshes based on feedback from the CT DEEP.

New London County Site Calibration

Two rounds of calibration were run on study Area 3. These iterations focused on refining the time zero results until the interplay between tide ranges, elevations, and coastal habitat maps in the initial conditions was deemed satisfactory. Results of the calibration of the initial condition are reported in the tables below and broken down by watershed. Overall, initial land cover changes are minimal indicating a strong agreement between spatial data and tidal information. Two main land cover conversions are observed: some dry lands are found by the model to be inundated at least once every 30 days and thus are converted to either wetlands or flooded developed categories. These areas are usually small fringes of dry land bordering open water. This conversion is mostly due to the wetland-layer horizontal resolution accuracy issues and uncertainty in the elevations assigned to these cells. The elevation assigned to each cell is an average of the LiDAR returns in that cell and may include open water and dry land. Another uncertainty stems from the definition of developed vs. undeveloped dry lands. Developed dry lands were derived from data with 30-m resolution data and rescaled to the 5-m cell size of the project.

The second common initial conversion is from irregularly-flooded marsh to regularly-flooded marsh. This result is somewhat expected as the boundary between low and high marsh is a spatially variable buffer area more than a precise line; thus, wetland classification in this interface is affected by significant uncertainty.

Uncertainty Analysis Setup

The base analyses (non-uncertainty-analysis runs, also called the “deterministic” model) consider a range of different possible SLR scenarios, but other model uncertainties such as variability in measured input parameters and spatial-data errors were not accounted for. For example, uncertainties arise when literature parameters are used rather than site-specific data. In addition, the strength of feedbacks between marsh vertical accretion rates and SLR can vary significantly from one site to another. SLAMM includes an uncertainty-analysis module that employs Monte-Carlo simulations to study the effects of uncertainties and to produce predictions of wetland coverages as distributions. This module enhances the value of the results by providing confidence intervals, worst and best case scenarios, likelihoods of wetland conversion, and other statistical indicators useful to better characterize possible future outcomes and assist decision making. In addition, simplified maps showing the likelihood of wetland coverage in each location were produced for this project.

All of the site-specific data required by SLAMM, such as the spatial distribution of elevations, wetland coverages, tidal ranges, accretion and erosion rates, local sea-level rise and subsidence rates, may be affected by uncertainties that can propagate into the predicted outputs. The propagation of input-parameter uncertainty into model predictions cannot be derived analytically due to the non-linear spatiotemporal relationships that govern wetland conversion. The Monte Carlo uncertainty analysis module within SLAMM uses efficient Latin-Hypercube sampling of the input parameters (McKay et al. 1979). This module generates hundreds of prediction results that are then assembled into probability distributions of estimated wetland coverages.

For each of the model input parameters, an uncertainty distribution was derived based on available site-specific data. Moreover, mechanistic considerations regarding the proper distributional family and the feasible bounds of the variable were considered. Distributions were derived reflecting the potential for measurement errors, uncertainty within measured central tendencies, and professional judgment (Firestone et al. 1997).

Because SLAMM calculates equilibrium effects of SLR based on relatively large time-steps, long-term erosion rates, accretion rates, and SLR rates were used to drive model predictions. Therefore, the uncertainty distributions described in the following section are based on long-term measurements rather than incorporating short-term variability within measurements. Cell-by-cell spatial variability has been considered for elevation data, but the majority of the input parameters have uncertainty distributions that vary on a subsite basis.

One important limitation that should be considered when interpreting these results is that the uncertainties of the general conceptual model in describing system behaviors are not taken into account (model framework uncertainty; Gaber et al. 2008). For example, within this uncertainty analysis, the flow chart of marsh succession is fixed. Low marshes must initially pass through a tidal flat category before becoming open water rather than directly converting to open water under any circumstance.

The next sections discuss each of the model's input parameters that are affected by uncertainties, and how they were handled within the uncertainty analysis for this project.

SLR by 2100

The extent of future sea-level rise by 2100 is a key model input parameter and possibly the most uncertain. The drivers of climate change used by scientists to derive potential SLR rates include future levels of economic activity, dominant fuel type (e.g., fossil or renewable, etc.), fuel consumption, and resulting greenhouse gas emissions. Because future values of these driving variables are uncertain, the exact extent of future sea-level rise is also therefore uncertain. Therefore, it is necessary to use a range of potential sea-level-rise scenarios in SLAMM analysis, to present a range of possibilities.

As described in Section 2.4, the deterministic SLR scenarios used in this SLAMM application correspond to the maximum of the General Climate Model (GCM), the Minimum and Maximum of the Rapid Ice Melt (RIM) estimates as described in the ClimAID report (Rozenzweig et al. 2011), and the intermediate scenario of 1 meter (39.4 inches) of SLR by 2100. The base year for these scenarios is 2002. In the uncertainty analysis, sea-level rise scenarios were drawn from the triangular probability distribution shown in Figure 34. The deterministic SLR scenarios are also presented in order to illustrate their relationship to the possible simulated SLR scenarios. Figure 34 shows that, under the probability distribution of SLR applied, 1m by 2100 is the "most likely" scenario of those simulated by the deterministic model runs.

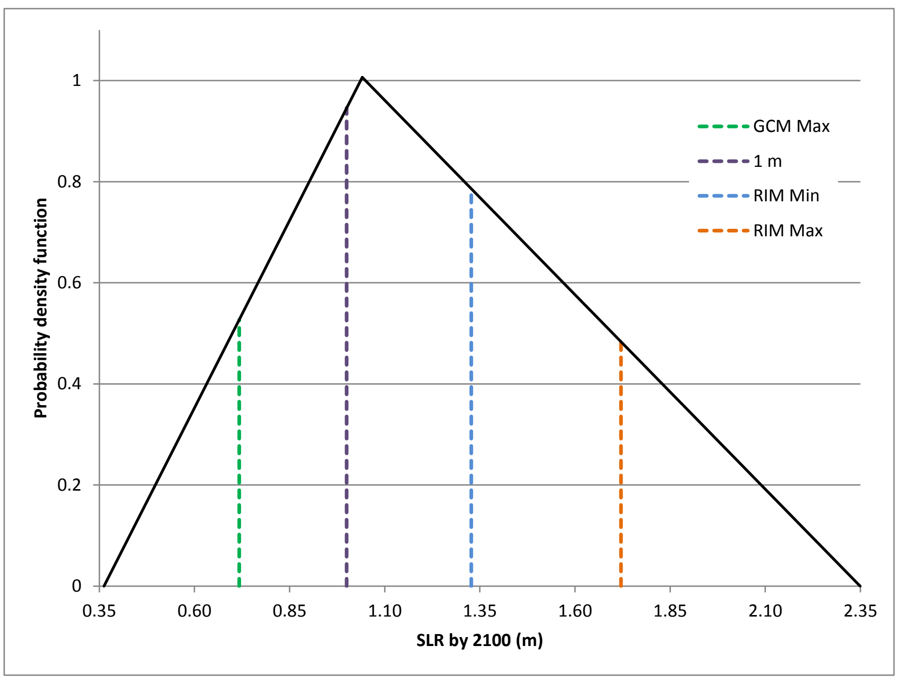


Figure 34. SLR probability distribution

In order to derive the probability distribution in Figure 34, information from the recent NYC Panel on Climate Change (NPCC2) report (C. Rosenzweig and W. Solecki (Editors), NPCC2 2013) was used in addition to the ClimAID report. The NPCC2 study estimates that by the 2020s the sea-level rise (with respect to 2000-2004 baseline level) at the Battery in NYC has a 10% probability to be between 0 and 5.08 cm (10th percentile) and a 90% probability to be less than or equal to 27.94 cm (90th percentile). By the 2050s, these estimated percentiles become 17.78 cm and 78.74 cm respectively, as presented in Table 32.

Table 32. Baseline and SLR Projections (Source NPCC2)

Sea-level rise baseline (2000-2004) 0 inches	Low-estimate (10th percentile)	Middle range (25th to 75th percentile)	High-estimate (90th percentile)
2020s	5.1 cm (2 in)	10.2 to 20.3 cm (4 to 8 in)	27.9 cm (11 in)
2050s	17.8 cm (7 in)	27.9 to 61.0 cm (11 to 24 in)	78.7 cm (31 in)

The sea-level rise estimates shown in Table 32 closely correspond to the GCM Min and RIM Max SLR scenarios. To incorporate these estimates and percentages the SLR predictions were extrapolated to 2100: the 10th percentile SLR projection was set to 36.2 cm (14.3 in), while the 90th percentile set to 1.84 m (72.4 in) by 2100. Assuming a symmetrical, triangular probability distribution, the most likely SLR scenario was estimated equal to 1.04 m (41 in) SLR by 2100. However, the historic SLR rate at the Battery (2.77 mm/yr) is already higher than the estimated current SLR rate of the 10th percentile SLR projection (2.2 mm/yr). It was deemed unlikely that future SLR rates will be lower than the historic recorded data during the past century. For this reason, the more conservative estimate was set to as the minimum possible SLR scenario rather than the 10th percentile, while 1.04-m and 1.84-m SLR by 2100 were kept as the most likely and the 90th percentile SLR scenarios, respectively. The highest possible SLR rate scenario was set to 2.35 m (92.5 in) by 2100.

Digital Elevation Map Uncertainty

LiDAR elevation data is subject to measurement errors due to equipment limitations. In addition, in marsh areas, the laser pulse used to measure elevations does not always reach the bare earth causing additional errors and uncertainty (Schmid et al. 2011). In this SLAMM application, elevation-data uncertainty was evaluated by randomly applying elevation-data error statistics and creating a series of equally likely elevation maps. Maps were created adding a spatially autocorrelated error field to the existing digital elevation map (Heuvelink 1998). Heuvelink's method has been widely recommended as an approach for assessing the effects of elevation data uncertainty (Darnell et al. 2008; Hunter and Goodchild 1997). This approach uses the normal distribution as specified by the Root Mean Squared Error (RMSE) for the LiDAR-derived dataset and applies it randomly over the entire study area, with spatial autocorrelation included, as shown in Figure 35. A stochastic analysis is then executed (implementing the model with one of these elevation maps) to assess the overall effects of elevation uncertainty. In this analysis, it was assumed that elevation errors were strongly spatially autocorrelated, using a p-value of 0.2495. The RMSE applied for the entire Connecticut study areas was set to 0.1 m, derived as a conservative estimate of RMSE of the different elevation sources used to cover the study area. In the past, running an elevation uncertainty analyses alone on elevation data sets with RMSE of 0.1 or even greater has shown very little effect on overall model predictions.[8]

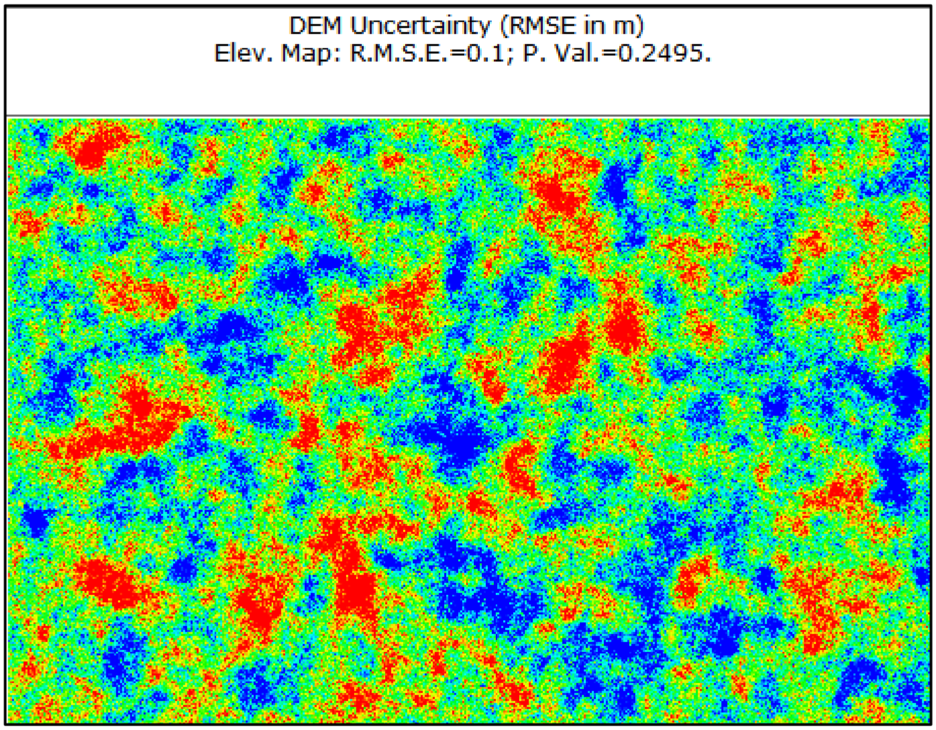


Figure 35. Example of a DEM uncertainty map. Min (blue) = -0.135m, Max (red) = 0.135m.

A different error field such as this one, based on 0.1 RMSE, is derived for each uncertainty iteration and added to the baseline digital elevation map.

Vertical Datum Correction

Correction of elevation data to a tidal basis using the NOAA VDATUM product is also subject to uncertainty due to measurement errors and VDATUM model errors. NOAA characterizes the "maximum cumulative uncertainty" for each location in the documentation of the model (National Oceanic and Atmospheric Association 2010). Like the DEM uncertainty, the vertical-datum-correction uncertainty was also applied via spatially variable autocorrelated maps. The RMSE for the datum correction was set to 10

[8] See, for example, the elevation uncertainty analysis performed for Saint Andrew and Choctawhatchee Bays starting on page 59 of this document: http://warrenpinnacle.com/prof/SLAMM/TNC/SLAMM_SAC_Florida_Final.pdf.

cm for the entire study area with the assumption of strong spatial autocorrelation with p-value of 0.2495 applied.

Great Diurnal Tide Range

Tide ranges are not measured at each cell and therefore there is spatial uncertainty associated with the tide range assigned. The error associated with the tide ranges applied was considered on an input subsite basis. The GT of each input subsite was represented by a unique probability distribution whose variability reflects the variability the tide data used to the point estimates. These distributions represent multipliers on point estimates, rather than the distribution of the tide range itself. (This approach allows SLAMM to remain flexible when using one probability distribution for many input subsites with varying tide range). An example of the SLAMM interface showing the uncertainty of the Pine Creek subsite in Fairfield County is shown in Figure 36.

In order to calculate the standard-deviation multiplier applied to each subsite, the standard deviation of the tide measurements used for each subsite was calculated. When less than four tide-range measurements were used to determine the GT for an input subsite, the difference between the GT applied and the maximum GT observed was calculated, as was the difference between the GT applied and the minimum GT observed; the greater of these two values was applied as the standard deviation. When subsites were added to represent muted tide ranges (behind a tide gate or upriver where tide data were not available), the standard deviation of nearby subsites were applied.

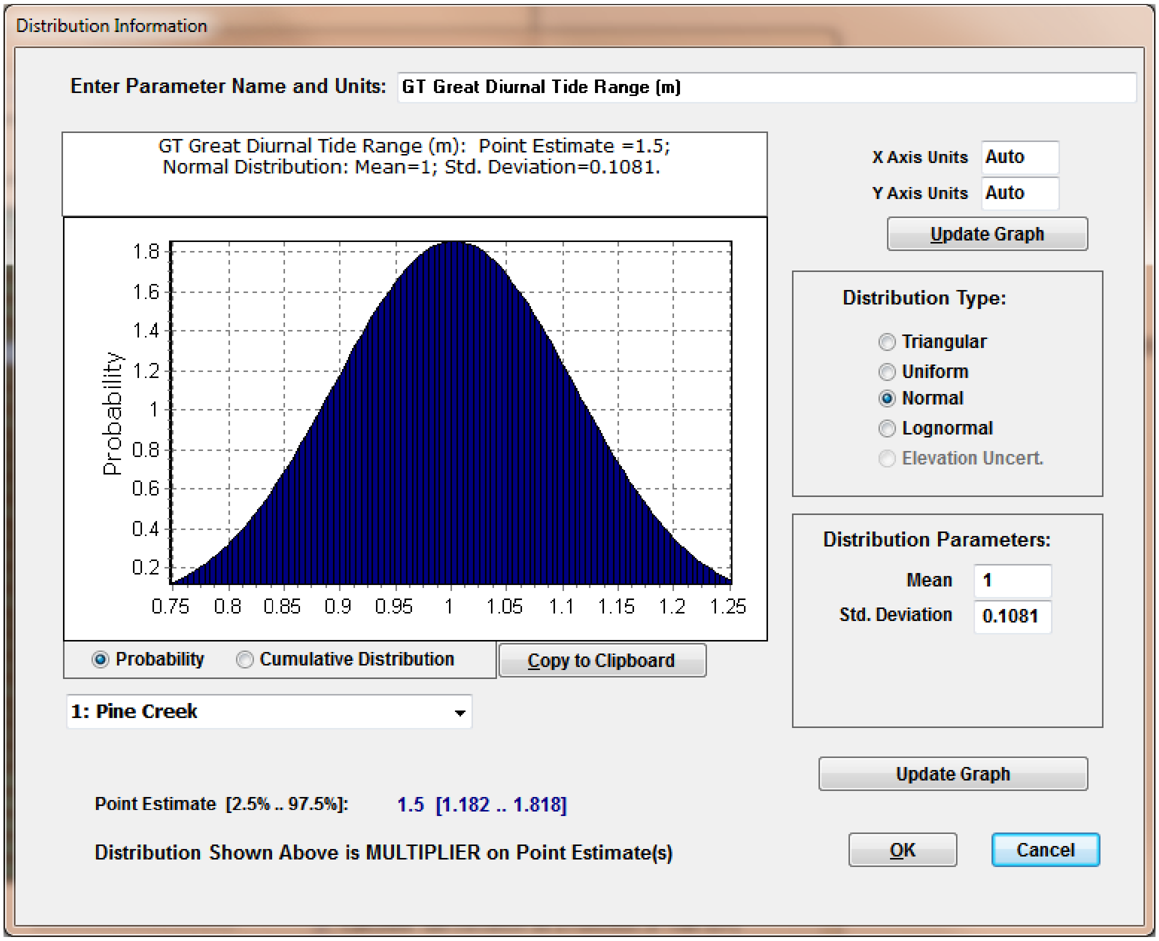


Figure 36. Example Input Distribution for Great Diurnal Tide Range Uncertainty

Wetland Boundary Elevation

As discussed in Section 2.7, the elevation of the coastal-wet-to-dry-land boundary WBE) was estimated as a 30-day inundation elevation and a linear relationship was used to derive site-specific WBE based on the local GT applied. However, this boundary is also subject to uncertainty due to tide-range uncertainty and spatial interpolation. The potential variability of the WBE was estimated by considering the range between the 20-day and 40-day inundation elevations at the three tide stations that have this information. The maximum difference between 20/40-day and the 30-day inundation elevation was 5 cm. Uncertainty distributions for all WBEs were modeled as Gaussian distributions with a standard deviation equal to 5 cm.

Since the tide ranges (GTs) are also part of the uncertainty analysis, the sampling of the WBE for each model realization was carried out by first sampling the GT from its uncertainty distribution, and then calculating the corresponding WBE using the linear relationship presented in Figure 30. Finally, a multiplier to apply to the WBE was derived from the Gaussian uncertainty distribution described above and applied to the parameter for the current model iteration.

Erosion

Historical erosion rates can be quite variable in both space and time and the projection of future erosion rates involves a combination of data and professional judgment. Uncertainty parameters associated with marsh, swamp, and tidal flat erosion parameters were applied uniformly across the study area. The long-term linear regression rates (LRR) determined by Barrett and Coworkers that were applied in the deterministic analysis had associated standard deviations reported (2014). However, these were standard deviations not used in the uncertainty analysis since the ranges were quite narrow and represented uncertainties in past erosion rates as opposed to potential future erosion rates. To reflect overall uncertainty, marsh was modeled using a uniform distribution ranging from 0 m/yr to 2.0 m/yr of erosion across the entire study area (Fagherazzi 2013). Swamp and Tidal Flat erosion uncertainty were assigned to triangular distributions ranging between 0 m/yr and 2.0 m/yr with most likely rates varying spatially and equal to the values used in the base analysis.

This approach was determined based on professional judgment and also maximum erosion rates measured in marshes at other locations in the US (Fagherazzi 2013). While a maximum erosion rate of 2.0 m/yr may be high for the CT coast, it also includes uncertainty due to the potential for future large storms.

Accretion

Accretion Point Estimate Uncertainty

Due to a lack of spatially variable site-specific data, uncertainty distributions for the following categories were applied uniformly throughout the entire study area:

- Accretion rates for freshwater marshes (inland and tidal).
- Swamp and tidal swamp accretion rates.
- Beach sedimentation rates.

Tidal fresh marsh accretion was applied as a triangular distribution with a minimum of 2 mm/yr and a maximum of 18 mm/yr, with a most likely value of 5 mm/yr (corresponding to multipliers of 0.4, 3.6, and 1, respectively). The minimum for this distribution was derived from work by Neubauer (2008) in the Hudson River while the maximum was derived from studies of tidal-fresh marshes along the mid-Atlantic coast (Neubauer et al. 2002). The distribution applied is presented in Figure 37.

