THE DEVELOPMENT OF A SALT MARSH MIGRATION TOOL AND ITS APPLICATION IN LONG ISLAND SOUND

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ABSTRACT

Given their location in the intertidal zone, coastal salt marshes will be one of the ecosystems first affected by sea level rise. As sea level rise increases, marshes will begin to migrate inland if surrounding topography and land use provide suitable habitat. The question remains whether or not this migration inland will provide enough new habitat to sustain current marsh area as the seaward edge of the marsh begins to become permanently inundated. This project created an ArcGIS tool using Python computer language that projects future salt marsh habitat under a variety of sea level rise and land use scenarios. The tool has several inputs including vegetation classifications, Digital Elevation Models (DEMs), current tidal conditions, and accretion rates. An object-oriented approach to image classification was used to develop the vegetation classifications and the DEMs were developed from LiDAR point clouds using the Geostastical Analyst in ArcGIS. This research expands on a presentation given at ASPRS 2009 in Baltimore, MD which used a preliminary version of the marsh migration tool to project future marsh habitat in eight study sites on the Connecticut coastline. This research has finished the development of the tool, making it more user-friendly and is currently expanding the geographic extent to include most of Long Island Sound.

INTRODUCTION

There is consensus in the scientific community that anthropogenic emissions of greenhouse gases are changing the earth's climate. Global temperature is increasing as more greenhouse gases are trapping the earth's emitted radiation. This increase in temperature may have detrimental effects on much of the world's natural habitat. One of the current effects of increased global temperature is increased global sea level rise (IPCC, 2007).

Increasing rates of global sea level rise have the potential to alter coastal salt marshes (IPCC, 2007). The flora and fauna that inhabit salt marshes are uniquely adapted to tolerate specific salinity ranges, which allow them to thrive in certain zones in the marsh community (Bertness, 1991). Thus, the height of sea level and, therefore, the degree and duration of inundation by salt water is of critical importance to the marsh ecosystem.

Salt marshes have two functional responses to increases in sea level. Historically, salt marshes have accreted inorganic and organic sediment to increase their elevation and keep pace with sea level rise (Titus, 1988; Bricker-Urso *et al.*, 1989; Dreyer and Niering, 1995; Nydick *et al.*, 1995; NECIA, 2007). However, salt marshes may not be able to accrete fast enough to maintain pace with the projected increases in sea level. Salt marshes can also migrate inland, as increased inundation presents new opportunity for marsh expansion. Marshes that are unable to accrete enough sediment and/or expand inland could become permanently inundated leading to further wetland loss (Brinson *et al.*, 1995). Even if marshes are not permanently inundated, increases in sea level could lead to different flooding regimes, which could dramatically alter the ecology of the salt marshes (Warren and Niering, 1993). It is therefore important to assess which marshes could be the most affected by changes in sea level, so that immediate and longer-term adaptation, mitigation and restoration efforts can be planned and implemented.

This project made use of high resolution remote sensing data, along with site specific *in-situ* data, to develop a salt marsh migration tool in ArcGIS that projects future marsh habitat under various sea level rise scenarios. Specifically, the tool uses elevation data derived from LiDAR (Light Detection and Ranging) to simulate inundation using a combination of the 'Map Algebra' tool and 'Cost Distance' tool. Using these simulated inundations, along with aerial photographs of current marsh conditions, and *in-situ* vegetation and accretion data, this tool enables a projection of marsh migration inland, marsh loss through inundation, and the redistribution of flora by the year 2100.

Inputs to the tool can also be modified to model the effects of implementing different land use policies adjoining the current marsh/upland interface. One policy permits land owners to construct walls or jetties to protect private property from the rising sea; effectively preventing marsh migration. A second policy scenario often referred to as the rolling-easement policy and currently being implemented in several states such as Rhode Island and Maine, was assessed (Titus, 1998). This policy states that there can be no new construction to hold back the sea. Also, once mean high water (MHW) rises onto private land, it becomes state property (Titus, 1998). This policy allows for marshes to migrate freely, without barriers imposed through human interventions. Modeling the effects of policy could lead to better visualization of impacts from current policy and more informed decision making regarding alternative policy outcomes by government officials.