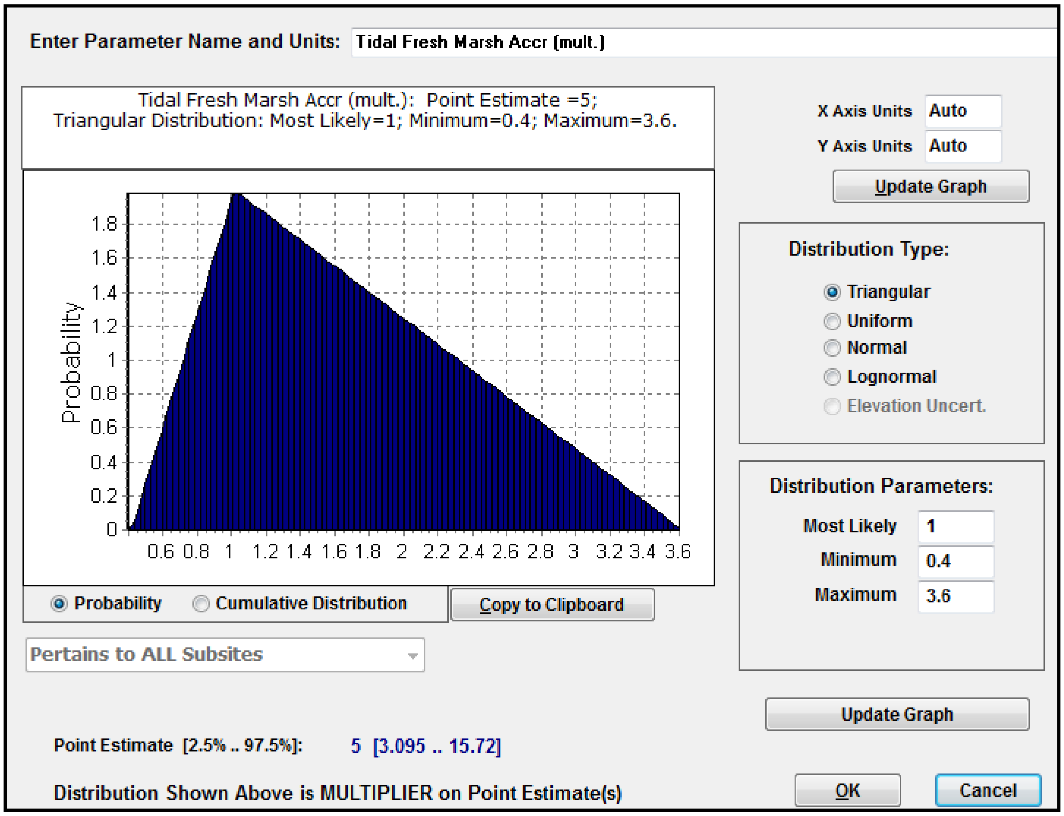


Figure 37. Tidal fresh marsh accretion distribution assigned for uncertainty analysis

Inland fresh marsh accretion uncertainty was modeled using a normal distribution (multiplier) with a standard deviation of 0.153, determined from data presented by Craft and coworkers (Craft and Casey 2000; Craft and Richardson 1998). This assignment resulted in a relatively narrow range of possible values with 2.5th and 97.5th percentile values of 0.7 and 1.3 mm/yr, respectively.

Tidal-swamp accretion was applied a uniform probability distribution. Based on data from Craft (Craft 2012b) collected in Georgia tidal swamps, a maximum of 2.8 mm/yr and a minimum of 0.6 mm/yr were applied.

Accretion observations by Craft were also used to inform the probability distribution for swamps. Based on unpublished data from the Altamaha River in Georgia, a uniform distribution with a minimum on 0.2 mm/yr and maximum 3.4 mm/yr was applied (Craft 2014).

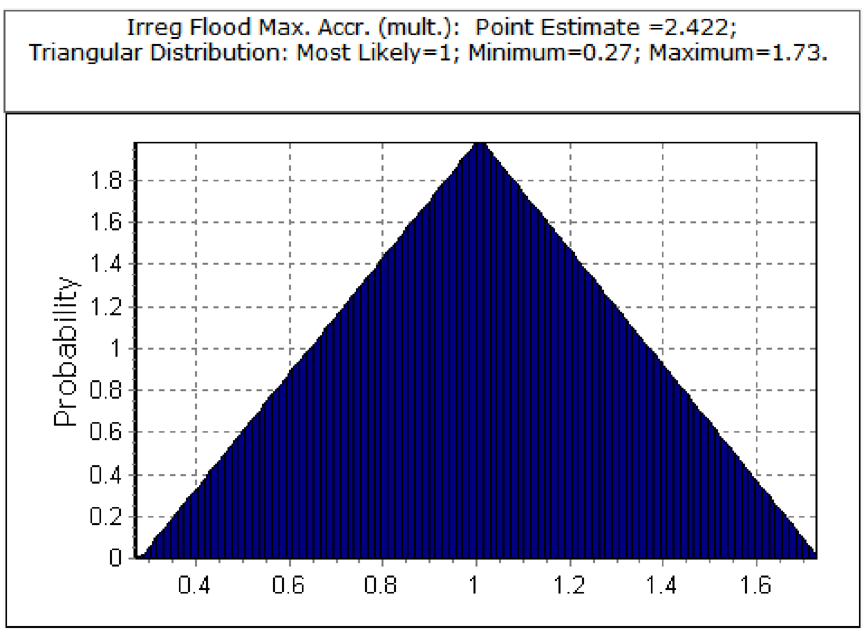
Beach-sedimentation-rate uncertainty was applied as a uniform distribution from 0.1 to 2 mm/yr. Beach sedimentation rates tend to be spatially variable, and are often lower than marsh accretion rates due to the lack of vegetation to trap sediments. The chosen range was fairly wide since there is a considerable amount of uncertainty in beach sedimentation due to the effects of storms and nourishment activities, which are not explicitly included in this study.

Mechanistic Accretion Model Uncertainty

The measured accretion-data variability described in Section 0 was used to estimate the uncertainty distributions attributed to tidal marsh accretion rates, as described below.

Irregularly flooded marsh. The linear accretion-to-elevation relationship used in the deterministic model was also used in the uncertainty analysis (see Section 0). However, the maximum and minimum accretion rates assigned at the upper and lower boundaries of the marsh elevation range (0.5 HTU to 1 WBE) were allowed to vary. These accretion rates were drawn separately from the same probability distribution. This probability distribution was derived using the variability of the available measured accretion rates with respect to the best-fit linear model (see Figure 32). The goal of the uncertainty analysis was to determine the ensemble of linear accretion models that would fit the available data within their confidence intervals. To do this, a triangular distribution was produced for accretion rates both at the maximum (1 WBE) and at the minimum (0.5 HTU) elevations as shown in Figure 38.

Figure 38. Uncertainty distributions for maximum and minimum accretion rates for irregularly flooded marsh



The “most likely” point on the distribution was assigned to 1.0, which would result in the accretion rate used for the deterministic runs— 2.42 mm/yr. The range for the triangular distribution was estimated by adding or subtracting two standard deviations of the observed accretion rate data. This produced a range from 0.65 to 4.19 mm/yr for accretion rates at the boundaries. For high marshes with elevations between these two points, the accretion rate was chosen through linear interpolation. The resulting model could have a positive or negative slope. Often accretion rates are higher at lower elevations due to tides and sediment capture. However, higher accretion rates at higher elevations are also possible due to increased organic production under conditions of lower salinity. Observed data for high marshes do not show a strong relationship with elevation (Figure 32).

Regularly-flooded marsh. For low tidal marsh, uncertainty in accretion-feedback curves was estimated by considering the uncertainty associated with the accretion curves shown in Figure 33. For these marshes, the available accretion data are very limited and do not provide enough information for a meaningful assessment of uncertainty. Therefore, accretion-rate variability was estimated using an analysis from nearby Long Island, NY where more data were available. As MEM contains several parameters that can be varied to calibrate the model, for simplicity it was assumed that the general accretion curves remain the same as in Figure 33. Given this assumption, the calibrated MEM model can be varied by modifying just the maximum and minimum accretion rates.

In the north shore of Long Island, data show that minimum accretion rates could vary in the range from 0 to 4.0 mm/yr while maximum accretion rates could be approximately plus or minus 3 mm/yr around the point estimates used in the deterministic runs. These values were applied also in Connecticut although some uncertainty ranges were conservatively widened to better reflect lack of knowledge. The identified uncertainty distributions are summarized in Table 33. The last two columns provide the range of 95% of the accretion sample values drawn from these distributions.

Table 33. Summary of uncertainty accretion rate distributions. All values mm/yr.

MAX Reg. Flood Accretion	Most Likely	Triangular Distribution Min-Max	2.5th percentile	97.5th percentile
Area 1	5.8	3.4 - 9.5	4.0	8.8
Area 2	8.7	4.0 - 12.5	5.0	11.6
Area 3	4.9	2.4 - 8.5	3.0	7.8

MIN Reg. Flood Accretion	Most Likely	Triangular Distribution Min-Max	2.5th percentile	97.5th percentile
Area 1	0.64	0.0 - 4.0	0.25	3.4
Area 2	0.28	0.0 - 4.0	0.17	3.4
Area 3	0.16	0.0 - 4.0	0.13	3.4

Sampling from these distributions separately, an accretion-feedback curve with the same general parabolic shape as the deterministic runs (Figure 33) will be produced by one of the uncertainty model's iterations. A low minimum accretion rate might be paired with a high maximum accretion rate for example, providing a very strong feedback. Given uncertainty about future suspended-sediment concentrations, spatial variability within marsh accretion rates, and relatively high uncertainty in our data sets, the intent was to be as conservative as possible and to sample from a wide range of feasible relationships between accretion rates and marsh elevations.

Appendix B: Great Diurnal Tide Ranges in CT (m)

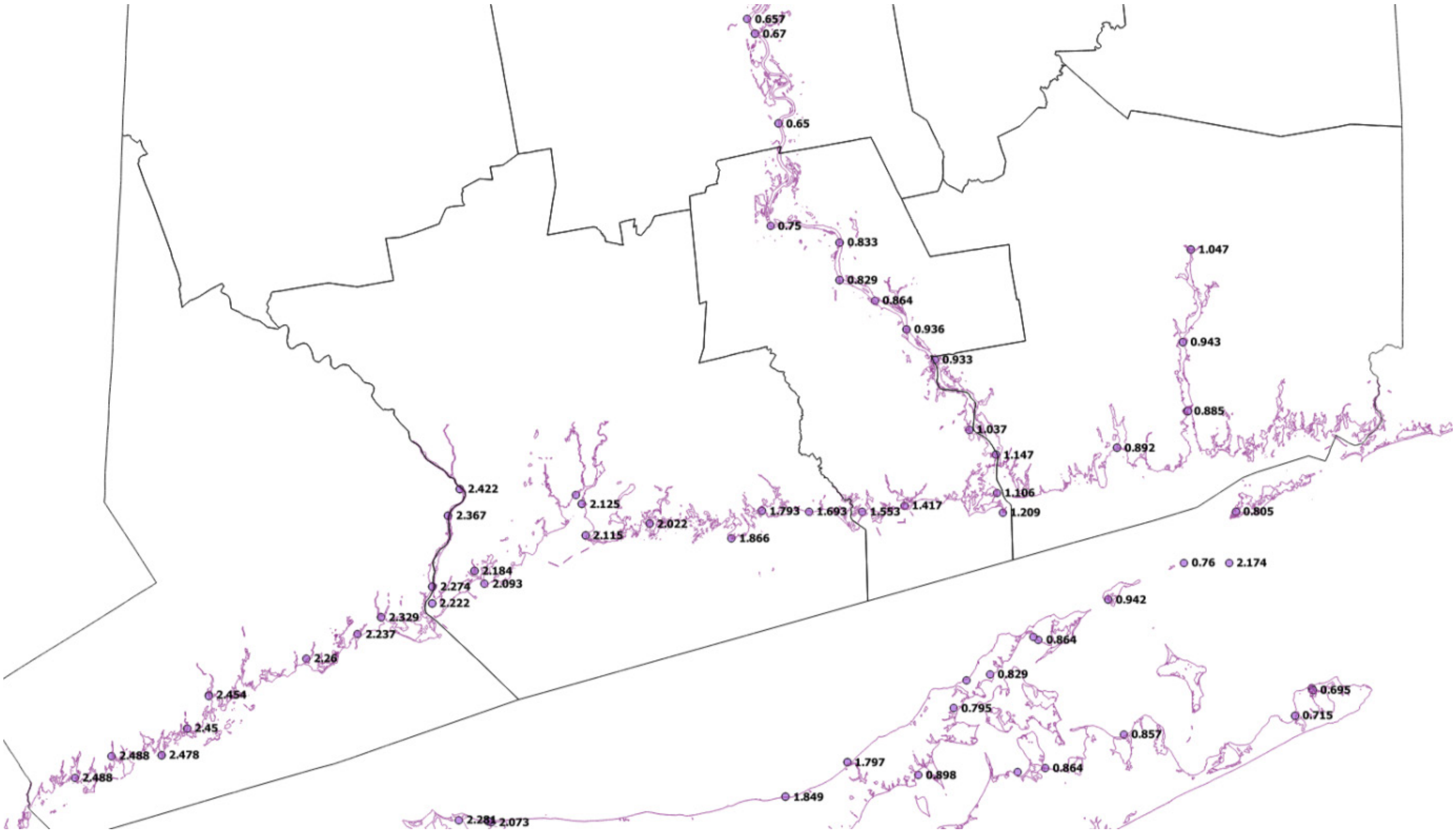


Figure 39. Great diurnal tide ranges in CT (m)

Appendix C: Infrastructure Results

Table 34. Amtrak Stations. 6 sites analyzed, 1 predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	0	0	0.0%	0.0%	0.0%
	2085	0	0	0	0.0%	0.0%	0.0%
	2100	0	0	0	0.0%	0.0%	0.0%
Low-Medium	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	0	0	0.0%	0.0%	0.0%
	2085	0	0	0	0.0%	0.0%	0.0%
	2100	0	1	0	0.0%	16.7%	16.7%
Medium	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	0	0	0.0%	0.0%	0.0%
	2085	0	1	0	0.0%	16.7%	16.7%
	2100	0	2	0	0.0%	33.3%	33.3%
Medium-High	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	1	0	0.0%	16.7%	16.7%
	2085	0	2	0	0.0%	33.3%	33.3%
	2100	1	1	0	16.7%	33.3%	33.3%
High	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	1	0	0.0%	16.7%	16.7%
	2085	1	1	0	16.7%	33.3%	33.3%
	2100	2	0	0	33.3%	33.3%	33.3%

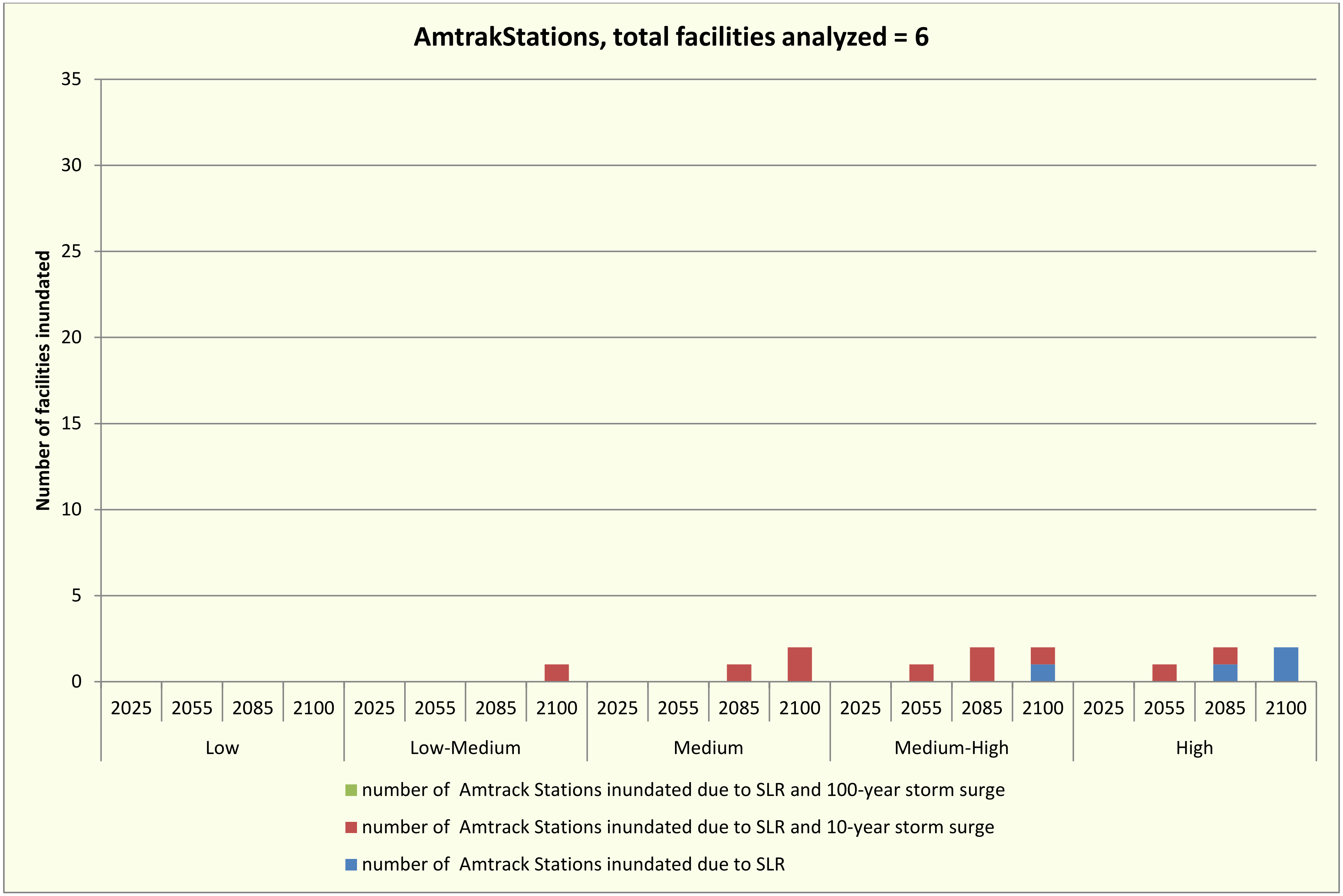

AmtrakStations, total facilities analyzed = 6
Number of facilities inundated
35
30
25
20
15
10
5
0
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number of Amtrack Stations inundated due to SLR and 100-year storm surge
number of Amtrack Stations inundated due to SLR and 10-year storm surge
number of Amtrack Stations inundated due to SLR

Table 35. Combined Airports. 28 sites analyzed, 2 predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	0	6	4	0.0%	21.4%	35.7%
	2055	0	6	4	0.0%	21.4%	35.7%
	2085	0	6	4	0.0%	21.4%	35.7%
	2100	0	7	3	0.0%	25.0%	35.7%
Low-Medium	2025	0	6	4	0.0%	21.4%	35.7%
	2055	0	6	4	0.0%	21.4%	35.7%
	2085	0	8	2	0.0%	28.6%	35.7%
	2100	4	6	0	14.3%	35.7%	35.7%
Medium	2025	0	6	4	0.0%	21.4%	35.7%
	2055	0	7	3	0.0%	25.0%	35.7%
	2085	5	5	0	17.9%	35.7%	35.7%
	2100	6	4	0	21.4%	35.7%	35.7%
Medium-High	2025	0	6	4	0.0%	21.4%	35.7%
	2055	2	6	2	7.1%	28.6%	35.7%
	2085	6	4	0	21.4%	35.7%	35.7%
	2100	10	0	1	35.7%	35.7%	39.3%
High	2025	0	6	4	0.0%	21.4%	35.7%
	2055	5	5	0	17.9%	35.7%	35.7%
	2085	10	0	2	35.7%	35.7%	42.9%
	2100	10	1	1	35.7%	39.3%	42.9%

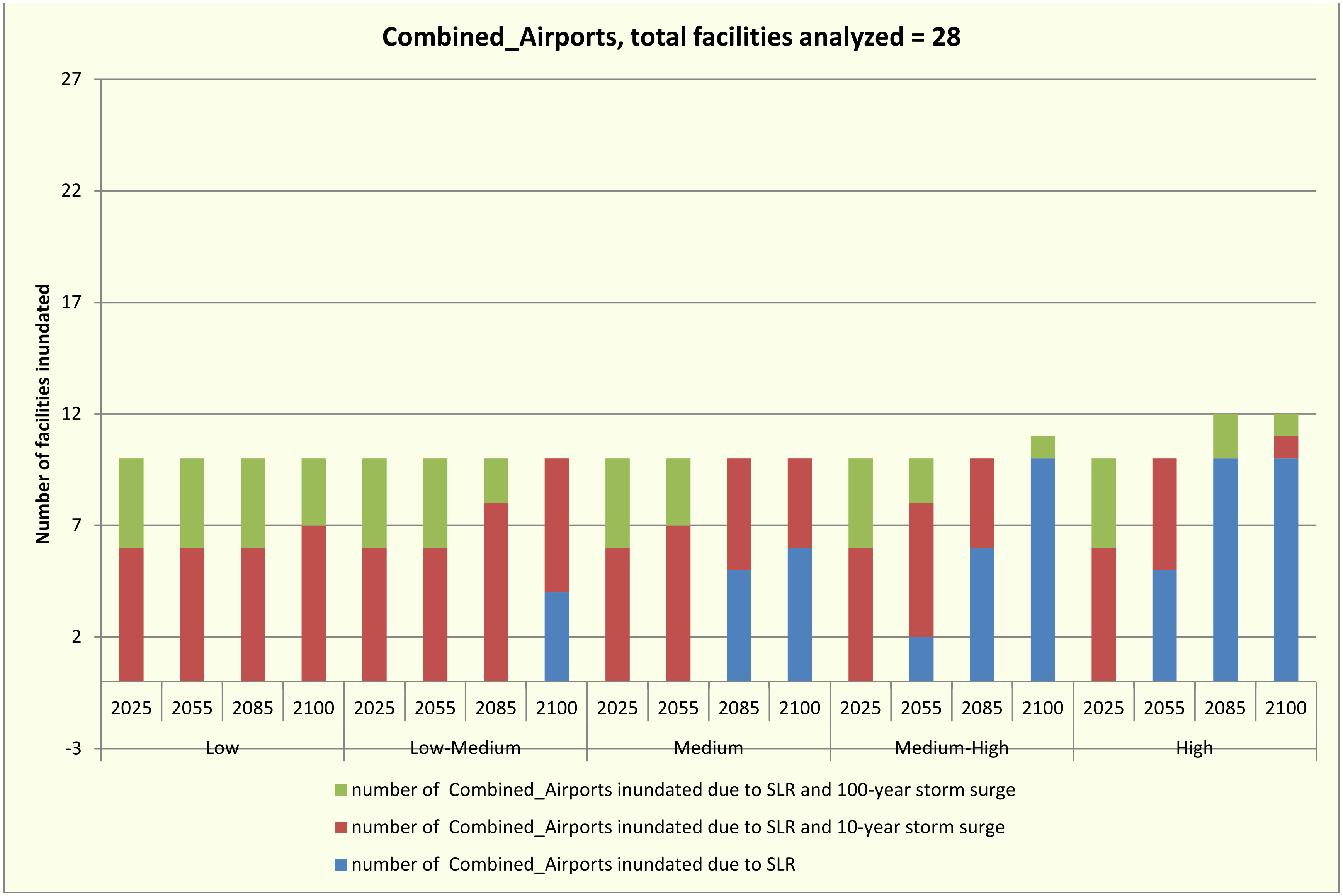
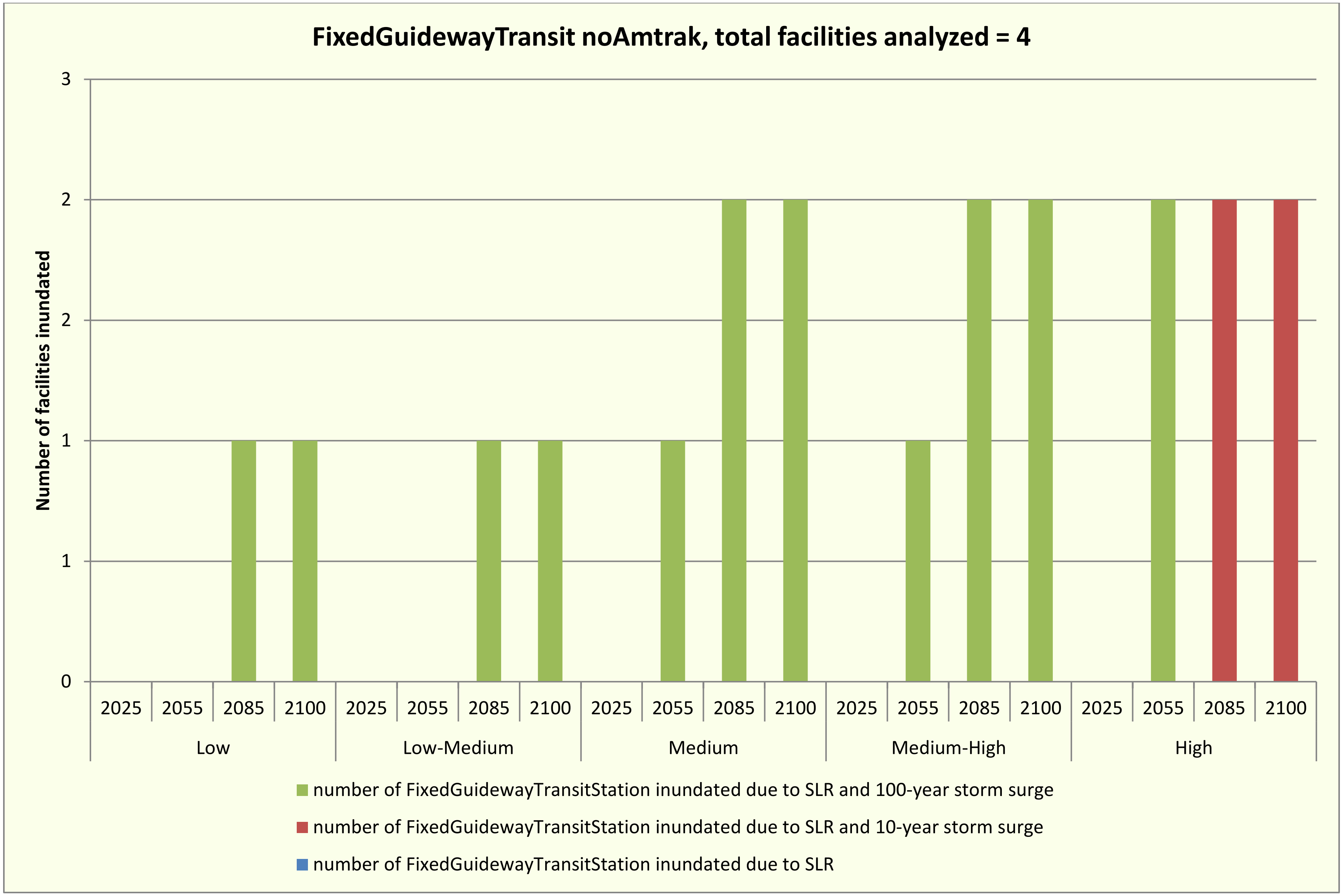

Combined_Airports, total facilities analyzed = 28
Number of facilities inundated
27
22
17
12
7
2
-3
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number of Combined_Airports inundated due to SLR and 100-year storm surge
number of Combined_Airports inundated due to SLR and 10-year storm surge
number of Combined_Airports inundated due to SLR

Table 36. Fixed Guideway Stations (Amtrak stations removed). 4 sites analyzed, 0 predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	0	0	0.0%	0.0%	0.0%
	2085	0	0	1	0.0%	0.0%	25.0%
	2100	0	0	1	0.0%	0.0%	25.0%
Low-Medium	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	0	0	0.0%	0.0%	0.0%
	2085	0	0	1	0.0%	0.0%	25.0%
	2100	0	0	1	0.0%	0.0%	25.0%
Medium	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	0	1	0.0%	0.0%	25.0%
	2085	0	0	2	0.0%	0.0%	50.0%
	2100	0	0	2	0.0%	0.0%	50.0%
Medium-High	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	0	1	0.0%	0.0%	25.0%
	2085	0	0	2	0.0%	0.0%	50.0%
	2100	0	0	2	0.0%	0.0%	50.0%
High	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	0	2	0.0%	0.0%	50.0%
	2085	0	2	0	0.0%	50.0%	50.0%
	2100	0	2	0	0.0%	50.0%	50.0%



FixedGuidewayTransit noAmtrak, total facilities analyzed = 4
Number of facilities inundated
3
2
2
1
1
0
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number of FixedGuidewayTransitStation inundated due to SLR and 100-year storm surge
number of FixedGuidewayTransitStation inundated due to SLR and 10-year storm surge
number of FixedGuidewayTransitStation inundated due to SLR

Table 37. GNIS_CulturalFeatures. 669 sites analyzed, 100 predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	2	26	35	0.3%	4.2%	9.4%
	2055	6	24	36	0.9%	4.5%	9.9%
	2085	9	25	37	1.3%	5.1%	10.6%
	2100	9	28	37	1.3%	5.5%	11.1%
Low-Medium	2025	4	24	35	0.6%	4.2%	9.4%
	2055	6	27	35	0.9%	4.9%	10.2%
	2085	12	26	37	1.8%	5.7%	11.2%
	2100	17	28	32	2.5%	6.7%	11.5%
Medium	2025	5	23	35	0.7%	4.2%	9.4%
	2055	9	27	37	1.3%	5.4%	10.9%
	2085	24	33	21	3.6%	8.5%	11.7%
	2100	30	35	24	4.5%	9.7%	13.3%
Medium-High	2025	5	24	34	0.7%	4.3%	9.4%
	2055	14	26	35	2.1%	6.0%	11.2%
	2085	32	35	25	4.8%	10.0%	13.8%
	2100	50	25	20	7.5%	11.2%	14.2%
High	2025	5	24	36	0.7%	4.3%	9.7%
	2055	24	32	22	3.6%	8.4%	11.7%
	2085	55	22	23	8.2%	11.5%	14.9%
	2100	73	15	24	10.9%	13.2%	16.7%

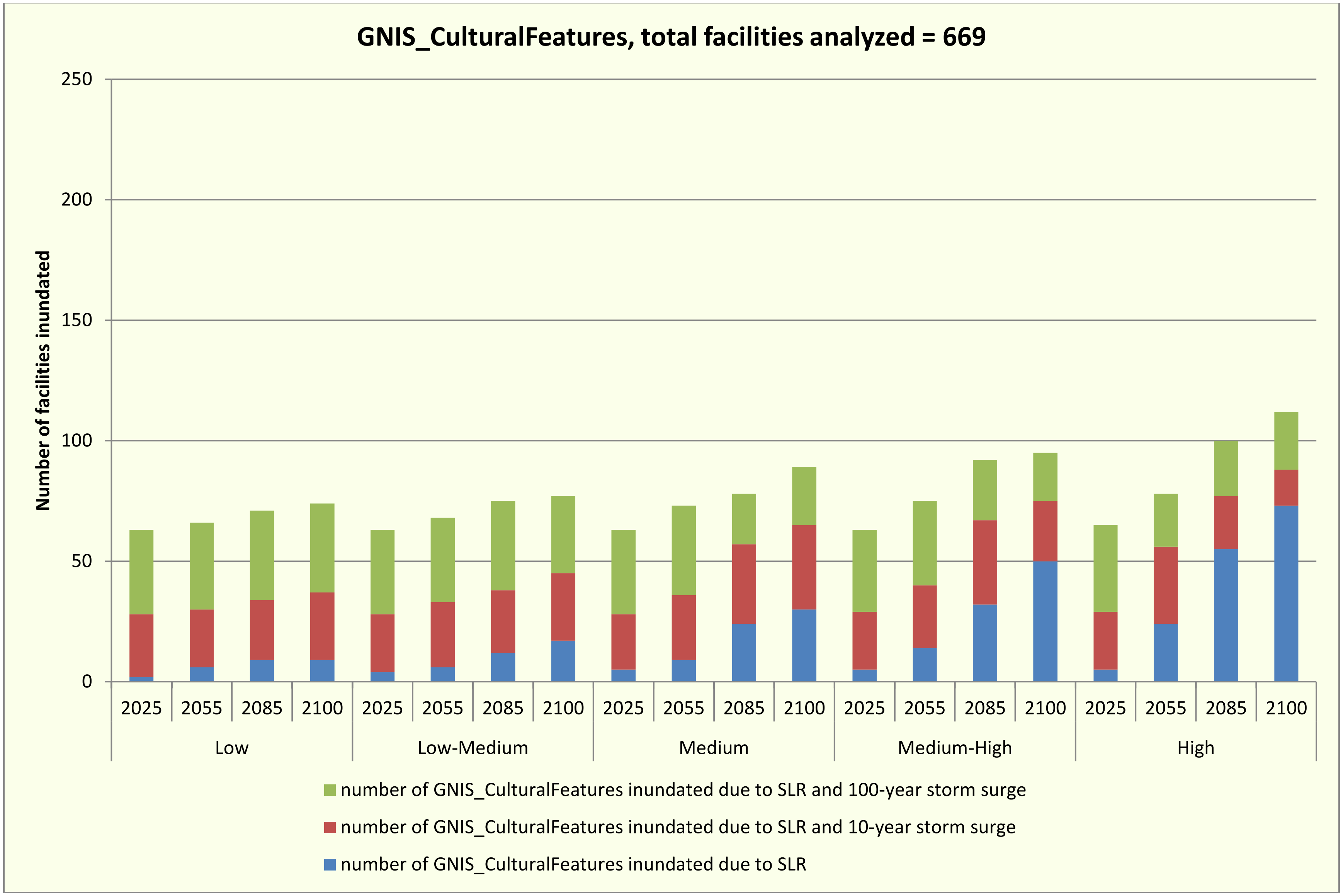

GNIS_CulturalFeatures, total facilities analyzed = 669
Number of facilities inundated
250
200
150
100
50
0
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number of GNIS_CulturalFeatures inundated due to SLR and 100-year storm surge
number of GNIS_CulturalFeatures inundated due to SLR and 10-year storm surge
number of GNIS_CulturalFeatures inundated due to SLR

Table 38. Combined Power Plants. 27 sites analyzed, 1 predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	0	0	8	0.0%	0.0%	29.6%
	2055	0	4	4	0.0%	14.8%	29.6%
	2085	0	4	4	0.0%	14.8%	29.6%
	2100	0	4	4	0.0%	14.8%	29.6%
Low-Medium	2025	0	1	7	0.0%	3.7%	29.6%
	2055	0	4	4	0.0%	14.8%	29.6%
	2085	0	4	4	0.0%	14.8%	29.6%
	2100	0	4	4	0.0%	14.8%	29.6%
Medium	2025	0	2	6	0.0%	7.4%	29.6%
	2055	0	4	4	0.0%	14.8%	29.6%
	2085	1	6	2	3.7%	25.9%	33.3%
	2100	3	4	2	11.1%	25.9%	33.3%
Medium-High	2025	0	3	5	0.0%	11.1%	29.6%
	2055	0	4	4	0.0%	14.8%	29.6%
	2085	3	4	2	11.1%	25.9%	33.3%
	2100	7	1	2	25.9%	29.6%	37.0%
High	2025	0	3	5	0.0%	11.1%	29.6%
	2055	1	6	2	3.7%	25.9%	33.3%
	2085	7	2	1	25.9%	33.3%	37.0%
	2100	9	1	0	33.3%	37.0%	37.0%

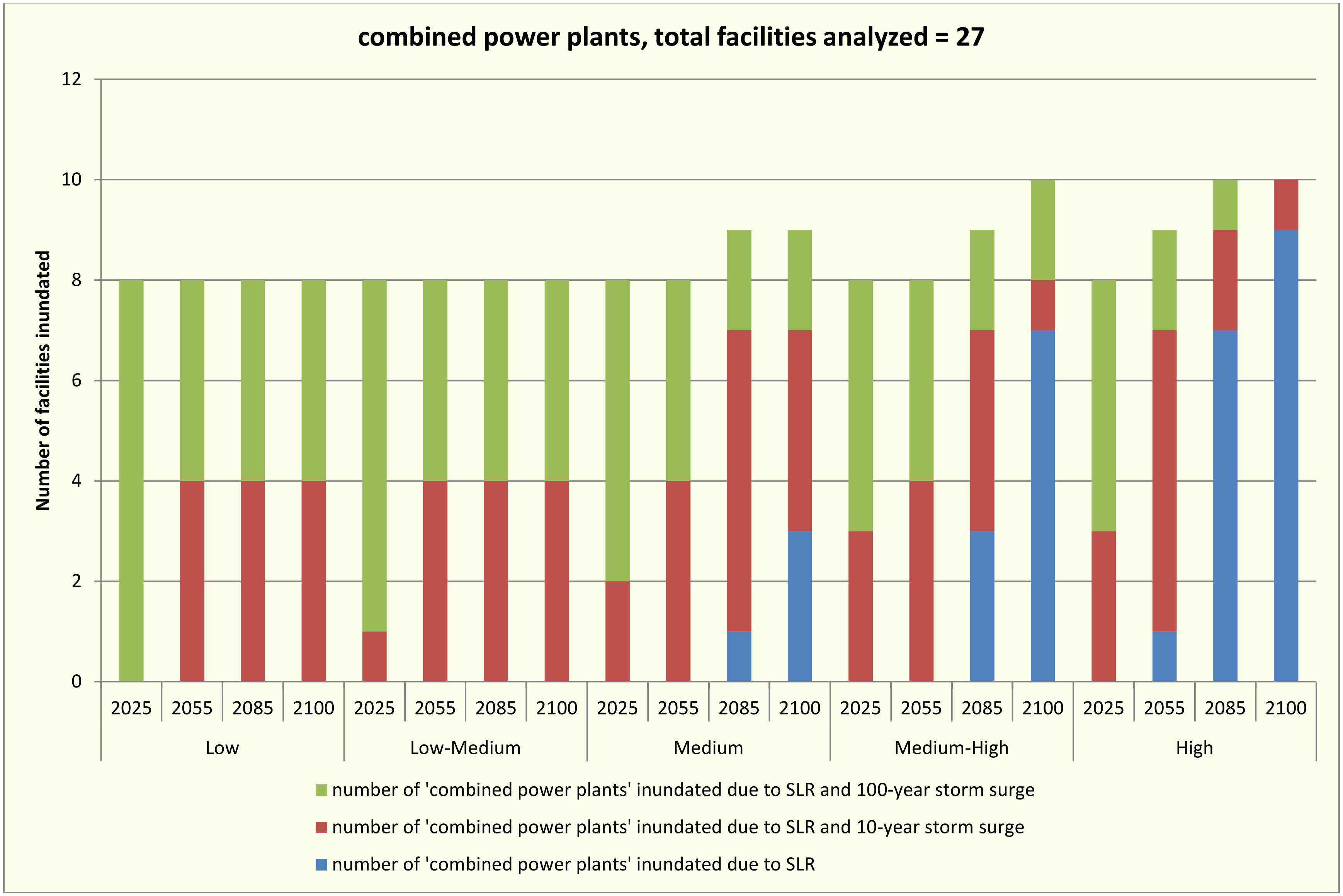

combined power plants, total facilities analyzed = 27
Number of facilities inundated
12
10
8
6
4
2
0
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number of 'combined power plants' inundated due to SLR and 100-year storm surge
number of 'combined power plants' inundated due to SLR and 10-year storm surge
number of 'combined power plants' inundated due to SLR

Table 39. TNC Fire Stations. 58 sites analyzed, 0 predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	0	1	2	0.0%	1.7%	5.2%
	2055	0	1	2	0.0%	1.7%	5.2%
	2085	0	1	2	0.0%	1.7%	5.2%
	2100	0	1	3	0.0%	1.7%	6.9%
Low-Medium	2025	0	1	2	0.0%	1.7%	5.2%
	2055	0	1	2	0.0%	1.7%	5.2%
	2085	0	1	3	0.0%	1.7%	6.9%
	2100	0	1	4	0.0%	1.7%	8.6%
Medium	2025	0	1	2	0.0%	1.7%	5.2%
	2055	0	1	3	0.0%	1.7%	6.9%
	2085	0	2	3	0.0%	3.4%	8.6%
	2100	0	2	5	0.0%	3.4%	12.1%
Medium-High	2025	0	1	2	0.0%	1.7%	5.2%
	2055	0	1	3	0.0%	1.7%	6.9%
	2085	0	3	5	0.0%	5.2%	13.8%
	2100	1	4	3	1.7%	8.6%	13.8%
High	2025	0	1	2	0.0%	1.7%	5.2%
	2055	0	2	3	0.0%	3.4%	8.6%
	2085	1	4	3	1.7%	8.6%	13.8%
	2100	5	1	4	8.6%	10.3%	17.2%