Results from the salt marsh migration tool are designed to:

- Predict the change in total marsh habitat under different sea level rise and land use scenarios
- Predict changes in flora distribution under different sea level rise and land use scenarios
- Predict which marshes will experience the most detrimental effects of sea level rise
- Predict which upland areas could be future salt marsh habitat, for environmental management and land acquisition

METHODS

To simulate salt marsh response to projected increases in sea level by the year 2100, two tools were developed in ArcGIS using Python programming language; one to simulate the Intergovernmental Panel on Climate Change (IPCC) 2007 worst case scenario of a 0.59-meter (1.94-feet) rise in sea level by 2100, and the other to simulate the Rahmstorf 2007 worst case scenario of a 1.25-meter (4.10-feet) rise in sea level by 2100. Graphs of these projections were used to obtain the increases in sea level at the three time steps the model simulates; 2040, 2070, and 2100. The tool inputs were also altered to simulate different land use policies.
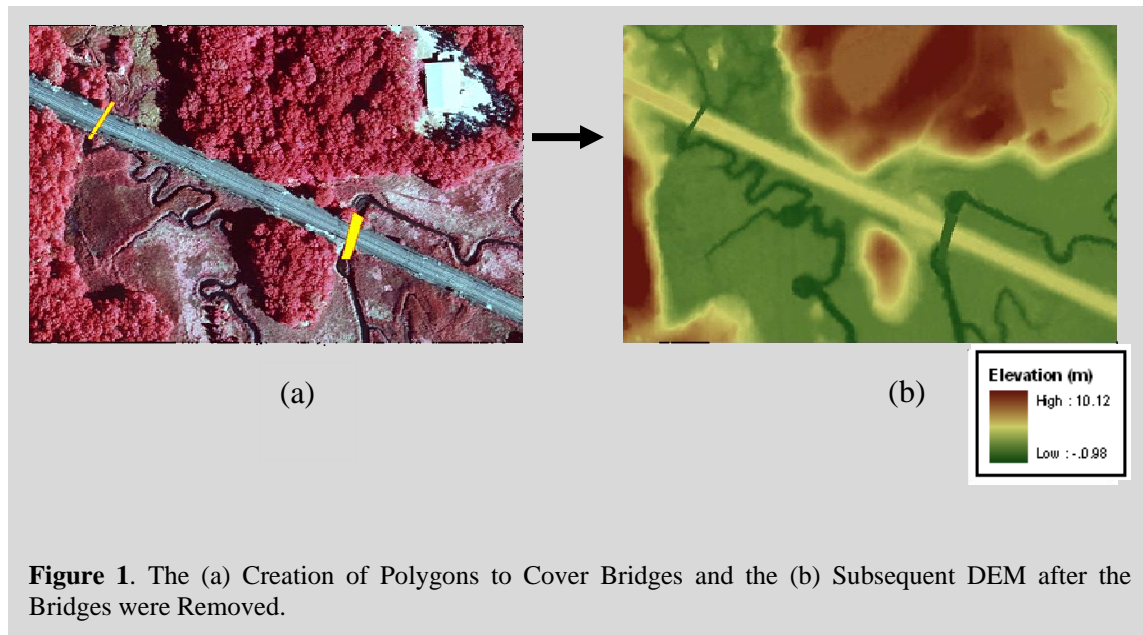
Model Inputs

There are seven inputs used in the salt marsh migration ArcGIS tools: a high resolution Digital Elevation Model (DEM), a land cover classification, site-specific Mean High Water (MHW), site specific Spring High Water (SPHW), site specific low marsh accretion rate, site specific high marsh accretion rate and the Root Mean Square Error (RMSE) of the DEM. The following will discuss how these inputs were created for Long Island Sound.