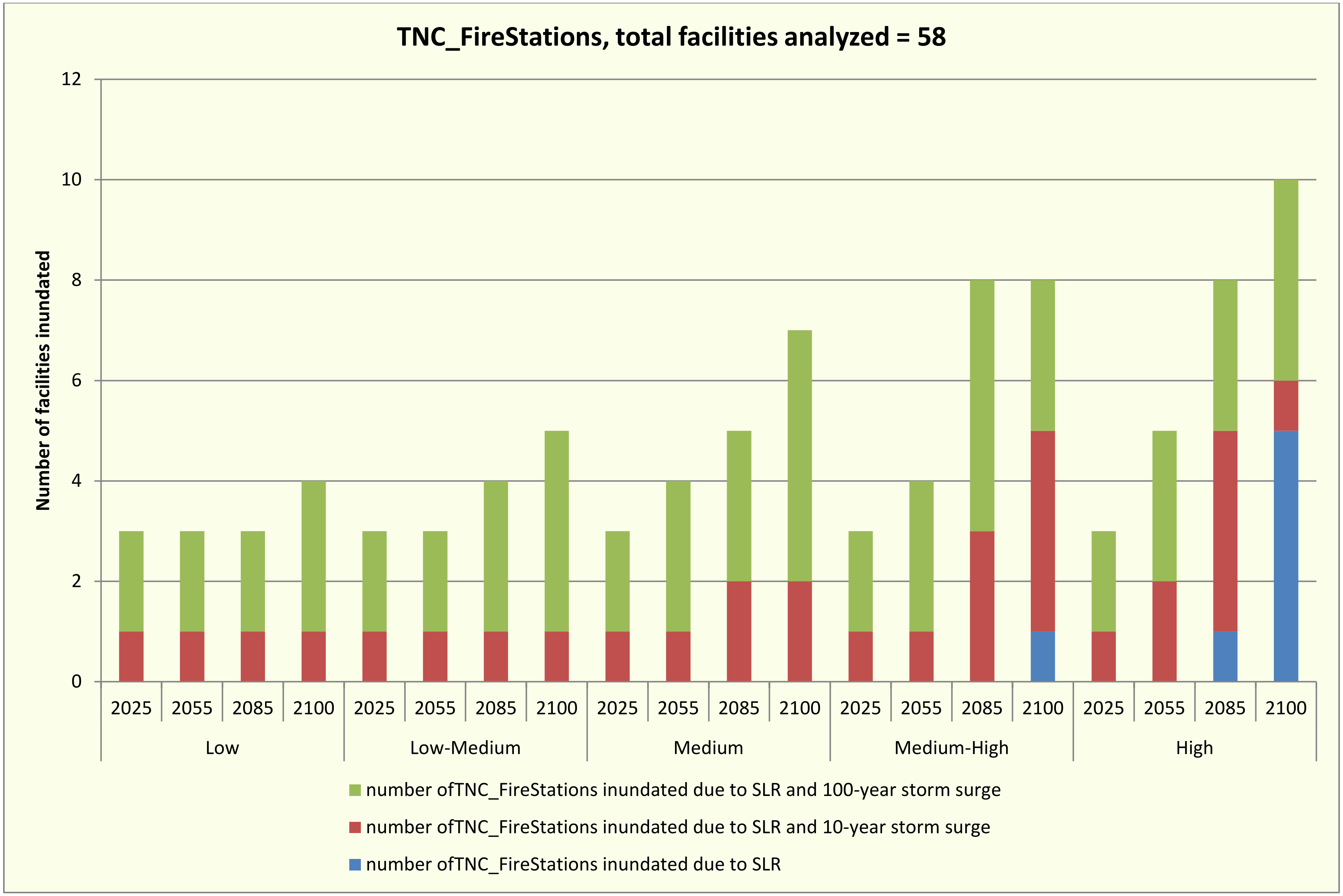

TNC_FireStations, total facilities analyzed = 58
Number of facilities inundated
0
2
4
6
8
10
12
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number ofTNC_FireStations inundated due to SLR and 100-year storm surge
number ofTNC_FireStations inundated due to SLR and 10-year storm surge
number ofTNC_FireStations inundated due to SLR

Table 40. GNIS_Structures, 1064 sites analyzed, 15 predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	2	19	55	0.1%	1.4%	5.0%
	2055	3	28	51	0.2%	2.0%	5.4%
	2085	6	32	53	0.4%	2.5%	6.0%
	2100	6	37	51	0.4%	2.8%	6.2%
Low-Medium	2025	2	21	55	0.1%	1.5%	5.1%
	2055	4	31	51	0.3%	2.3%	5.6%
	2085	6	40	52	0.4%	3.0%	6.4%
	2100	9	42	51	0.6%	3.3%	6.7%
Medium	2025	2	24	53	0.1%	1.7%	5.2%
	2055	6	37	51	0.4%	2.8%	6.2%
	2085	15	46	53	1.0%	4.0%	7.5%
	2100	27	43	57	1.8%	4.6%	8.3%
Medium-High	2025	2	26	52	0.1%	1.8%	5.2%
	2055	8	40	51	0.5%	3.1%	6.5%
	2085	34	42	54	2.2%	5.0%	8.5%
	2100	54	36	60	3.5%	5.9%	9.8%
High	2025	3	27	51	0.2%	2.0%	5.3%
	2055	14	47	52	0.9%	4.0%	7.4%
	2085	62	44	61	4.1%	7.0%	11.0%
	2100	87	46	69	5.7%	8.7%	13.2%

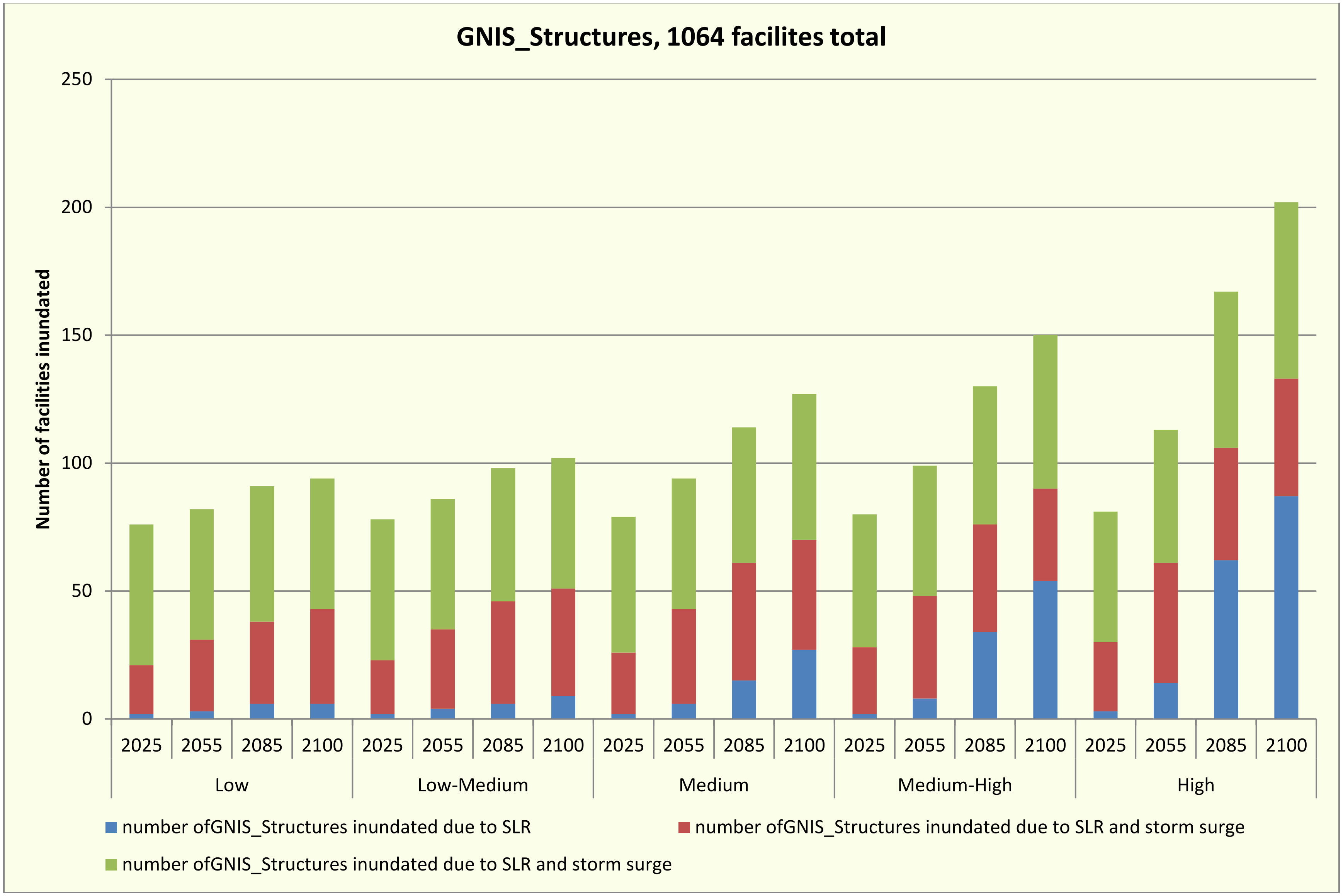
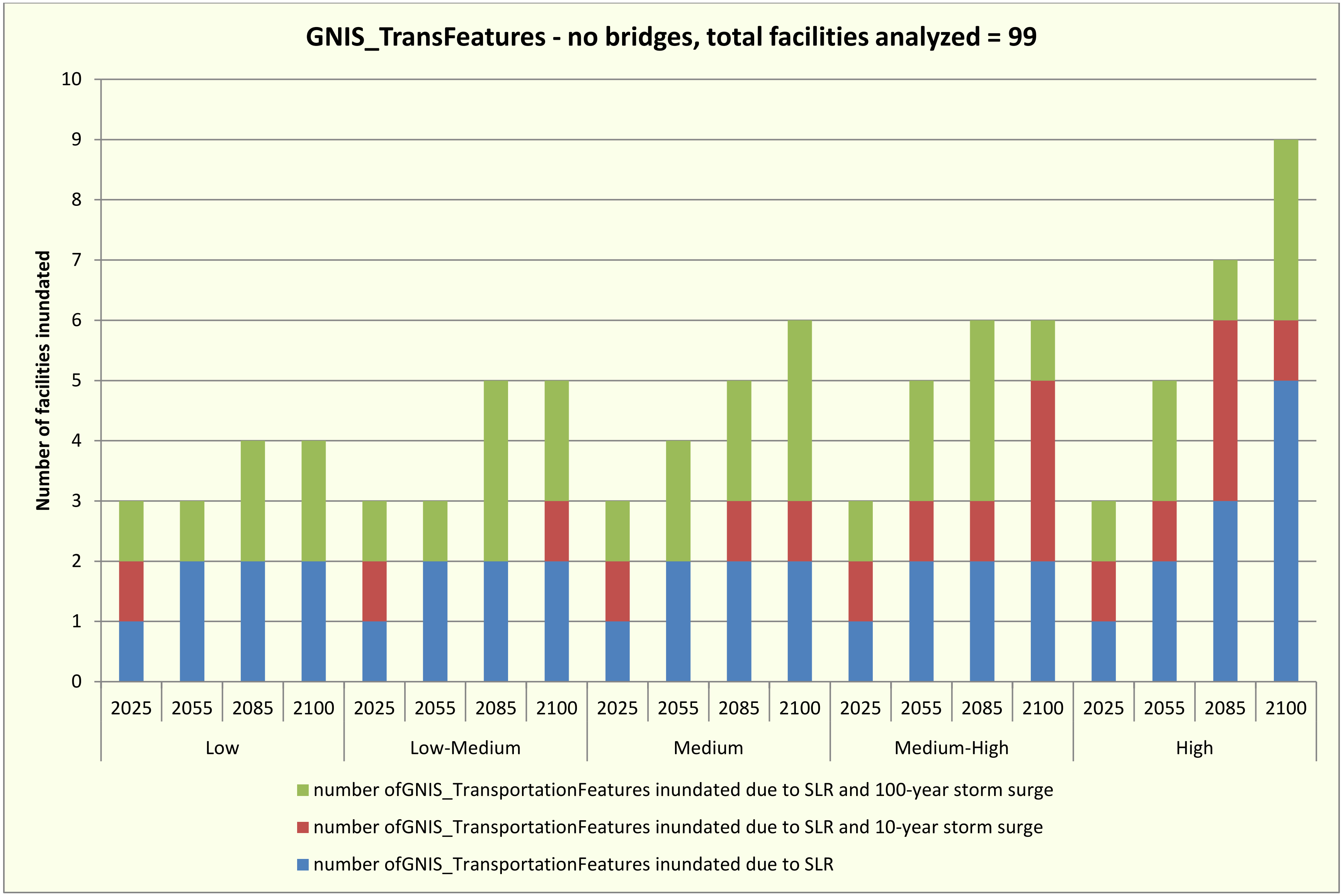

GNIS_Structures, 1064 facilites total
Number of facilities inundated
250
200
150
100
50
0
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number ofGNIS_Structures inundated due to SLR
number ofGNIS_Structures inundated due to SLR and storm surge
number ofGNIS_Structures inundated due to SLR and storm surge

Table 41. GNIS_TransFeatures – bridges removed. 99 sites analyzed, 2 predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	1	1	1	1.0%	2.0%	3.0%
	2055	2	0	1	2.0%	2.0%	3.0%
	2085	2	0	2	2.0%	2.0%	4.0%
	2100	2	0	2	2.0%	2.0%	4.0%
Low-Medium	2025	1	1	1	1.0%	2.0%	3.0%
	2055	2	0	1	2.0%	2.0%	3.0%
	2085	2	0	3	2.0%	2.0%	5.1%
	2100	2	1	2	2.0%	3.0%	5.1%
Medium	2025	1	1	1	1.0%	2.0%	3.0%
	2055	2	0	2	2.0%	2.0%	4.0%
	2085	2	1	2	2.0%	3.0%	5.1%
	2100	2	1	3	2.0%	3.0%	6.1%
Medium-High	2025	1	1	1	1.0%	2.0%	3.0%
	2055	2	1	2	2.0%	3.0%	5.1%
	2085	2	1	3	2.0%	3.0%	6.1%
	2100	2	3	1	2.0%	5.1%	6.1%
High	2025	1	1	1	1.0%	2.0%	3.0%
	2055	2	1	2	2.0%	3.0%	5.1%
	2085	3	3	1	3.0%	6.1%	7.1%
	2100	5	1	3	5.1%	6.1%	9.1%



GNIS_TransFeatures - no bridges, total facilities analyzed = 99
Number of facilities inundated
0
1
2
3
4
5
6
7
8
9
10
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number ofGNIS_TransportationFeatures inundated due to SLR and 100-year storm surge
number ofGNIS_TransportationFeatures inundated due to SLR and 10-year storm surge
number ofGNIS_TransportationFeatures inundated due to SLR

Table 42. HSP_Law Enforcement Locations. 44 sites analyzed, 0 predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	0	1	2	0.0%	2.3%	6.8%
	2055	0	2	1	0.0%	4.5%	6.8%
	2085	0	2	1	0.0%	4.5%	6.8%
	2100	0	2	1	0.0%	4.5%	6.8%
Low-Medium	2025	0	1	2	0.0%	2.3%	6.8%
	2055	0	2	1	0.0%	4.5%	6.8%
	2085	0	2	1	0.0%	4.5%	6.8%
	2100	0	3	0	0.0%	6.8%	6.8%
Medium	2025	0	1	2	0.0%	2.3%	6.8%
	2055	0	2	1	0.0%	4.5%	6.8%
	2085	2	1	1	4.5%	6.8%	9.1%
	2100	2	1	1	4.5%	6.8%	9.1%
Medium-High	2025	0	2	1	0.0%	4.5%	6.8%
	2055	0	2	1	0.0%	4.5%	6.8%
	2085	2	1	1	4.5%	6.8%	9.1%
	2100	3	0	2	6.8%	6.8%	11.4%
High	2025	0	2	1	0.0%	4.5%	6.8%
	2055	1	2	1	2.3%	6.8%	9.1%
	2085	3	1	1	6.8%	9.1%	11.4%
	2100	3	1	2	6.8%	9.1%	13.6%

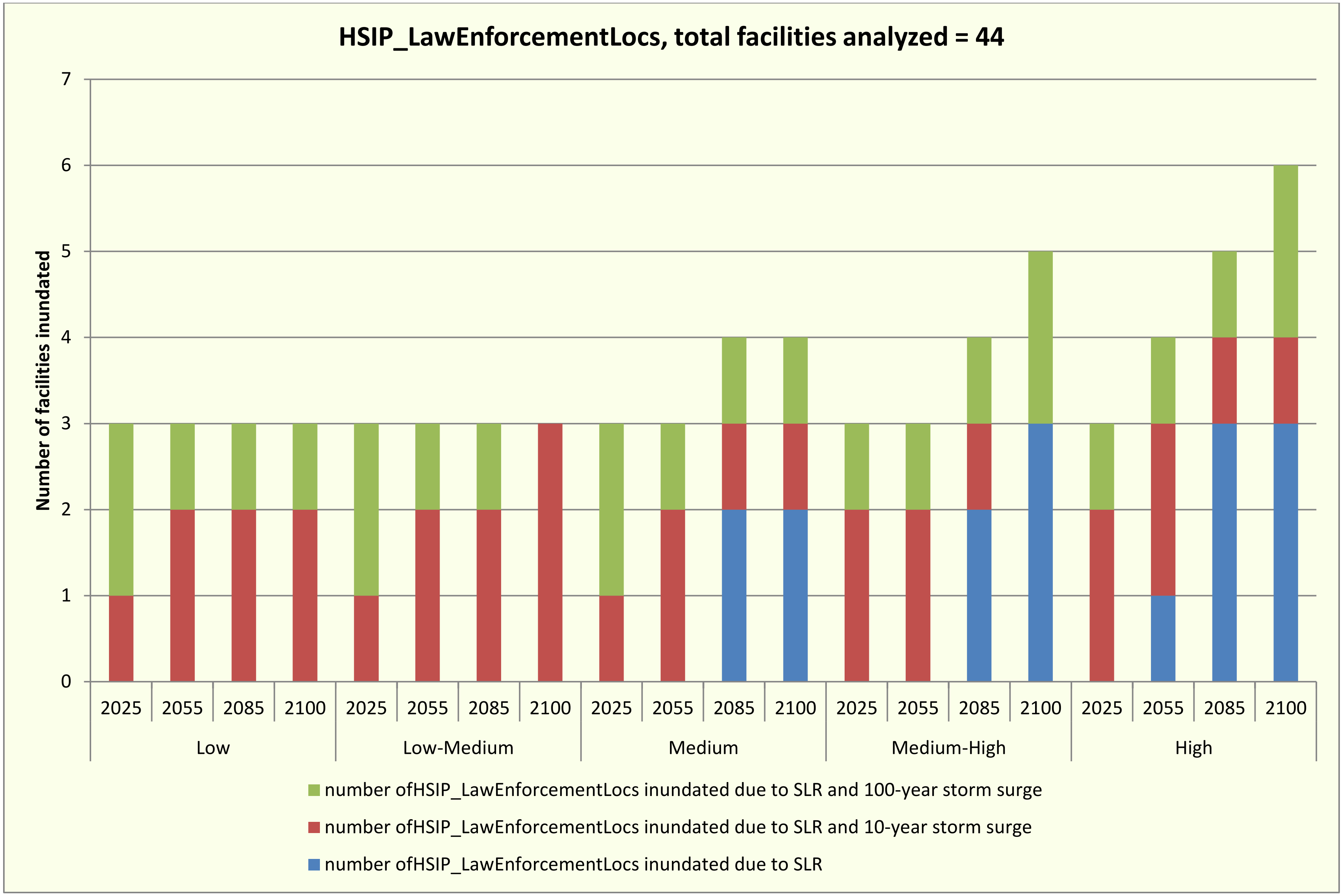

HSIP_LawEnforcementLocs, total facilities analyzed = 44
Number of facilities inundated
0
1
2
3
4
5
6
7
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number ofHSIP_LawEnforcementLocs inundated due to SLR and 100-year storm surge
number ofHSIP_LawEnforcementLocs inundated due to SLR and 10-year storm surge
number ofHSIP_LawEnforcementLocs inundated due to SLR

Table 43. TNC_PoliceStations,. 46 sites analyzed, 1 predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	0	1	1	0.0%	2.2%	4.3%
	2055	0	1	2	0.0%	2.2%	6.5%
	2085	0	1	3	0.0%	2.2%	8.7%
	2100	0	1	3	0.0%	2.2%	8.7%
Low-Medium	2025	0	1	1	0.0%	2.2%	4.3%
	2055	0	1	2	0.0%	2.2%	6.5%
	2085	0	1	3	0.0%	2.2%	8.7%
	2100	0	1	4	0.0%	2.2%	10.9%
Medium	2025	0	1	1	0.0%	2.2%	4.3%
	2055	0	1	3	0.0%	2.2%	8.7%
	2085	1	0	4	2.2%	2.2%	10.9%
	2100	1	1	4	2.2%	4.3%	13.0%
Medium-High	2025	0	1	1	0.0%	2.2%	4.3%
	2055	0	1	3	0.0%	2.2%	8.7%
	2085	1	2	3	2.2%	6.5%	13.0%
	2100	1	3	2	2.2%	8.7%	13.0%
High	2025	0	1	1	0.0%	2.2%	4.3%
	2055	1	0	4	2.2%	2.2%	10.9%
	2085	2	3	1	4.3%	10.9%	13.0%
	2100	4	2	0	8.7%	13.0%	13.0%