Digital Elevation Models (DEMS). The DEMs for CT were generated from LiDAR point clouds. The points were interpolated using the 'Geostatistical Analyst' in ArcGIS to a 0.61-meter (two-foot) raster. An 'Ordinary Kriging' interpolation method was used with a 'Gaussian' semivariogram, and four neighbor points. The interpolated rasters then had to be mosaicked together in a fashion that reduced edge effect errors. These errors associated with the edge of the raster occur because the interpolation can only use points from one side on the edge of a shapefile. This resulted in overlapping areas between interpolated rasters having different values. To remove these errors the rasters were clipped back 1.52 meter (five feet), by using the 36 sections of each tile created by splitting the tile scheme. However, this time they were buffered to 1.52 meter (five feet) instead of 3.05 meter (ten feet). These sections were then used to extract the interpolated rasters and all the extracted rasters were then mosaicked together. The result was a seamless 0.61-meter (two-foot) DEM for each study site in CT. For NY, the DEMS were already provided in 1.52 meter (five foot) rasters.

The DEMs for both CT and NY then had to be processed to remove any artificial impediments to flow. LiDAR is unable to penetrate pavement, thus the data returned on bridges appears as a ground return. This created artificial dams in the DEMs, which created errors in the flooding model to be discussed later. Aerial imagery was used to identify all bridges and overpasses in the eight study sites. To remove the bridges a new polygon shapefile was created in ArcCatalog and edited to outline all bridges and overpasses. Then, the shapefile was exported to a 0.61-meter (two-foot) raster in CT and 1.52 meter (five feet) raster in NY. The raster was then reclassified giving

bridges a value of 0 and all other areas a value of 1. The resulting reclassification was then multiplied by the DEM producing a raster that had an elevation of 0 (i.e., sea level) for any bridges or overpasses (Figure1).

Figure 1. The (a) Creation of Polygons to Cover Bridges and the (b) Subsequent DEM after the Bridges were Removed.

Land Cover Classifications. For the land cover classifications an object-oriented approach to image classification was implemented. The classifications were broken into broad upland categories of: 'urban', 'agrigrass' (a combined agricultural and grassland category), and 'forest', and more specific marsh categories: 'low marsh', 'high marsh', 'iva' (*Iva frutescens* L. (marsh elder)), 'phrag' (*Pragmites australia* Cav. (common reed)), 'sand', and 'water'. The classifications were done in eCognition using the DEMs as well as 4-band 1 foot CIR imagery in the segmentation and classification process.

Tide Levels. Simplistically stated, there are two general habitats in salt marshes; low marsh and high marsh (Lefor *et al.*, 1987; Mckee and Patrick Jr., 1988; Bertness, 1991). The distinction between the two is based on the frequency of inundation. Low marsh habitats lie below the MHW line and are flooded semi-diurnally. High marsh habitats are above MHW and are only flooded occasionally by spring high water SPHW and storm events (Lefor *et al.*, 1987; Mckee and Patrick Jr., 1988; Titus, 1988; Bertness, 1991). By modeling these tide levels in addition to increases in sea level, it is possible to project future low marsh and high marsh habitat. NOAA tide gauges in proximity to the study area were used to generate site specific tide values. The MHW and SPHW were calculated for each of the tide gauges using data from the NOAA website[*]. Tide levels from the year of imagery retrieval (2005 for CT and 2007 for NY) were used. The average Mean Higher High Water (MHHW) for each month was used as the MHW. The SPHW was calculated by taking the average of the highest tide for all twelve months.   Once the MHW and SPHW values were calculated from the surrounding NOAA tide gauges, the values were linearly interpolated to generate site-specific tide conditions.

Accretion Rates. Site-specific accretion rates were another input that had to be calculated. In general, areas with greater tidal amplitude have higher accretion rates. Also, areas of low marsh accrete more since their increased frequency of inundation leads to increased access to sediment (Harrison and Bloom, 1977). Accretion data available for the study sites was limited to a few sites. Again, to generate site specific rates, linear interpolation was used between known values.

DEM Root Mean Square Error (RMSE). This tool generates probability maps for future low marsh and high marsh habitat for 2100 based on the RMSE of the DEM.   These maps take into account the built in error of the DEM and create an output which shows areas that have higher probability of becoming marsh based on this error. For this project, the RMSE was calculated by comparing the DEM elevations to established National Geodetic Survey benchmarks, and established micro-relief plots in some of the marshes. To date the RMSE has only been calculated for the DEMs in CT and was 0.12 meters (0.38 feet).

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[*] National Oceanic and Atmospheric Administration http://tidesandcurrents.noaa.gov/

Tool Process

  The two tools developed have the same procedure but only differ in the sea level rise rates depending on which scenario is desired (IPCC or Rahmstorf). For this reason this paper will discuss the procedure for one tool.

  The tool begins by generating data layers that will be used in processes down the line. The first step is the creation of a 'Source' layer which will be used in the 'Cost Distance' tool to simulate flooding. The 'Source' layer is the raster from which the flood will originate from and therefore represents the ocean. It is created by using 'Map Algebra' to select all elevations under 0m in the DEM.

Table 1. The RMSE Percentiles used to Create Different LiDAR Layers	
RMSE =0.12m	
Percentile	LiDAR adjustment (m)
2.50%	-0.23
18.33%	-0.10
34.16%	-0.05
50.00%	0.00
65.83%	0.05
81.66%	0.10
97.50%	0.23

  The next step is the creation of six adjusted DEMs that span the 95% confidence interval for the RMSE. The RMSE value is multiplied by the z-value of the corresponding percentiles shown in Table 1. These are the LiDAR adjustment values which are added to the original DEM to create six additional DEMs. Each DEM is then used separately in the following procedure to create output shapefiles.

  After the base layers are created, the accretion rates for the first time step of 34 years from 2006 to 2040 are generated. Using the classification shapefile, developed earlier, a new field named "Accretion" is added to the attribute table. Then the low marsh areas are selected, and given the low marsh accretion rates in the "Accretion" field. The areas classified as 'high marsh', 'iva', or 'phrag' are similarly given the high marsh accretion rates. The classification is then converted to a raster (either 0.61-meter (two-foot) raster for CT or a 1.52 meter (five feet) raster in NY) with the 'Polygon to Raster' tool with "Accretion" as the value field (Figure 2). This raster is then multiplied by the first time step of 34 years, and added to the DEM.