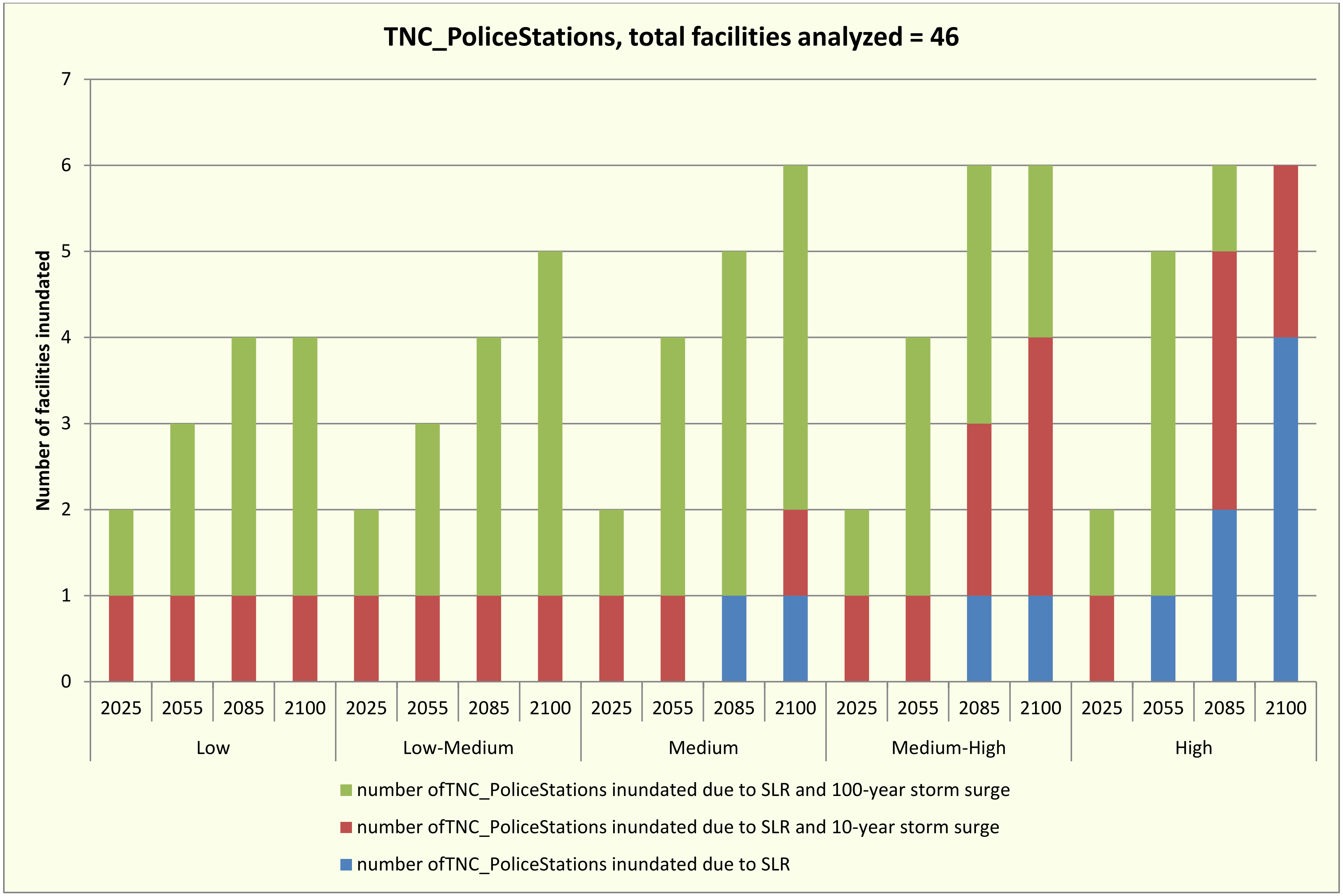

TNC_PoliceStations, total facilities analyzed = 46
Number of facilities inundated
0
1
2
3
4
5
6
7
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number ofTNC_PoliceStations inundated due to SLR and 100-year storm surge
number ofTNC_PoliceStations inundated due to SLR and 10-year storm surge
number ofTNC_PoliceStations inundated due to SLR

Table 44. HSIP_NursingHomes, 101 sites analyzed, none predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	0	0	1	0.0%	0.0%	1.0%
	2055	0	0	1	0.0%	0.0%	1.0%
	2085	0	0	1	0.0%	0.0%	1.0%
	2100	0	0	1	0.0%	0.0%	1.0%
Low-Medium	2025	0	0	1	0.0%	0.0%	1.0%
	2055	0	0	1	0.0%	0.0%	1.0%
	2085	0	0	1	0.0%	0.0%	1.0%
	2100	0	0	1	0.0%	0.0%	1.0%
Medium	2025	0	0	1	0.0%	0.0%	1.0%
	2055	0	0	1	0.0%	0.0%	1.0%
	2085	0	0	1	0.0%	0.0%	1.0%
	2100	0	1	1	0.0%	1.0%	2.0%
Medium-High	2025	0	0	1	0.0%	0.0%	1.0%
	2055	0	0	1	0.0%	0.0%	1.0%
	2085	0	1	1	0.0%	1.0%	2.0%
	2100	0	1	1	0.0%	1.0%	2.0%
High	2025	0	0	1	0.0%	0.0%	1.0%
	2055	0	0	1	0.0%	0.0%	1.0%
	2085	0	1	2	0.0%	1.0%	3.0%
	2100	1	1	4	1.0%	2.0%	6.0%

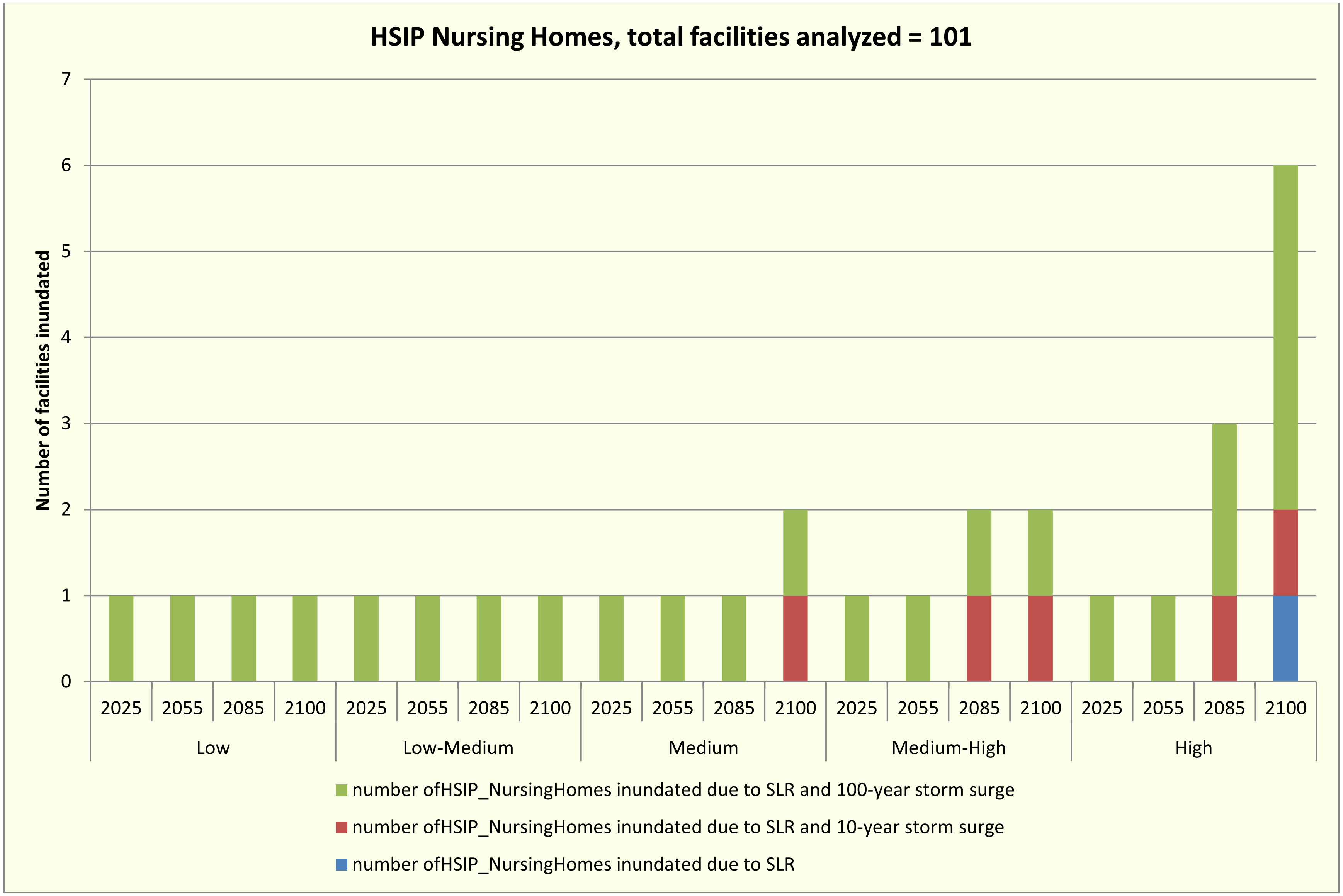

HSIP Nursing Homes, total facilities analyzed = 101
Number of facilities inundated
0
1
2
3
4
5
6
7
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number ofHSIP_NursingHomes inundated due to SLR and 100-year storm surge
number ofHSIP_NursingHomes inundated due to SLR and 10-year storm surge
number ofHSIP_NursingHomes inundated due to SLR

Table 45. HSIP_Urgent Care Facilities, 10 sites analyzed, none predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	0	0	1	0.0%	0.0%	11.1%
	2055	0	0	1	0.0%	0.0%	11.1%
	2085	0	0	1	0.0%	0.0%	11.1%
	2100	0	1	0	0.0%	11.1%	11.1%
Low-Medium	2025	0	0	1	0.0%	0.0%	11.1%
	2055	0	0	1	0.0%	0.0%	11.1%
	2085	0	1	0	0.0%	11.1%	11.1%
	2100	0	1	0	0.0%	11.1%	11.1%
Medium	2025	0	0	1	0.0%	0.0%	11.1%
	2055	0	0	1	0.0%	0.0%	11.1%
	2085	0	1	0	0.0%	11.1%	11.1%
	2100	1	0	0	11.1%	11.1%	11.1%
Medium-High	2025	0	0	1	0.0%	0.0%	11.1%
	2055	0	1	0	0.0%	11.1%	11.1%
	2085	1	0	0	11.1%	11.1%	11.1%
	2100	1	0	0	11.1%	11.1%	11.1%
High	2025	0	0	1	0.0%	0.0%	11.1%
	2055	0	1	0	0.0%	11.1%	11.1%
	2085	1	0	0	11.1%	11.1%	11.1%
	2100	1	0	0	11.1%	11.1%	11.1%

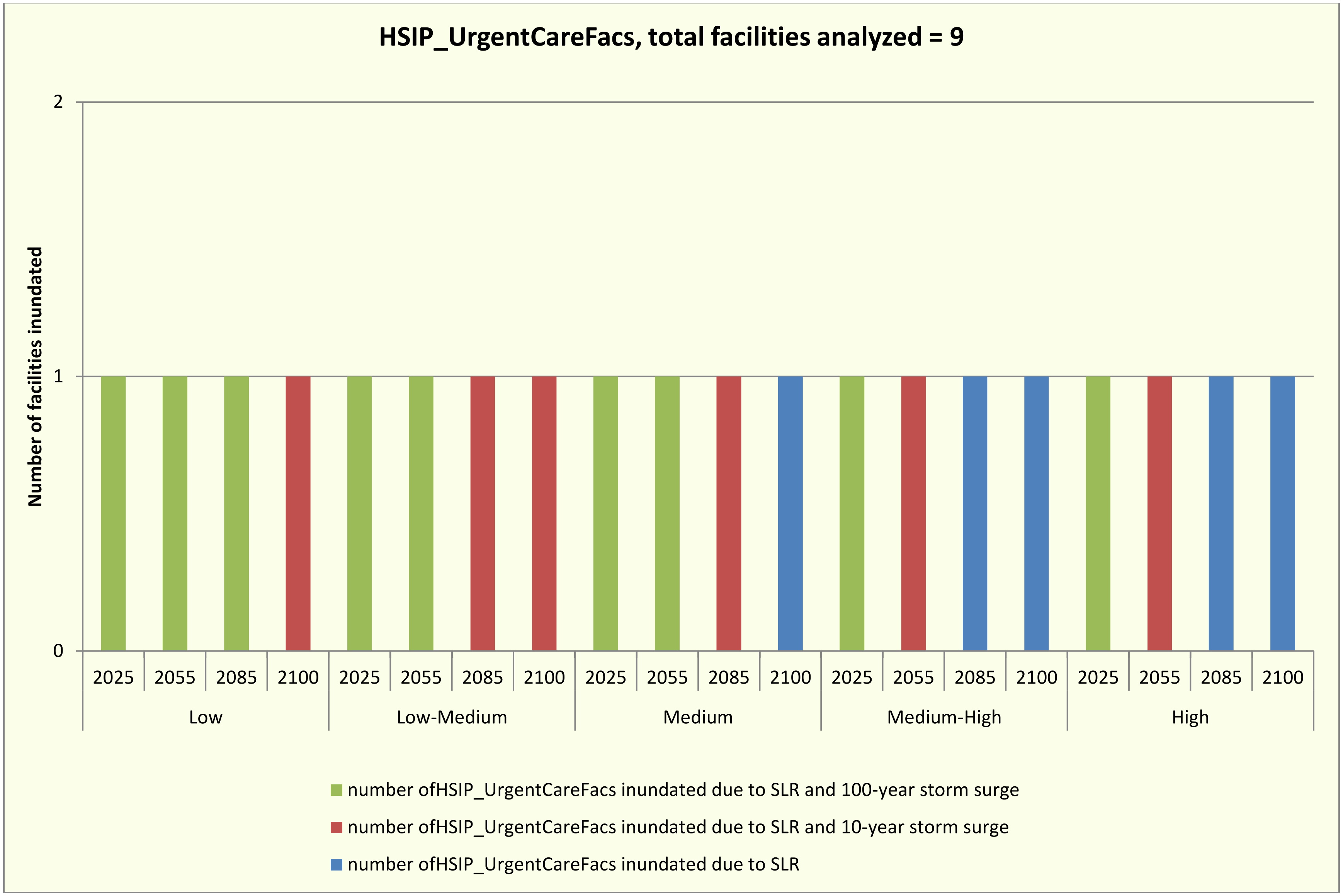
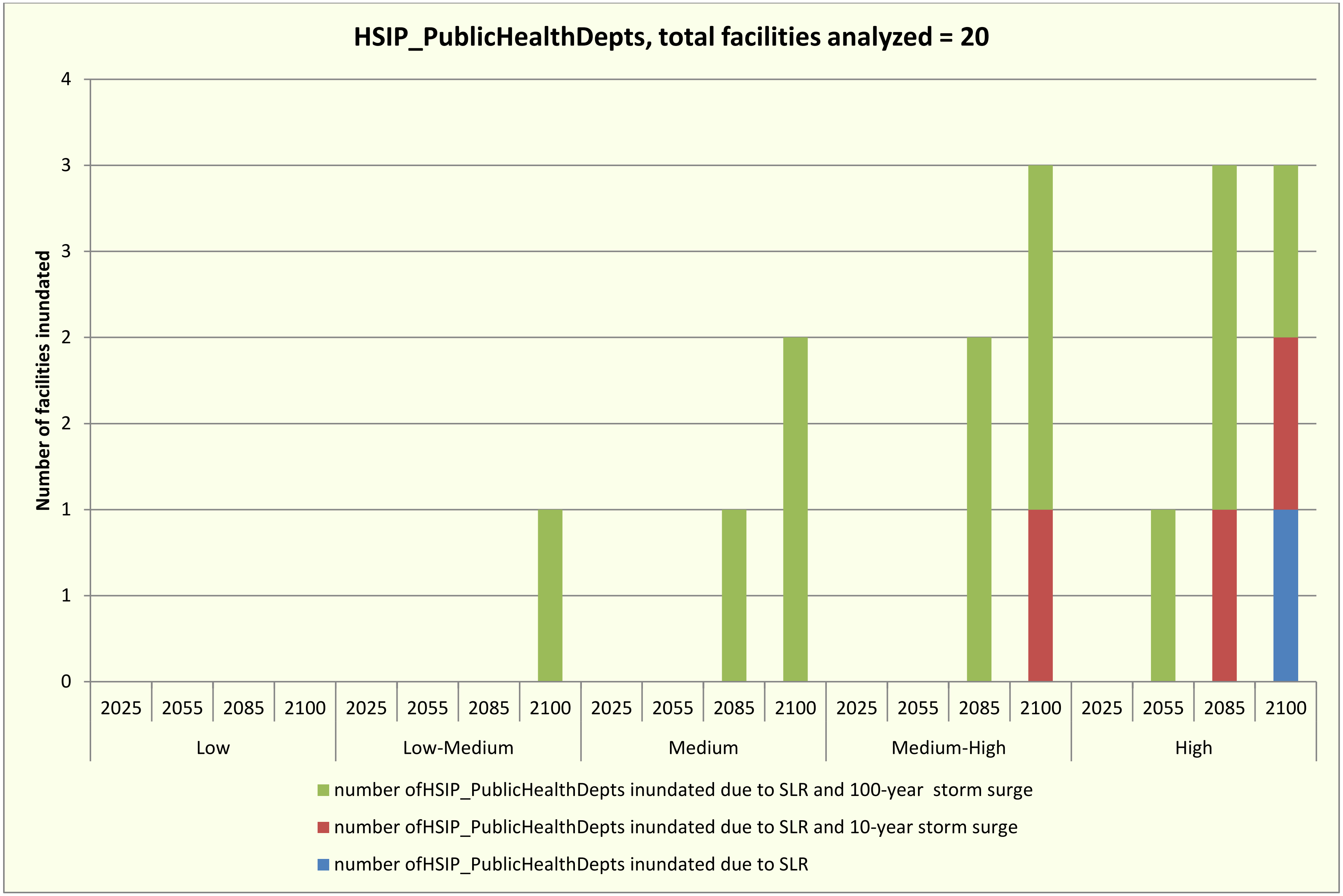

HSIP_UrgentCareFacs, total facilities analyzed = 9
Number of facilities inundated
2
1
0
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number ofHSIP_UrgentCareFacs inundated due to SLR and 100-year storm surge
number ofHSIP_UrgentCareFacs inundated due to SLR and 10-year storm surge
number ofHSIP_UrgentCareFacs inundated due to SLR

Table 46. HSIP_Public Health Depts, 20 sites analyzed, none predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	0	0	0.0%	0.0%	0.0%
	2085	0	0	0	0.0%	0.0%	0.0%
	2100	0	0	0	0.0%	0.0%	0.0%
Low-Medium	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	0	0	0.0%	0.0%	0.0%
	2085	0	0	0	0.0%	0.0%	0.0%
	2100	0	0	1	0.0%	0.0%	5.0%
Medium	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	0	0	0.0%	0.0%	0.0%
	2085	0	0	1	0.0%	0.0%	5.0%
	2100	0	0	2	0.0%	0.0%	10.0%
Medium-High	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	0	0	0.0%	0.0%	0.0%
	2085	0	0	2	0.0%	0.0%	10.0%
	2100	0	1	2	0.0%	5.0%	15.0%
High	2025	0	0	0	0.0%	0.0%	0.0%
	2055	0	0	1	0.0%	0.0%	5.0%
	2085	0	1	2	0.0%	5.0%	15.0%
	2100	1	1	1	5.0%	10.0%	15.0%



HSIP_PublicHealthDepts, total facilities analyzed = 20
Number of facilities inundated
0
1
1
2
2
3
3
4
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number ofHSIP_PublicHealthDepts inundated due to SLR and 100-year storm surge
number ofHSIP_PublicHealthDepts inundated due to SLR and 10-year storm surge
number ofHSIP_PublicHealthDepts inundated due to SLR

Table 47. TNC_Schools, 356 sites analyzed, none predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	0	3	5	0.0%	0.8%	2.2%
	2055	1	2	5	0.3%	0.8%	2.2%
	2085	1	5	4	0.3%	1.7%	2.8%
	2100	1	5	5	0.3%	1.7%	3.1%
Low-Medium	2025	0	3	5	0.0%	0.8%	2.2%
	2055	1	3	4	0.3%	1.1%	2.2%
	2085	1	5	5	0.3%	1.7%	3.1%
	2100	1	5	6	0.3%	1.7%	3.4%
Medium	2025	0	3	5	0.0%	0.8%	2.2%
	2055	1	5	5	0.3%	1.7%	3.1%
	2085	3	5	6	0.8%	2.2%	3.9%
	2100	4	4	7	1.1%	2.2%	4.2%
Medium-High	2025	0	3	5	0.0%	0.8%	2.2%
	2055	1	5	6	0.3%	1.7%	3.4%
	2085	5	3	9	1.4%	2.2%	4.8%
	2100	7	5	10	2.0%	3.4%	6.2%
High	2025	1	2	5	0.3%	0.8%	2.2%
	2055	3	5	6	0.8%	2.2%	3.9%
	2085	7	6	12	2.0%	3.7%	7.0%
	2100	11	8	16	3.1%	5.3%	9.8%