Figure 2. (a) Classification for Barn Island and (b) Corresponding Accretion(m) for 2040.
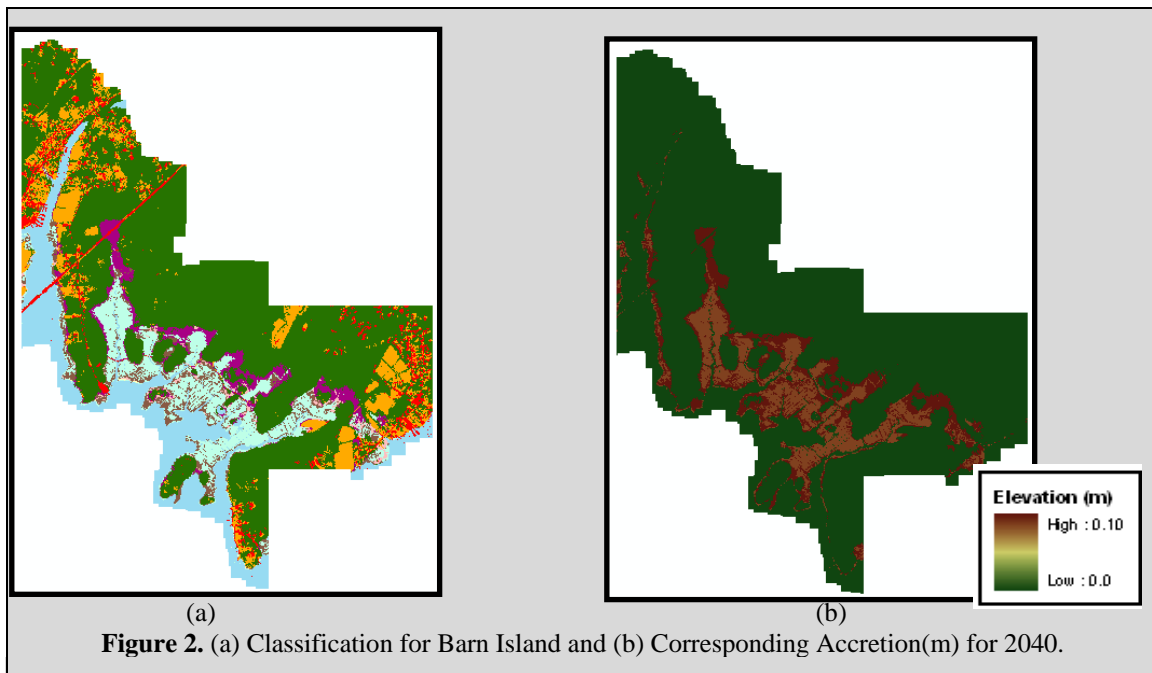
  This new DEM, adjusted to account for accretion, is the projected elevation for the year 2040, and is used to model the sea level rise scenarios of 2040. The flooding is simulated using two processes: level slicing and the 'Cost Distance' tool from ArcGIS. The first step is level slicing. The projected height of sea level by 2040 is used to calculate all the areas in the 2040 DEM under that height (Figure 3). This is done by using the Raster Calculator and the simple algorithm:

If 2040 DEM<=2040 Sea Level Height, then 1, else 0

The algorithm output is a raster with a value of 1 (true) for areas under the flood height and a value of 0 (false) for areas above the flood height. The output is then reclassified so that areas under the flood height are reclassified to 0 and the areas above the flood height reclassified to 1. Once the reclassification is complete, the 'Cost Distance' tool is used. For this tool the 'Cost Raster' is the reclassified level slice, the 'Source Data' is the 'Source' layer created earlier, and the 'Maximum Threshold' is set to 0.5. The 'Cost Distance' tool 'grows' from the ocean and sums the values of the pixels encompasses. Since the maximum threshold is 0.5 it does not include any pixels that have a value of 1. In this way the 'Cost Distance' tool generates one connected flooded region (Figure 4). The 'Cost Distance' output raster is then converted to a polygon.
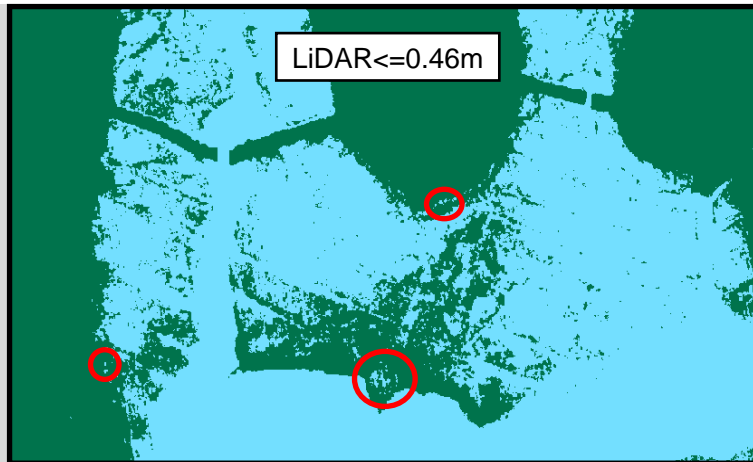

Figure 3. Level Slice of Barn Island, CT, the Light Blue Shows the Area Under 0.46m. Notice the Unconnected Blue Areas in the Red Circles.

The previous flooding methodology is then repeated for two more floods in the 2040 time step. The two floods are the projected increase in sea level by 2040 plus the current MHW and the projected increase in sea level by 2040 plus the current SPHW. The resulting three flooded areas all overlap, so, to generate unique areas for low marsh and high marsh, the 'Erase' tool is used. First, the 2040 sea level plus MHW is erased from the 2040 sea level plus SPHW. This generates a polygon that represents the area between MHW and SPHW for 2040 - predicted area of high marsh habitat. Next, the 2040 sea level polygon is erased from the 2040 sea level + MHW polygon generating the area between sea level and MHW - predicted area of low marsh habitat.
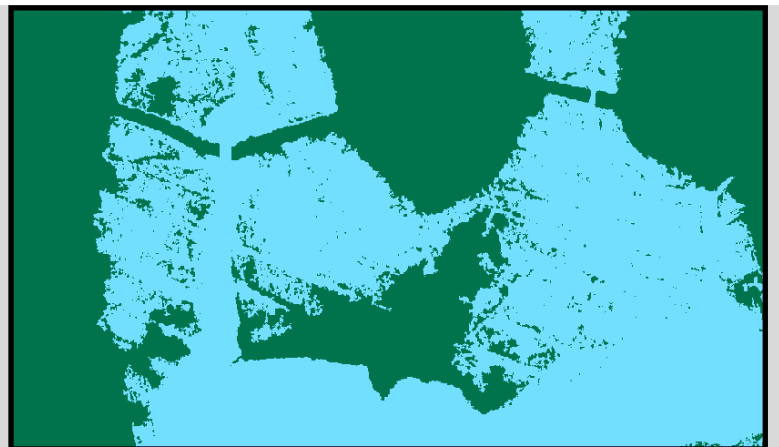

Figure 4. The output from the Cost Distance Tool.

For the 2070 time step, the low marsh and high marsh accretion rates were entered into the "Accretion" field of the 2040 low marsh and high marsh polygons, respectively. These two polygons are converted to raster, multiplied by 30 to generate the 2070 accretion, and added to the 2040 DEM to generate the 2070 DEM.

The 2070 elevation and the respective increases in sea level by 2070 are used to simulate 2070 conditions. The projected areas of low marsh and high marsh for 2070 are used to simulate accretion rates for 2100, and the process is repeated to create the final two polygons: one that represents predicted areas of low marsh for 2100, and one that represented predicted areas of high marsh for 2100. There were two tools that were constructed, one for the IPCC sea level rise scenario and one for the Rahmstorf sea level rise scenario, hence providing were two predictions for each marsh (Figure 5).

The model is iterated so that each of the seven DEMs (one original and six created based on the RMSE) is used to generate shapefiles for predicted low marsh and high marsh habitat by 2100. The resulting shapefiles from using the original DEM are considered the most reliable assessment of future habitat and is what is shown in Figure 5. To account for DEM error, the results from all seven DEMs are aggregated to create probability maps. The output shapefiles are converted to rasters, using the 'Polygon to Raster' tool, and given a value of 1 for areas that were indicated to be new marsh habitat, and 0 for areas that were not predicted to be marsh habitat. Areas predicted

to be low marsh are added together, and similarly the areas predicted to be high marsh are added together. The product of these aggregations are two probability maps, for each site, under each sea level rise scenario. The values, ranging from 1 to 7, indicate the 95% confidence interval for the respective marsh habitat. Areas with higher values had a higher probability of becoming the respective marsh type (Figure 6). Areas with a value of seven are best suited for land acquisition.