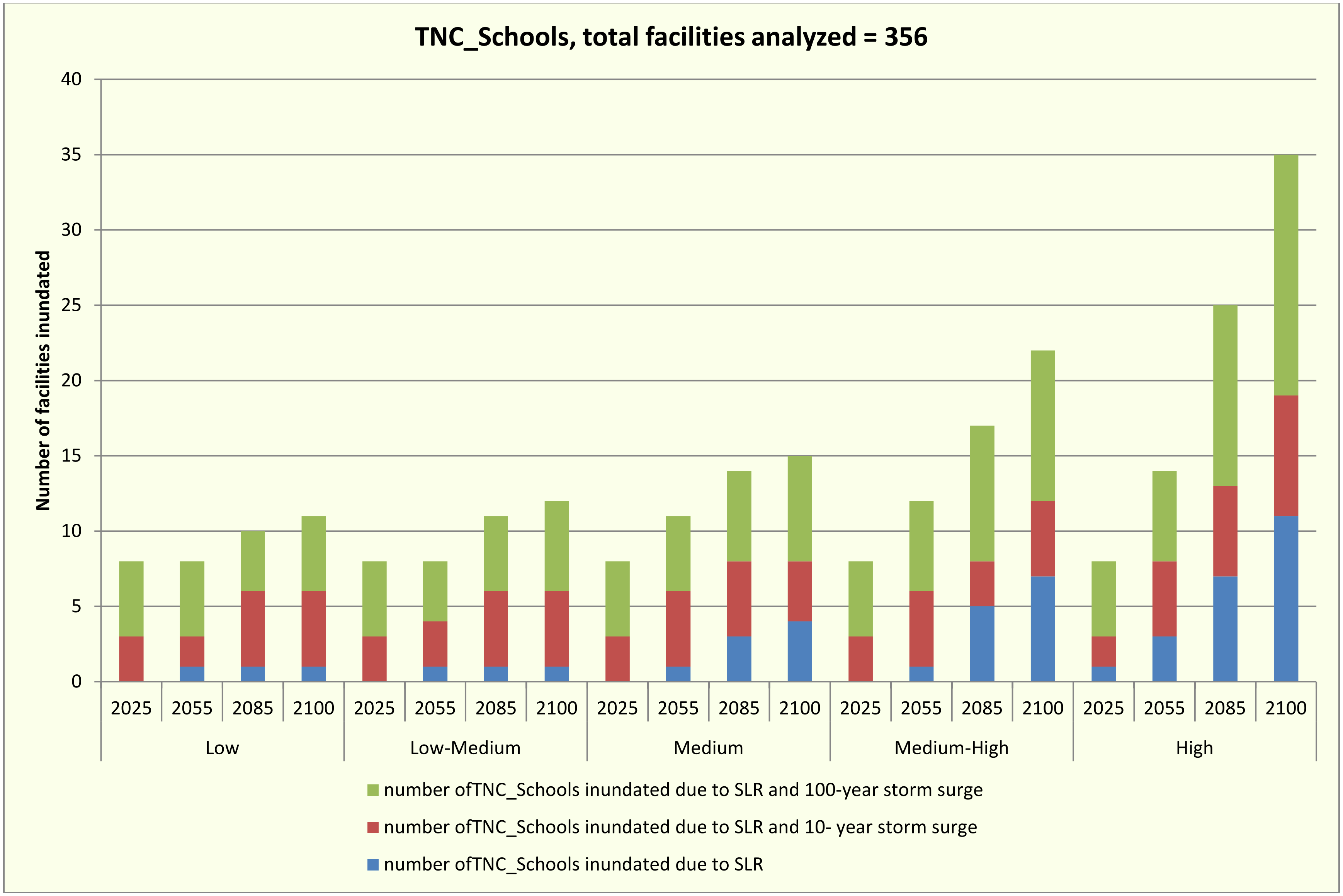
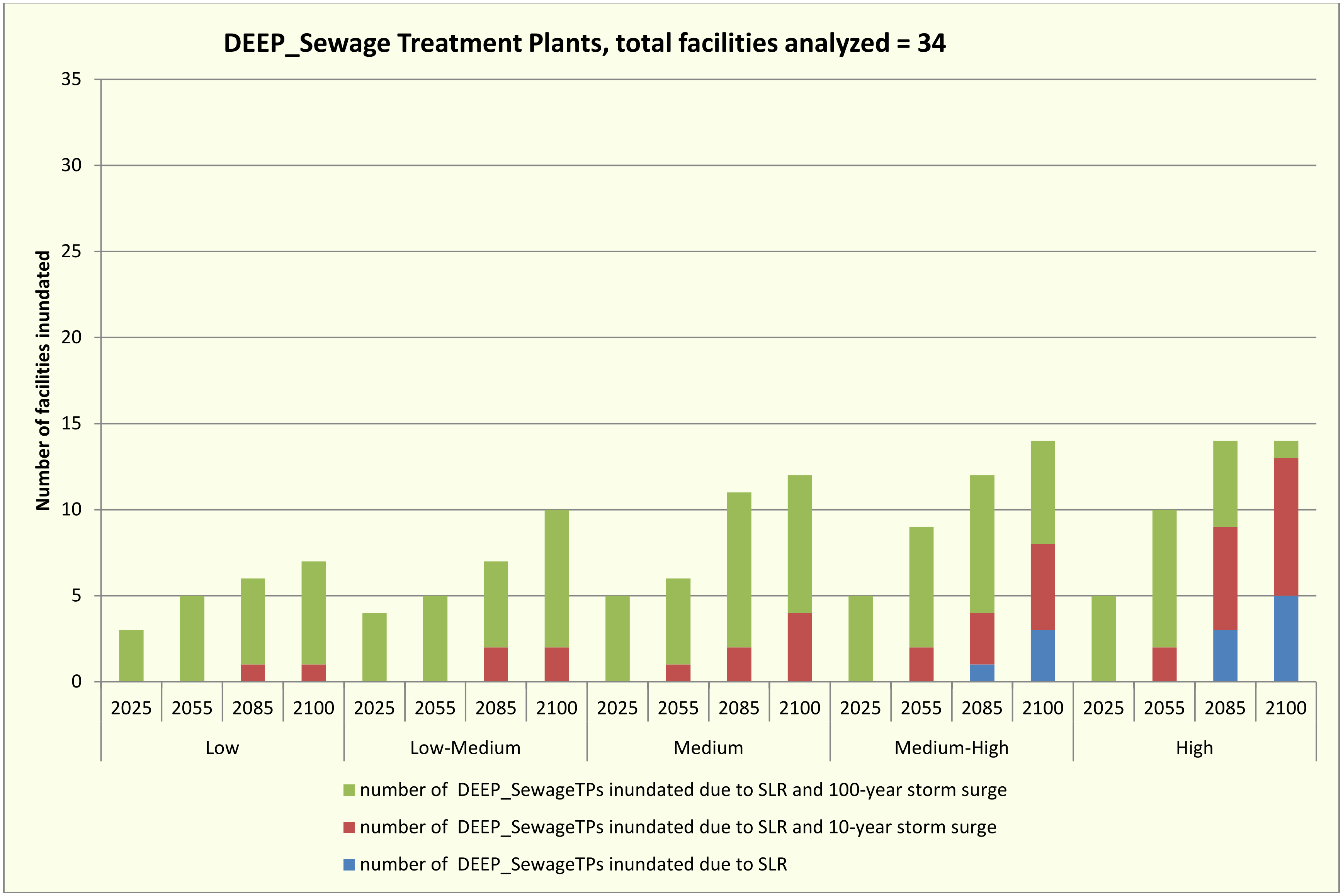

TNC_Schools, total facilities analyzed = 356
Number of facilities inundated
0
5
10
15
20
25
30
35
40
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number ofTNC_Schools inundated due to SLR and 100-year storm surge
number ofTNC_Schools inundated due to SLR and 10- year storm surge
number ofTNC_Schools inundated due to SLR

Table 48. DEEP_Sewage Treatment Plants, 34 sites analyzed, none predicted to flood at time zero

SLR Scenario	Year	Number of sites inundated due to SLR	Number inundated due to SLR & 10 year storm surge	Number inundated due to SLR & 100 year storm surge	% sites inundated due to SLR	% sites inundated due to SLR & 10 year storm surge	% sites inundated due to SLR & 100 year storm surge
Low	2025	0	3	5	0.0%	0.8%	2.2%
	2055	1	2	5	0.3%	0.8%	2.2%
	2085	1	5	4	0.3%	1.7%	2.8%
	2100	1	5	5	0.3%	1.7%	3.1%
Low-Medium	2025	0	3	5	0.0%	0.8%	2.2%
	2055	1	3	4	0.3%	1.1%	2.2%
	2085	1	5	5	0.3%	1.7%	3.1%
	2100	1	5	6	0.3%	1.7%	3.4%
Medium	2025	0	3	5	0.0%	0.8%	2.2%
	2055	1	5	5	0.3%	1.7%	3.1%
	2085	3	5	6	0.8%	2.2%	3.9%
	2100	4	4	7	1.1%	2.2%	4.2%
Medium-High	2025	0	3	5	0.0%	0.8%	2.2%
	2055	1	5	6	0.3%	1.7%	3.4%
	2085	5	3	9	1.4%	2.2%	4.8%
	2100	7	5	10	2.0%	3.4%	6.2%
High	2025	1	2	5	0.3%	0.8%	2.2%
	2055	3	5	6	0.8%	2.2%	3.9%
	2085	7	6	12	2.0%	3.7%	7.0%
	2100	11	8	16	3.1%	5.3%	9.8%


DEEP_Sewage Treatment Plants, total facilities analyzed = 34
Number of facilities inundated
0
5
10
15
20
25
30
35
2025
2055
2085
2100
Low
Low-Medium
Medium
Medium-High
High
number of DEEP_SewageTPs inundated due to SLR and 100-year storm surge
number of DEEP_SewageTPs inundated due to SLR and 10-year storm surge
number of DEEP_SewageTPs inundated due to SLR

Appendix D: Model Results by Watershed

Southwest Coast Watershed

The Southwest Coast watershed is the largest portion of the study area, and results are similar to the results for the entire study area. Table 49 shows that irregularly-flooded marshes are expected to decline by at least 25% by 2100 and up to 97%. Low marshes, on the other hand, are predicted to increase by a factor of 2 to 5 by 2100 depending on the SLR scenario examined.

Table 49. Southwest Coast Watershed Landcover Change Summary

Land cover category	Acres in 2010	Percentage Land cover change from 2010 to 2100 for different SLR scenarios				
		NYC Low	NYC Low-Medium	NYC Medium	NYC High-Medium	NYC High
Undeveloped Dry Land	120,225	-0.3	-0.4	-0.9	-1.4	-2.0
Developed Dry Land	47,558	-0.7	-1.6	-4.3	-6.8	-10.1
Estuarine Open Water	42,817	0.2	0.3	0.6	1.0	2.3
Swamp	4,410	-0.1	-0.3	-1.7	-2.2	-2.6
Inland Open Water	3,475	-0.5	-1.1	-1.7	-2.0	-2.2
Irreg.-Flooded Marsh	978	-4.2	-10.9	-64.3	-91.3	-97.5
Estuarine Beach	617	-2.0	-3.4	-8.3	-15.4	-38.4
Regularly-Flooded Marsh	430	52.2	86.4	299.1	451.6	500.2
Inland-Fresh Marsh	323	-5.0	-8.0	-14.9	-17.0	-17.8
Trans. Salt Marsh	305	49.0	94.1	160.4	170.0	93.8
Tidal Flat	205	-0.9	-10.3	-25.9	-2.8	198.0
Flooded Developed Dry Land	152	231.3	511.3	1344.4	2114.7	3148.3
Inland Shore	119	0.0	0.0	0.0	0.0	0.0
Rocky Intertidal	27	-1.1	-2.2	-6.6	-13.4	-58.2
Riverine Tidal	22	-79.5	-83.8	-87.8	-88.9	-92.1
Tidal Swamp	18	-1.6	-5.1	-16.1	-30.7	-42.3
Tidal-Fresh Marsh	14	0.0	-2.3	-25.1	-53.6	-78.5

(positive indicates a gain, negative is a loss)

Table 50. Southwest Coast Watershed, NYC Low (Acres)

	Initial	2010	2025	2055	2085	2100
Undeveloped Dry Land	120,487	120,225	120,201	120,104	119,959	119,897
Developed Dry Land	47,710	47,558	47,547	47,480	47,280	47,206
Estuarine Open Water	42,804	42,817	42,837	42,856	42,875	42,885
Swamp	4,423	4,410	4,410	4,407	4,405	4,404
Inland Open Water	3,482	3,475	3,471	3,464	3,459	3,457
Irreg.-Flooded Marsh	1,112	978	978	957	941	937
Estuarine Beach	617	617	616	612	607	604
Inland-Fresh Marsh	342	323	322	316	308	307
Regularly-Flooded Marsh	302	430	557	588	642	654
Tidal Flat	195	205	212	216	208	203
Inland Shore	119	119	119	119	119	119
Riverine Tidal	27	22	6	6	5	5
Rocky Intertidal	27	27	27	27	26	26
Tidal Swamp	18	18	18	17	17	17
Tidal-Fresh Marsh	15	14	14	14	14	14
Trans. Salt Marsh	14	305	196	280	397	455
Flooded Developed Dry Land	0	152	163	229	430	503
Total (incl. water)	**221,694**	**221,694**	**221,694**	**221,694**	**221,694**	**221,694**

Table 51. Southwest Coast Watershed, NYC Low-Medium (Acres)

	Initial	2010	2025	2055	2085	2100
Undeveloped Dry Land	120,487	120,225	120,182	120,030	119,831	119,688
Developed Dry Land	47,710	47,558	47,536	47,357	47,115	46,781
Estuarine Open Water	42,804	42,817	42,840	42,863	42,899	42,940
Swamp	4,423	4,410	4,409	4,406	4,401	4,398
Inland Open Water	3,482	3,475	3,469	3,463	3,455	3,437
Irreg.-Flooded Marsh	1,112	978	970	940	901	872
Estuarine Beach	617	617	615	610	602	596
Inland-Fresh Marsh	342	323	321	312	305	298
Regularly-Flooded Marsh	302	430	571	621	731	801
Tidal Flat	195	205	213	216	198	184
Inland Shore	119	119	119	119	119	119
Riverine Tidal	27	22	6	5	4	4
Rocky Intertidal	27	27	27	26	26	26
Tidal Swamp	18	18	18	17	17	17
Tidal-Fresh Marsh	15	14	14	14	14	14
Trans. Salt Marsh	14	305	209	341	481	592
Flooded Developed Dry Land	0	152	174	352	595	929
Total (incl. water)	**221,694**	**221,694**	**221,694**	**221,694**	**221,694**	**221,694**

Table 52. Southwest Coast Watershed, NYC Medium (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	120,487	120,225	120,165	119,910	119,434	119,128
	Developed Dry Land	47,710	47,558	47,524	47,219	46,187	45,514
	Estuarine Open Water	42,804	42,817	42,842	42,885	43,010	43,081
	Swamp	4,423	4,410	4,408	4,402	4,349	4,336
	Inland Open Water	3,482	3,475	3,469	3,458	3,420	3,416
	Irreg.-Flooded Marsh	1,112	978	961	899	652	349
	Estuarine Beach	617	617	615	605	584	566
	Inland-Fresh Marsh	342	323	319	307	278	275
	Regularly-Flooded Marsh	302	430	586	693	1,163	1,715
	Tidal Flat	195	205	215	218	181	152
	Inland Shore	119	119	119	119	119	119
	Riverine Tidal	27	22	6	5	4	3
	Rocky Intertidal	27	27	27	26	26	25
	Tidal Swamp	18	18	18	17	16	15
	Tidal-Fresh Marsh	15	14	14	13	12	11
	Trans. Salt Marsh	14	305	221	426	738	794
	Flooded Developed Dry Land	0	152	185	491	1,522	2,195
	Total (incl. water)	**221,694**	**221,694**	**221,694**	**221,694**	**221,694**	**221,694**

Table 53. Southwest Coast Watershed, NYC Medium-High (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	120,487	120,225	120,138	119,765	119,018	118,596
	Developed Dry Land	47,710	47,558	47,506	46,918	45,270	44,344
	Estuarine Open Water	42,804	42,817	42,844	42,926	43,115	43,236
	Swamp	4,423	4,410	4,407	4,398	4,326	4,314
	Inland Open Water	3,482	3,475	3,468	3,440	3,414	3,406
	Irreg.-Flooded Marsh	1,112	978	952	844	217	85
	Estuarine Beach	617	617	614	599	558	522
	Inland-Fresh Marsh	342	323	318	300	274	269
	Regularly-Flooded Marsh	302	430	601	813	1,922	2,370
	Tidal Flat	195	205	217	218	164	199
	Inland Shore	119	119	119	119	119	119
	Riverine Tidal	27	22	6	5	3	2
	Rocky Intertidal	27	27	27	26	25	23
	Tidal Swamp	18	18	17	17	14	12
	Tidal-Fresh Marsh	15	14	14	13	9	7
	Trans. Salt Marsh	14	305	241	502	807	824
	Flooded Developed Dry Land	0	152	203	792	2,439	3,366
	Total (incl. water)	**221,694**	**221,694**	**221,694**	**221,694**	**221,694**	**221,694**

Table 54. Southwest Coast Watershed, NYC High (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	120,487	120,225	120,118	119,445	118,360	117,879
	Developed Dry Land	47,710	47,558	47,492	46,215	43,846	42,773
	Estuarine Open Water	42,804	42,817	42,846	43,000	43,346	43,812
	Swamp	4,423	4,410	4,407	4,345	4,306	4,297
	Inland Open Water	3,482	3,475	3,467	3,433	3,403	3,399
	Irreg.-Flooded Marsh	1,112	978	942	521	51	24
	Estuarine Beach	617	617	613	584	495	380
	Inland-Fresh Marsh	342	323	317	278	267	266
	Regularly-Flooded Marsh	302	430	616	1,268	2,443	2,579
	Tidal Flat	195	205	220	212	409	611
	Inland Shore	119	119	119	119	119	119
	Riverine Tidal	27	22	6	4	2	2
	Rocky Intertidal	27	27	27	26	21	11
	Tidal Swamp	18	18	17	16	11	10
	Tidal-Fresh Marsh	15	14	14	10	4	3
	Trans. Salt Marsh	14	305	254	724	745	591
	Flooded Developed Dry Land	0	152	218	1,495	3,864	4,937
	Total (incl. water)	**221,694**	**221,694**	**221,694**	**221,694**	**221,694**	**221,694**

Housatonic River Watershed

Like the results of the previous study, in the Housatonic River watershed, the high marshes are most plentiful initially but most vulnerable, with more than 97% loss predicted by 2100 under the NYC High scenario.

Table 55. Housatonic River Watershed land cover change summary
(positive indicates a gain, negative is a loss)

Land cover category	Acres in 2010	Percentage Land cover change from 2010 to 2100 for different SLR scenarios				
		NYC Low	NYC Low-Medium	NYC Medium	NYC High-Medium	NYC High
Developed Dry Land	6,552	-0.5	-1.5	-2.8	-4.5	-7.5
Undeveloped Dry Land	6,202	-0.8	-1.5	-2.8	-4.0	-5.6
Estuarine Open Water	3,903	0.6	1.5	3.0	4.9	8.9
Irreg.-Flooded Marsh	660	-2.3	-9.8	-55.8	-87.9	-97.7
Swamp	315	0.0	0.0	0.0	-0.4	-0.4
Regularly-Flooded Marsh	295	21.6	50.2	160.7	234.3	196.7
Estuarine Beach	138	-2.5	-6.1	-15.9	-26.8	-44.7
Trans. Salt Marsh	104	-1.2	9.6	15.3	15.6	-18.5
Inland Open Water	98	-0.9	-5.9	-9.7	-11.2	-12.2
Tidal Flat	92	-13.8	-36.9	-14.7	18.4	230.8
Inland-Fresh Marsh	36	-8.7	-22.5	-34.3	-46.0	-51.2
Tidal-Fresh Marsh	31	0.0	-1.6	-13.9	-52.1	-78.4
Flooded Developed Dry Land	30	102.3	326.8	614.8	990.8	1652.8
Tidal Swamp	9	-7.7	-12.8	-33.7	-43.7	-52.6
Riverine Tidal	3	-35.1	-41.0	-73.8	-84.2	-91.8

Table 56. Housatonic River Watershed NYC Low (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	6,268	6,202	6,200	6,180	6,164	6,153
	Developed Dry Land	6,582	6,552	6,550	6,539	6,529	6,521
	Estuarine Open Water	3,885	3,903	3,905	3,910	3,920	3,927
	Swamp	315	315	315	315	315	315
	Inland Open Water	115	98	98	98	97	97
	Irreg.-Flooded Marsh	710	660	660	653	647	645
	Estuarine Beach	138	138	138	138	136	135
	Inland-Fresh Marsh	38	36	36	34	33	33
	Regularly-Flooded Marsh	248	295	326	339	353	358
	Tidal Flat	81	92	94	92	85	79
	Riverine Tidal	4	3	2	2	2	2
	Tidal Swamp	9	9	9	9	8	8
	Tidal-Fresh Marsh	31	31	31	31	31	31
	Trans. Salt Marsh	44	104	72	86	95	103
	Flooded Developed Dry Land	0	30	32	43	53	60
	Total (incl. water)	**18,468**	**18,468**	**18,468**	**18,468**	**18,468**	**18,468**

Table 57. Housatonic River Watershed NYC Low-Medium (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	6,268	6,202	6,198	6,172	6,142	6,111
	Developed Dry Land	6,582	6,552	6,547	6,534	6,506	6,455
	Estuarine Open Water	3,885	3,903	3,905	3,914	3,939	3,961
	Swamp	315	315	315	315	315	315
	Inland Open Water	115	98	98	97	97	92
	Irreg.-Flooded Marsh	710	660	657	647	622	595
	Estuarine Beach	138	138	138	137	133	130
	Inland-Fresh Marsh	38	36	36	34	30	28
	Regularly-Flooded Marsh	248	295	331	353	398	443
	Tidal Flat	81	92	94	90	71	58
	Riverine Tidal	4	3	2	2	2	2
	Tidal Swamp	9	9	9	9	8	8
	Tidal-Fresh Marsh	31	31	31	31	31	30
	Trans. Salt Marsh	44	104	72	86	100	114
	Flooded Developed Dry Land	0	30	34	47	76	127
	Total (incl. water)	**18,468**	**18,468**	**18,468**	**18,468**	**18,468**	**18,468**

Table 58. Housatonic River Watershed NYC Medium (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	6,268	6,202	6,192	6,153	6,073	6,031
	Developed Dry Land	6,582	6,552	6,545	6,520	6,413	6,369
	Estuarine Open Water	3,885	3,903	3,905	3,929	3,993	4,020
	Swamp	315	315	315	315	315	315
	Inland Open Water	115	98	98	97	91	89
	Irreg.-Flooded Marsh	710	660	654	621	458	291
	Estuarine Beach	138	138	138	135	124	116
	Inland-Fresh Marsh	38	36	34	33	26	24
	Regularly-Flooded Marsh	248	295	336	389	587	768
	Tidal Flat	81	92	96	89	74	78
	Riverine Tidal	4	3	2	2	1	1
	Tidal Swamp	9	9	9	8	7	6
	Tidal-Fresh Marsh	31	31	31	30	28	27
	Trans. Salt Marsh	44	104	77	87	110	120
	Flooded Developed Dry Land	0	30	37	61	169	212
	Total (incl. water)	**18,468**	**18,468**	**18,468**	**18,468**	**18,468**	**18,468**

Table 59. Housatonic River Watershed NYC Medium-High (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	6,268	6,202	6,186	6,125	6,020	5,955
	Developed Dry Land	6,582	6,552	6,542	6,488	6,352	6,258
	Estuarine Open Water	3,885	3,903	3,906	3,952	4,036	4,095
	Swamp	315	315	315	315	315	313
	Inland Open Water	115	98	98	94	89	87
	Irreg.-Flooded Marsh	710	660	651	573	195	80
	Estuarine Beach	138	138	138	132	114	101
	Inland-Fresh Marsh	38	36	34	29	24	20
	Regularly-Flooded Marsh	248	295	340	443	845	985
	Tidal Flat	81	92	98	92	106	109
	Riverine Tidal	4	3	2	1	1	0
	Tidal Swamp	9	9	9	8	6	5
	Tidal-Fresh Marsh	31	31	31	29	23	15
	Trans. Salt Marsh	44	104	78	94	115	120
	Flooded Developed Dry Land	0	30	39	94	230	324
	Total (incl. water)	**18,468**	**18,468**	**18,468**	**18,468**	**18,468**	**18,468**

Table 60. Housatonic River Watershed NYC Medium-High (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	6,268	6,202	6,182	6,074	5,921	5,853
	Developed Dry Land	6,582	6,552	6,540	6,415	6,188	6,061
	Estuarine Open Water	3,885	3,903	3,907	3,997	4,159	4,250
	Swamp	315	315	315	315	313	313
	Inland Open Water	115	98	98	91	87	86
	Irreg.-Flooded Marsh	710	660	648	391	38	15
	Estuarine Beach	138	138	138	124	94	77
	Inland-Fresh Marsh	38	36	34	26	19	18
	Regularly-Flooded Marsh	248	295	345	612	1,026	874
	Tidal Flat	81	92	101	112	105	304
	Riverine Tidal	4	3	2	1	0	0
	Tidal Swamp	9	9	9	7	5	4
	Tidal-Fresh Marsh	31	31	30	25	10	7
	Trans. Salt Marsh	44	104	79	112	110	85
	Flooded Developed Dry Land	0	30	42	167	393	520
	Total (incl. water)	**18,468**	**18,468**	**18,468**	**18,468**	**18,468**	**18,468**

South Central Coast Watershed

Within the south central coast watershed tide ranges are starting to decrease compared to the watersheds to the west. Therefore, while low marshes are predicted to thrive under many SLR scenarios, more tidal flats and open waters start to be predicted, especially under higher SLR scenarios.

Table 61. South Central Coast Watershed Landcover Change Summary

(positive indicates a gain, negative is a loss)

Land cover category	Acres in 2010	Percentage Land cover change from 2010 to 2100 for different SLR scenarios				
		NYC Low	NYC Low-Medium	NYC Medium	NYC High-Medium	NYC High
Estuarine Open Water	57,793	0.4	0.6	1.1	2.1	5.7
Undeveloped Dry Land	26,368	-1.5	-2.6	-4.9	-7.2	-11.8
Developed Dry Land	21,008	-0.8	-1.4	-3.5	-6.2	-12.7
Irreg.-Flooded Marsh	5,109	-6.0	-19.9	-82.9	-94.6	-98.0
Swamp	2,206	-1.8	-2.9	-5.8	-8.9	-16.5
Regularly-Flooded Marsh	863	73.8	180.0	608.7	613.3	273.4
Estuarine Beach	648	-14.5	-20.1	-31.9	-41.7	-61.6
Inland Open Water	473	-1.0	-1.6	-2.9	-4.8	-8.6
Tidal Flat	345	-19.6	-37.2	-36.9	169.7	850.5
Trans. Salt Marsh	291	24.3	55.6	95.9	123.9	226.9
Inland-Fresh Marsh	285	-7.4	-13.4	-32.6	-40.5	-49.2
Tidal-Fresh Marsh	96	0.0	-0.3	-3.5	-17.9	-81.7
Rocky Intertidal	84	-8.7	-13.4	-22.4	-30.7	-45.8
Flooded Developed Dry Land	80	212.2	372.7	918.0	1621.2	3343.1
Tidal Swamp	77	-4.5	-6.8	-37.0	-60.4	-81.7
Riverine Tidal	32	-43.5	-44.6	-45.0	-45.0	-45.4

Table 62. South Central Coast NYC Low (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	57,759	57,793	57,829	57,929	58,009	58,044
	Undeveloped Dry Land	26,627	26,368	26,342	26,196	26,035	25,967
	Developed Dry Land	21,087	21,008	21,001	20,942	20,873	20,839
	Irreg.-Flooded Marsh	5,486	5,109	5,104	4,968	4,842	4,803
	Swamp	2,223	2,206	2,201	2,186	2,171	2,167
	Estuarine Beach	651	648	637	602	570	554
	Regularly-Flooded Marsh	507	863	1,030	1,209	1,423	1,501
	Inland Open Water	474	473	468	469	468	468
	Tidal Flat	330	345	368	333	292	277
	Inland-Fresh Marsh	294	285	283	274	266	264
	Tidal-Fresh Marsh	96	96	96	96	96	96
	Rocky Intertidal	91	84	84	81	78	77
	Tidal Swamp	82	77	77	75	74	74
	Riverine Tidal	37	32	19	18	18	18
	Trans. Salt Marsh	12	291	132	233	328	362
	Inland Shore	1	1	1	1	1	1
	Flooded Developed Dry Land	0	80	87	146	214	249
	Total (incl. water)	**115,758**	**115,758**	**115,758**	**115,758**	**115,758**	**115,758**

Table 63. South Central Coast NYC Low-Medium (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	57,759	57,793	57,836	57,968	58,088	58,165
	Undeveloped Dry Land	26,627	26,368	26,312	26,117	25,875	25,690
	Developed Dry Land	21,087	21,008	20,989	20,909	20,798	20,711
	Irreg.-Flooded Marsh	5,486	5,109	5,057	4,831	4,431	4,094
	Swamp	2,223	2,206	2,196	2,175	2,155	2,143
	Estuarine Beach	651	643	630	588	543	514
	Regularly-Flooded Marsh	507	863	1,090	1,388	1,955	2,417
	Inland Open Water	474	473	468	468	465	465
	Tidal Flat	330	345	369	318	256	217
	Inland-Fresh Marsh	294	285	279	270	251	247
	Tidal-Fresh Marsh	96	96	96	96	95	95
	Rocky Intertidal	91	84	83	80	75	73
	Tidal Swamp	82	77	76	75	73	72
	Riverine Tidal	37	32	19	18	18	18
	Trans. Salt Marsh	12	296	159	278	389	461
	Inland Shore	1	1	1	1	1	1
	Flooded Developed Dry Land	0	80	98	178	289	377
	Total (incl. water)	**115,758**	**115,758**	**115,758**	**115,758**	**115,758**	**115,758**

Table 64. South Central Coast NYC Medium (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	57,759	57,793	57,847	58,042	58,299	58,429
	Undeveloped Dry Land	26,627	26,368	26,280	25,974	25,386	25,066
	Developed Dry Land	21,087	21,008	20,977	20,844	20,537	20,276
	Irreg.-Flooded Marsh	5,486	5,109	4,996	4,411	2,098	873
	Swamp	2,223	2,206	2,191	2,159	2,102	2,078
	Estuarine Beach	651	648	629	568	479	441
	Regularly-Flooded Marsh	507	863	1,153	1,897	4,649	6,119
	Inland Open Water	474	473	468	466	461	459
	Tidal Flat	330	345	368	286	193	218
	Inland-Fresh Marsh	294	285	278	263	214	192
	Tidal-Fresh Marsh	96	96	96	95	93	92
	Rocky Intertidal	91	84	83	77	69	65
	Tidal Swamp	82	77	76	73	66	49
	Riverine Tidal	37	32	19	18	17	17
	Trans. Salt Marsh	12	291	188	341	543	571
	Inland Shore	1	1	1	1	1	1
	Flooded Developed Dry Land	0	80	110	243	550	812
	Total (incl. water)	**115,758**	**115,758**	**115,758**	**115,758**	**115,758**	**115,758**

Table 65. South Central Coast NYC Medium-High (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	57,759	57,793	57,860	58,137	58,591	58,998
	Undeveloped Dry Land	26,627	26,368	26,247	25,793	24,963	24,461
	Developed Dry Land	21,087	21,008	20,964	20,768	20,182	19,715
	Irreg.-Flooded Marsh	5,486	5,109	4,926	3,779	587	277
	Swamp	2,223	2,206	2,186	2,142	2,069	2,011
	Estuarine Beach	651	648	625	540	436	377
	Regularly-Flooded Marsh	507	863	1,226	2,605	6,177	6,159
	Inland Open Water	474	473	468	464	457	450
	Tidal Flat	330	345	366	273	381	931
	Inland-Fresh Marsh	294	285	276	248	186	169
	Tidal-Fresh Marsh	96	96	95	94	89	79
	Rocky Intertidal	91	84	82	74	64	58
	Tidal Swamp	82	77	75	72	43	31
	Riverine Tidal	37	32	19	18	17	17
	Trans. Salt Marsh	12	291	217	430	609	652
	Inland Shore	1	1	1	1	1	1
	Flooded Developed Dry Land	0	80	123	320	906	1,372
	Total (incl. water)	**115,758**	**115,758**	**115,758**	**115,758**	**115,758**	**115,758**

Table 66. South Central Coast NYC High (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	57,759	57,793	57,876	58,364	59,705	61,092
	Undeveloped Dry Land	26,627	26,368	26,209	25,401	24,080	23,258
	Developed Dry Land	21,087	21,008	20,948	20,548	19,350	18,342
	Irreg.-Flooded Marsh	5,486	5,109	4,847	1,386	175	100
	Swamp	2,223	2,206	2,181	2,096	1,956	1,842
	Estuarine Beach	651	648	619	488	342	249
	Regularly-Flooded Marsh	507	863	1,307	5,017	5,550	3,224
	Inland Open Water	474	473	467	460	439	432
	Tidal Flat	330	345	365	372	1,293	3,281
	Inland-Fresh Marsh	294	285	274	212	159	145
	Tidal-Fresh Marsh	96	96	95	92	52	18
	Rocky Intertidal	91	84	81	69	54	46
	Tidal Swamp	82	77	75	64	24	14
	Riverine Tidal	37	32	19	17	17	17
	Trans. Salt Marsh	12	291	253	631	823	953
	Inland Shore	1	1	1	1	1	1
	Flooded Developed Dry Land	0	80	139	540	1,737	2,745
	Total (incl. water)	**115,758**	**115,758**	**115,758**	**115,758**	**115,758**	**115,758**

Connecticut River Watershed

The narrow Connecticut River watershed continues the trend of increasing vulnerability (from west to east) with 94% to 99% of high marsh habitat predicted to be lost in SLR scenarios of over 1 meter (Table 67). As many as 3,600 acres of additional open water is predicted if SLR reaches 1.7 meters. Tidal fresh habitats are predicted to be flooded more frequently and likely converted on the basis of increased salinity.

Table 67 Connecticut River Watershed Landcover Change Summary

(positive indicates a gain, negative is a loss)

Land cover category	Acres in 2010	Percentage Land cover change from 2010 to 2100 for different SLR scenarios				
		NYC Low	NYC Low-Medium	NYC Medium	NYC High-Medium	NYC High
Undeveloped Dry Land	22,716	-1.1	-1.6	-2.6	-3.5	-5.0
Estuarine Open Water	5,691	9.6	10.8	14.2	25.1	73.8
Developed Dry Land	2,565	-0.6	-1.1	-2.3	-3.8	-6.6
Irreg.-Flooded Marsh	2,347	-5.3	-18.1	-90.5	-97.4	-98.9
Swamp	829	-0.3	-0.6	-2.7	-4.1	-5.6
Tidal-Fresh Marsh	568	0.0	-2.1	-22.2	-63.2	-95.1
Riverine Tidal	519	-74.8	-77.5	-80.7	-83.1	-86.0
Tidal Swamp	364	-12.2	-32.5	-69.0	-81.8	-90.5
Inland Open Water	336	-1.3	-1.4	-1.8	-2.8	-4.7
Trans. Salt Marsh	315	17.2	19.4	-3.8	-15.4	-19.8
Regularly-Flooded Marsh	256	112.5	282.8	1036.9	466.4	104.8
Tidal Flat	83	-81.4	-76.2	108.3	1987.4	548.6
Inland-Fresh Marsh	57	-3.7	-5.7	-6.5	-10.3	-12.4
Estuarine Beach	20	-39.6	-44.4	-55.4	-64.3	-77.1
Flooded Developed Dry Land	8	207.4	372.8	767.6	1282.7	2226.9

Table 68. Connecticut River Watershed NYC Low (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	23,020	22,716	22,696	22,593	22,506	22,471
	Estuarine Open Water	5,615	5,691	6,048	6,175	6,220	6,236
	Developed Dry Land	2,573	2,565	2,564	2,559	2,553	2,550
	Irreg.-Flooded Marsh	2,529	2,347	2,338	2,292	2,242	2,223
	Swamp	834	829	829	828	827	826
	Tidal-Fresh Marsh	598	568	568	568	568	568
	Riverine Tidal	567	519	179	151	136	130
	Tidal Swamp	374	364	363	350	330	320
	Inland Open Water	336	336	333	333	332	332
	Tidal Flat	65	83	112	46	23	15
	Regularly-Flooded Marsh	57	256	350	414	507	545
	Inland-Fresh Marsh	57	57	57	56	55	55
	Estuarine Beach	44	20	17	14	13	12
	Trans. Salt Marsh	6	315	211	283	341	368
	Flooded Developed Dry Land	0	8	8	14	20	23
	Total (incl. water)	**36,675**	**36,675**	**36,675**	**36,675**	**36,675**	**36,675**

Table 69. Connecticut River Watershed NYC Low-Medium (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	23,020	22,716	22,673	22,553	22,428	22,361
	Estuarine Open Water	5,615	5,691	6,059	6,206	6,272	6,305
	Developed Dry Land	2,573	2,565	2,564	2,556	2,545	2,537
	Irreg.-Flooded Marsh	2,529	2,347	2,322	2,239	2,081	1,921
	Swamp	834	829	829	827	825	824
	Tidal-Fresh Marsh	598	568	568	565	561	556
	Riverine Tidal	567	519	178	144	128	116
	Tidal Swamp	374	364	361	339	291	246
	Inland Open Water	336	336	333	333	332	332
	Tidal Flat	65	83	109	43	22	20
	Regularly-Flooded Marsh	57	256	375	490	740	981
	Inland-Fresh Marsh	57	57	56	55	54	54
	Estuarine Beach	44	20	16	13	12	11
	Trans. Salt Marsh	6	315	223	295	357	375
	Total (incl. water)	**36,675**	**36,675**	**36,675**	**36,675**	**36,675**	**36,675**

Table 70. Connecticut River Watershed NYC Medium (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	23,020	22,716	22,652	22,478	22,256	22,135
	Estuarine Open Water	5,615	5,691	6,070	6,262	6,402	6,500
	Developed Dry Land	2,573	2,565	2,562	2,550	2,524	2,507
	Irreg.-Flooded Marsh	2,529	2,347	2,302	2,077	689	223
	Swamp	834	829	828	826	822	807
	Tidal-Fresh Marsh	598	568	564	546	490	442
	Riverine Tidal	567	519	177	137	108	100
	Tidal Swamp	374	364	357	306	156	113
	Inland Open Water	336	336	333	332	331	330
	Tidal Flat	65	83	107	42	73	173
	Regularly-Flooded Marsh	57	256	407	723	2,408	2,915
	Inland-Fresh Marsh	57	57	56	54	53	53
	Estuarine Beach	44	20	15	13	10	9
	Trans. Salt Marsh	6	315	232	307	304	303
	Flooded Developed Dry Land	0	8	11	23	49	66
	Total (incl. water)	**36,675**	**36,675**	**36,675**	**36,675**	**36,675**	**36,675**

Table 71. Connecticut River Watershed NYC Medium-High (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	23,020	22,716	22,628	22,399	22,099	21,925
	Estuarine Open Water	5,615	5,691	6,080	6,313	6,597	7,120
	Developed Dry Land	2,573	2,565	2,561	2,542	2,502	2,468
	Irreg.-Flooded Marsh	2,529	2,347	2,279	1,687	135	61
	Swamp	834	829	828	824	805	795
	Tidal-Fresh Marsh	598	568	559	517	370	209
	Riverine Tidal	567	519	177	130	99	88
	Tidal Swamp	374	364	353	253	100	66
	Inland Open Water	336	336	333	332	330	327
	Tidal Flat	65	83	107	60	494	1,736
	Regularly-Flooded Marsh	57	256	446	1,213	2,728	1,452
	Inland-Fresh Marsh	57	57	56	54	53	51
	Estuarine Beach	44	20	15	12	9	7
	Trans. Salt Marsh	6	315	241	308	283	266
	Flooded Developed Dry Land	0	8	12	31	71	104
	Total (incl. water)	**36,675**	**36,675**	**36,675**	**36,675**	**36,675**	**36,675**

Table 72. Connecticut River Watershed NYC High (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	23,020	22,716	22,605	22,263	21,818	21,574
	Estuarine Open Water	5,615	5,691	6,088	6,409	8,256	9,894
	Developed Dry Land	2,573	2,565	2,559	2,525	2,448	2,397
	Irreg.-Flooded Marsh	2,529	2,347	2,250	476	47	25
	Swamp	834	829	828	822	789	782
	Tidal-Fresh Marsh	598	568	554	424	66	28
	Riverine Tidal	567	519	176	117	84	73
	Tidal Swamp	374	364	348	149	51	35
	Inland Open Water	336	336	333	331	325	320
	Tidal Flat	65	83	111	239	1,608	539
	Regularly-Flooded Marsh	57	256	491	2,538	741	525
	Inland-Fresh Marsh	57	57	56	53	50	50
	Estuarine Beach	44	20	15	11	7	5
	Trans. Salt Marsh	6	315	249	270	259	252
	Flooded Developed Dry Land	0	8	13	48	125	176
	Total (incl. water)	**36,675**	**36,675**	**36,675**	**36,675**	**36,675**	**36,675**

Southeast Coast Watershed

The coastal Southeast Coast watershed is split into two pieces with the narrow Thames watershed cutting in the middle. This watershed has the most vulnerable developed dry land in the study area with up to 16% of these lands vulnerable to regular flooding by 2100. Up to 27% of coastal fresh-water swamps and up to 69% of tidal swamps are also predicted to be vulnerable.

Table 73 Southeast Coast Watershed Landcover Change Summary
(positive indicates a gain, negative is a loss)

Land cover category	Acres in 2010	Percentage Land cover change from 2010 to 2100 for different SLR scenarios				
		NYC Low	NYC Low-Medium	NYC Medium	NYC High-Medium	NYC High
Estuarine Open Water	43,716	0.1	0.1	0.3	2.0	4.5
Undeveloped Dry Land	15,619	-1.6	-2.6	-4.7	-7.3	-11.5
Developed Dry Land	6,418	-1.3	-2.4	-5.5	-10.1	-17.3
Irreg.-Flooded Marsh	1,255	-4.4	-37.2	-85.7	-92.7	-96.3
Swamp	738	-3.1	-5.7	-9.2	-17.2	-27.9
Trans. Salt Marsh	262	63.5	95.3	81.0	95.3	76.1
Tidal Swamp	180	-0.9	-4.8	-34.3	-55.0	-73.7
Inland Open Water	174	-0.7	-2.1	-4.8	-14.3	-15.7
Estuarine Beach	167	-2.6	-4.7	-13.2	-25.2	-51.5
Regularly-Flooded Marsh	113	121.8	556.1	1328.8	759.6	632.7
Inland-Fresh Marsh	94	-3.9	-14.2	-18.4	-30.8	-40.5
Flooded Developed Dry Land	39	217.2	396.2	915.3	1682.6	2886.6
Tidal-Fresh Marsh	21	0.0	0.0	-1.0	-8.8	-48.9
Tidal Flat	11	-40.5	7.4	1270.2	5876.0	5623.3
Rocky Intertidal	11	-5.3	-8.8	-18.1	-28.7	-44.4

Table 74. Southeast Coast Watershed NYC Low (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	43,713	43,716	43,719	43,748	43,755	43,758
	Undeveloped Dry Land	15,799	15,619	15,602	15,507	15,410	15,367
	Developed Dry Land	6,456	6,418	6,414	6,388	6,351	6,334
	Irreg.-Flooded Marsh	1,308	1,255	1,255	1,235	1,210	1,200
	Swamp	742	738	738	726	717	715
	Tidal Swamp	181	180	180	180	179	178
	Inland Open Water	174	174	174	173	173	173
	Estuarine Beach	164	167	166	165	163	162
	Inland-Fresh Marsh	95	94	94	92	90	90
	Trans. Salt Marsh	81	262	217	306	391	428
	Regularly-Flooded Marsh	62	113	165	189	234	251
	Tidal-Fresh Marsh	21	21	21	21	21	21
	Rocky Intertidal	11	11	11	11	11	11
	Tidal Flat	8	11	20	10	8	7
	Flooded Developed Dry Land	0	39	42	69	105	122
	Total (incl. water)	**68,818**	**68,818**	**68,818**	**68,818**	**68,818**	**68,818**

Table 75. Southeast Coast Watershed NYC Low-Medium (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	43,713	43,716	43,720	43,755	43,768	43,778
	Undeveloped Dry Land	15,799	15,619	15,583	15,462	15,313	15,220
	Developed Dry Land	6,456	6,418	6,410	6,371	6,311	6,265
	Irreg.-Flooded Marsh	1,308	1,255	1,248	1,207	1,047	788
	Swamp	742	738	737	719	704	696
	Tidal Swamp	181	180	180	179	176	171
	Inland Open Water	174	174	174	173	173	171
	Estuarine Beach	164	167	166	164	161	159
	Inland-Fresh Marsh	95	94	93	91	87	80
	Trans. Salt Marsh	81	262	231	339	452	512
	Regularly-Flooded Marsh	62	113	176	230	438	743
	Tidal-Fresh Marsh	21	21	21	21	21	21
	Rocky Intertidal	11	11	11	11	10	10
	Tidal Flat	8	11	21	11	11	12
	Flooded Developed Dry Land	0	39	46	86	145	191
	Total (incl. water)	**68,818**	**68,818**	**68,818**	**68,818**	**68,818**	**68,818**

Table 76. Southeast Coast Watershed NYC Medium (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	43,713	43,716	43,721	43,767	43,809	43,849
	Undeveloped Dry Land	15,799	15,619	15,564	15,375	15,069	14,879
	Developed Dry Land	6,456	6,418	6,404	6,338	6,184	6,065
	Irreg.-Flooded Marsh	1,308	1,255	1,239	1,033	286	180
	Swamp	742	738	730	707	684	670
	Tidal Swamp	181	180	180	177	143	118
	Inland Open Water	174	174	174	173	171	166
	Estuarine Beach	164	167	166	162	153	145
	Inland-Fresh Marsh	95	94	92	90	77	77
	Trans. Salt Marsh	81	262	250	385	465	474
	Regularly-Flooded Marsh	62	113	191	443	1,442	1,618
	Tidal-Fresh Marsh	21	21	21	21	21	21
	Rocky Intertidal	11	11	11	11	10	9
	Tidal Flat	8	11	23	16	33	156
	Flooded Developed Dry Land	0	39	52	118	272	392
	Total (incl. water)	**68,818**	**68,818**	**68,818**	**68,818**	**68,818**	**68,818**

Table 77. Southeast Coast Watershed NYC Medium-High (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	43,713	43,716	43,722	43,781	43,908	44,571
	Undeveloped Dry Land	15,799	15,619	15,543	15,273	14,803	14,474
	Developed Dry Land	6,456	6,418	6,398	6,291	6,006	5,769
	Irreg.-Flooded Marsh	1,308	1,255	1,228	598	147	91
	Swamp	742	738	726	696	652	611
	Tidal Swamp	181	180	180	172	108	81
	Inland Open Water	174	174	174	173	166	149
	Estuarine Beach	164	167	166	160	141	125
	Inland-Fresh Marsh	95	94	92	83	70	65
	Trans. Salt Marsh	81	262	265	431	484	512
	Regularly-Flooded Marsh	62	113	209	937	1,219	973
	Tidal-Fresh Marsh	21	21	21	21	20	19
	Rocky Intertidal	11	11	11	10	9	8
	Tidal Flat	8	11	25	25	634	682
	Flooded Developed Dry Land	0	39	58	165	450	687
	Total (incl. water)	**68,818**	**68,818**	**68,818**	**68,818**	**68,818**	**68,818**

Table 78. Southeast Coast Watershed NYC High (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	43,713	43,716	43,722	43,814	45,102	45,665
	Undeveloped Dry Land	15,799	15,619	15,520	15,077	14,247	13,826
	Developed Dry Land	6,456	6,418	6,392	6,188	5,616	5,305
	Irreg.-Flooded Marsh	1,308	1,255	1,211	237	70	46
	Swamp	742	738	722	682	562	532
	Tidal Swamp	181	180	180	139	68	47
	Inland Open Water	174	174	174	171	148	147
	Estuarine Beach	164	167	165	153	112	81
	Inland-Fresh Marsh	95	94	91	77	62	56
	Trans. Salt Marsh	81	262	282	422	560	461
	Regularly-Flooded Marsh	62	113	235	1,408	871	830
	Tidal-Fresh Marsh	21	21	21	21	16	11
	Rocky Intertidal	11	11	11	10	7	6
	Tidal Flat	8	11	27	151	536	653
	Flooded Developed Dry Land	0	39	64	268	840	1,152
	Total (incl. water)	**68,818**	**68,818**	**68,818**	**68,818**	**68,818**	**68,818**

Thames Watershed

The area of the Thames Watershed that is below 5 meters elevation is somewhat limited. Within this study area, from 1% to 6% of developed lands are predicted to be flooded by 2100 depending on the SLR scenario evaluated. This watershed has few intertidal wetlands, with under 250 total acres of habitat. Within these habitats a similar pattern of high marsh loss and low marsh increases are predicted as found throughout the entire study area.

Table 79 Thames Watershed Landcover Change Summary

(positive indicates a gain, negative is a loss)

Land cover category	Acres in 2010	Percentage Land cover change from 2010 to 2100 for different SLR scenarios				
		NYC Low	NYC Low-Medium	NYC Medium	NYC High-Medium	NYC High
Estuarine Open Water	6,553	0.2	0.4	0.8	1.2	2.6
Undeveloped Dry Land	6,240	-0.5	-0.8	-1.4	-2.3	-4.3
Developed Dry Land	3,716	-0.4	-0.6	-1.5	-3.5	-6.8
Swamp	85	-2.0	-2.7	-4.0	-8.8	-11.6
Trans. Salt Marsh	79	-39.0	-38.2	-36.8	-12.2	8.0
Inland Open Water	47	-1.3	-1.9	-2.8	-2.9	-3.8
Irreg.-Flooded Marsh	25	-9.4	-24.0	-77.7	-90.5	-92.8
Inland-Fresh Marsh	22	-5.2	-6.9	-7.8	-8.0	-18.6
Flooded Developed Dry Land	14	92.1	156.5	393.0	891.7	1755.3
Estuarine Beach	14	-2.1	-4.2	-13.4	-28.2	-56.4
Regularly-Flooded Marsh	11	529.6	613.4	838.9	711.1	893.3
Tidal Swamp	6	-2.1	-7.5	-23.6	-42.6	-71.7
Tidal Flat	4	-39.2	-13.8	196.4	965.3	1345.8
Rocky Intertidal	2	-11.5	-20.2	-35.3	-48.2	-64.6
Tidal-Fresh Marsh	1	0.0	-0.2	-18.5	-55.0	-64.7

Table 80. Thames Watershed NYC Low (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	6,552	6,553	6,553	6,564	6,568	6,569
	Undeveloped Dry Land	6,316	6,240	6,237	6,222	6,211	6,207
	Developed Dry Land	3,730	3,716	3,715	3,710	3,705	3,702
	Swamp	85	85	85	84	84	84
	Inland Open Water	47	47	47	46	46	46
	Irreg.-Flooded Marsh	30	25	25	24	23	23
	Inland-Fresh Marsh	24	22	21	21	21	20
	Estuarine Beach	14	14	14	14	14	14
	Tidal Swamp	7	6	6	6	6	6
	Regularly-Flooded Marsh	5	11	62	59	64	67
	Tidal Flat	4	4	4	6	4	2
	Rocky Intertidal	2	2	2	2	1	1
	Trans. Salt Marsh	1	79	31	40	45	48
	Tidal-Fresh Marsh	1	1	1	1	1	1
	Flooded Developed Dry Land	0	14	15	20	25	28
	Total (incl. water)	**16,819**	**16,819**	**16,819**	**16,819**	**16,819**	**16,819**

Table 81. Thames Watershed NYC Low-Medium (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	6,552	6,553	6,553	6,568	6,576	6,580
	Undeveloped Dry Land	6,316	6,240	6,233	6,217	6,201	6,191
	Developed Dry Land	3,730	3,716	3,714	3,708	3,699	3,693
	Swamp	85	85	84	84	83	83
	Inland Open Water	47	47	47	46	46	46
	Irreg.-Flooded Marsh	30	25	25	23	21	19
	Inland-Fresh Marsh	24	22	21	21	20	20
	Estuarine Beach	14	14	14	14	14	14
	Tidal Swamp	7	6	6	6	6	6
	Regularly-Flooded Marsh	5	11	64	60	69	76
	Tidal Flat	4	4	5	6	3	3
	Rocky Intertidal	2	2	2	2	1	1
	Trans. Salt Marsh	1	79	34	40	45	49
	Tidal-Fresh Marsh	1	1	1	1	1	1
	Flooded Developed Dry Land	0	14	17	22	31	37
	Total (incl. water)	**16,819**	**16,819**	**16,819**	**16,819**	**16,819**	**16,819**

Table 82. Thames Watershed NYC Medium (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	6,552	6,553	6,553	6,577	6,593	6,602
	Undeveloped Dry Land	6,316	6,240	6,230	6,208	6,175	6,153
	Developed Dry Land	3,730	3,716	3,713	3,703	3,680	3,659
	Swamp	85	85	84	83	82	82
	Inland Open Water	47	47	47	46	46	46
	Irreg.-Flooded Marsh	30	25	24	21	9	6
	Inland-Fresh Marsh	24	22	21	20	20	20
	Estuarine Beach	14	14	14	14	13	12
	Tidal Swamp	7	6	6	6	5	5
	Regularly-Flooded Marsh	5	11	67	64	90	99
	Tidal Flat	4	4	5	7	8	12
	Rocky Intertidal	2	2	2	1	1	1
	Trans. Salt Marsh	1	79	34	39	44	50
	Tidal-Fresh Marsh	1	1	1	1	1	1
	Flooded Developed Dry Land	0	14	18	27	50	71
	Total (incl. water)	**16,819**	**16,819**	**16,819**	**16,819**	**16,819**	**16,819**

Table 83. Thames Watershed NYC Medium-High (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	6,552	6,553	6,553	6,584	6,611	6,633
	Undeveloped Dry Land	6,316	6,240	6,227	6,196	6,146	6,097
	Developed Dry Land	3,730	3,716	3,711	3,697	3,650	3,587
	Swamp	85	85	84	83	81	78
	Inland Open Water	47	47	47	46	46	46
	Irreg.-Flooded Marsh	30	25	24	17	4	2
	Inland-Fresh Marsh	24	22	21	20	20	20
	Estuarine Beach	14	14	14	14	12	10
	Tidal Swamp	7	6	6	6	5	4
	Regularly-Flooded Marsh	5	11	69	71	92	86
	Tidal Flat	4	4	5	9	21	42
	Rocky Intertidal	2	2	2	1	1	1
	Trans. Salt Marsh	1	79	35	40	49	69
	Tidal-Fresh Marsh	1	1	1	1	1	0
	Flooded Developed Dry Land	0	14	19	34	80	143
	Total (incl. water)	**16,819**	**16,819**	**16,819**	**16,819**	**16,819**	**16,819**

Table 84. Thames Watershed NYC High (Acres)

		Initial	2010	2025	2055	2085	2100
	Estuarine Open Water	6,552	6,553	6,553	6,596	6,670	6,720
	Undeveloped Dry Land	6,316	6,240	6,224	6,176	6,054	5,972
	Developed Dry Land	3,730	3,716	3,710	3,682	3,549	3,462
	Swamp	85	85	84	82	77	75
	Inland Open Water	47	47	47	46	46	45
	Irreg.-Flooded Marsh	30	25	23	9	2	2
	Inland-Fresh Marsh	24	22	21	20	20	18
	Estuarine Beach	14	14	14	13	9	6
	Tidal Swamp	7	6	6	5	3	2
	Regularly-Flooded Marsh	5	11	72	80	81	105
	Tidal Flat	4	4	6	21	47	57
	Rocky Intertidal	2	2	2	1	1	1
	Trans. Salt Marsh	1	79	35	39	80	85
	Tidal-Fresh Marsh	1	1	1	1	0	0
	Flooded Developed Dry Land	0	14	20	48	181	268
	Total (incl. water)	**16,819**	**16,819**	**16,819**	**16,819**	**16,819**	**16,819**

Pawcatuck Watershed (CT portion)

The portion of the Pawcatuck watershed within the Connecticut study area is limited to 1,144 total acres. However, within this region, undeveloped dry lands are predicted to be quite vulnerable with 5% to 18% losses predicted by 2100. Developed-dry land losses range from 2% to 8% by 2100.

Table 85 Pawcatuck Watershed (CT) Landcover Change Summary
(positive indicates a gain, negative is a loss)

Land cover category	Acres in 2010	Percentage Land cover change from 2010 to 2100 for different SLR scenarios				
		NYC Low	NYC Low-Medium	NYC Medium	NYC High-Medium	NYC High
Undeveloped Dry Land	549	-2.2	-3.6	-7.5	-13.1	-19.5
Developed Dry Land	478	-0.5	-1.0	-2.4	-4.7	-9.3
Estuarine Open Water	295	0.9	1.1	2.0	7.5	21.7
Swamp	54	-0.2	-0.2	-0.3	-1.3	-6.3
Irreg.-Flooded Marsh	39	-2.9	-13.8	-85.7	-93.7	-98.6
Trans. Salt Marsh	10	69.6	107.0	147.0	244.9	146.3
Riverine Tidal	4	-38.9	-40.7	-51.5	-56.3	-70.9
Inland Open Water	3	0.0	-3.3	-3.3	-19.8	-19.8
Flooded Developed Dry Land	3	90.4	190.5	458.1	895.0	1770.6
Regularly-Flooded Marsh	1	412.2	968.4	4052.8	2955.6	3410.5
Inland-Fresh Marsh	1	0.0	0.0	0.0	-96.2	-98.4
Tidal Swamp	0	0.0	-15.5	-100.0	-100.0	-100.0

Table 86. Pawcatuck Watershed (CT) NYC Low (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	558	549	548	544	539	537
	Developed Dry Land	481	478	478	477	477	476
	Estuarine Open Water	294	295	296	297	297	297
	Swamp	54	54	54	54	54	54
	Irreg.-Flooded Marsh	40	39	39	39	38	38
	Riverine Tidal	6	4	3	3	3	3
	Inland Open Water	3	3	3	3	3	3
	Trans. Salt Marsh	1	10	8	12	16	17
	Inland-Fresh Marsh	1	1	1	1	1	1
	Regularly-Flooded Marsh	0	1	5	5	6	7
	Tidal Flat	0	0	0	0	0	0
	Flooded Developed Dry Land	0	3	3	3	4	5
	Total (incl. water)	**1,438**	**1,438**	**1,438**	**1,438**	**1,438**	**1,438**

Table 87. Pawcatuck Watershed (CT) NYC Low-Medium (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	558	549	547	541	535	529
	Developed Dry Land	481	478	478	477	476	474
	Estuarine Open Water	294	295	296	297	298	298
	Swamp	54	54	54	54	54	54
	Irreg.-Flooded Marsh	40	39	39	38	36	34
	Riverine Tidal	6	4	3	3	3	3
	Inland Open Water	3	3	3	3	3	3
	Trans. Salt Marsh	1	10	9	13	18	21
	Inland-Fresh Marsh	1	1	1	1	1	1
	Regularly-Flooded Marsh	0	1	5	6	10	14
	Tidal Flat	0	0	0	0	0	0
	Flooded Developed Dry Land	0	3	3	4	5	7
	Total (incl. water)	**1,438**	**1,438**	**1,438**	**1,438**	**1,438**	**1,438**

Table 88. Pawcatuck Watershed (CT) NYC Medium (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	558	549	546	537	520	508
	Developed Dry Land	481	478	478	476	471	467
	Estuarine Open Water	294	295	296	298	299	301
	Swamp	54	54	54	54	54	54
	Irreg.-Flooded Marsh	40	39	39	36	11	6
	Riverine Tidal	6	4	3	3	3	2
	Inland Open Water	3	3	3	3	3	3
	Trans. Salt Marsh	1	10	9	15	21	25
	Inland-Fresh Marsh	1	1	1	1	1	1
	Regularly-Flooded Marsh	0	1	5	10	45	55
	Tidal Flat	0	0	0	0	1	3
	Flooded Developed Dry Land	0	3	3	5	10	14
	Total (incl. water)	**1,438**	**1,438**	**1,438**	**1,438**	**1,438**	**1,438**

Table 89. Pawcatuck Watershed (CT) NYC Medium-High (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	558	549	545	533	503	478
	Developed Dry Land	481	478	478	475	465	456
	Estuarine Open Water	294	295	296	298	302	317
	Swamp	54	54	54	54	54	54
	Irreg.-Flooded Marsh	40	39	38	29	4	2
	Riverine Tidal	6	4	3	3	2	2
	Inland Open Water	3	3	3	3	3	2
	Trans. Salt Marsh	1	10	10	16	27	35
	Inland-Fresh Marsh	1	1	1	1	0	0
	Regularly-Flooded Marsh	0	1	6	20	48	41
	Tidal Flat	0	0	0	1	14	27
	Flooded Developed Dry Land	0	3	3	6	15	25
	Total (incl. water)	**1,438**	**1,438**	**1,438**	**1,438**	**1,438**	**1,438**

Table 90. Pawcatuck Watershed (CT) NYC High (Acres)

		Initial	2010	2025	2055	2085	2100
	Undeveloped Dry Land	558	549	544	521	465	442
	Developed Dry Land	481	478	478	471	449	434
	Estuarine Open Water	294	295	296	299	338	359
	Swamp	54	54	54	54	53	51
	Irreg.-Flooded Marsh	40	39	38	8	1	1
	Riverine Tidal	6	4	3	3	2	1
	Inland Open Water	3	3	3	3	2	2
	Trans. Salt Marsh	1	10	10	20	34	25
	Inland-Fresh Marsh	1	1	1	1	0	0
	Regularly-Flooded Marsh	0	1	7	46	42	47
	Tidal Flat	0	0	0	3	20	29
	Flooded Developed Dry Land	0	3	3	10	32	47
	Total (incl. water)	**1,438**	**1,438**	**1,438**	**1,438**	**1,438**	**1,438**