The model permits marsh migration onto any land cover type. This is representative of a rolling-easement land use policy. As previously mentioned, rolling-easement is a policy adapted by several coastal states which prevents land owners from retarding the advance of the sea with hard structures like sea walls. Several states, including Connecticut, have not enacted a rolling-easement type policy, providing the land owners with the ability to develop hard structures on uplands adjacent to but out of the jurisdictional wetland line. To simulate land owners who desire to protect property, the model was run for both sea level rise scenarios again, but with alterations to the original DEMs. The current 2005 land cover classifications were given a new field, names "Walls" in the attribute table. Any areas classified as 'urban' or 'agrigrass' were a value of 15.24 meters (50.00 feet) in the "Walls" field. The classification was then converted to a raster with the value based on the "Walls" attribute. This raster was then added to the corresponding DEM, in effect augmenting elevation to the point where inundation would not occur in even the most extreme flooding scenario and run through both the IPCC and Rahmstorf models. The result is the lack of marsh migration onto any 'urban' or 'agrigrass' land cover.

DISCUSSION

The salt marsh migration tool was developed to assist with decision making for salt marsh management. The tool was designed to produce two general outputs for environmental management. First, the output shapefiles generated from the unadjusted DEM offer the most reliable assessment of future marsh conditions (Figure 5). These outputs can be used to estimate future low and high marsh area, as well as assess the impacts of different sea level rise and land use scenarios. These results will show environmental managers which marshes could be the most impacted and provide opportunity to try and mitigate those effects.

Once the most impacted marshes have been identified, the second output of the tool, the probability maps, can be used (Figure 6). The first output of the migration tool uses only one DEM, to get a general assessment of future marsh area. However, using one DEM assumes that the DEM has inconsequential error. Unfortunately, that is not the case. When dealing with small increases in sea level errors in DEMs (even those derived from LiDAR) can have substantial consequences. For this reason, probability maps are better suited for making decisions on smaller scales. The probability maps can be used to assess which upland areas have a higher probability of becoming marsh and thus be candidates for land acquisition. In this way limited resources can be used wisely to have the biggest impact on marsh sustainability.

While the salt marsh migration tool offers projections of future low marsh and high marsh habitat it is not without limitations. Several aspects of the tool are simplistic models of complex marsh processes. The tidal conditions and accretion rates are held constant over the study site and through time. While this is not accurate, the model was simplified due to lack of readily available tidal and accretion data. In addition, sea level rise is constant throughout the study site, negating hydrologic activity. Again, this was due to lack of data, as complex hydrologic models for marshes are rare and the inclusion of such data in the tool would inhibit the models use in most areas. While the tool is simplistic in nature, it is designed to be used anywhere with limited input data to get a general assessment on future marsh conditions.
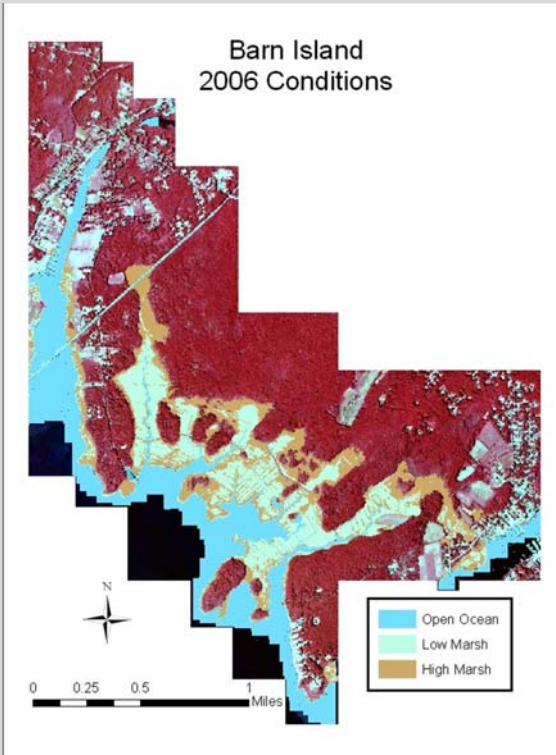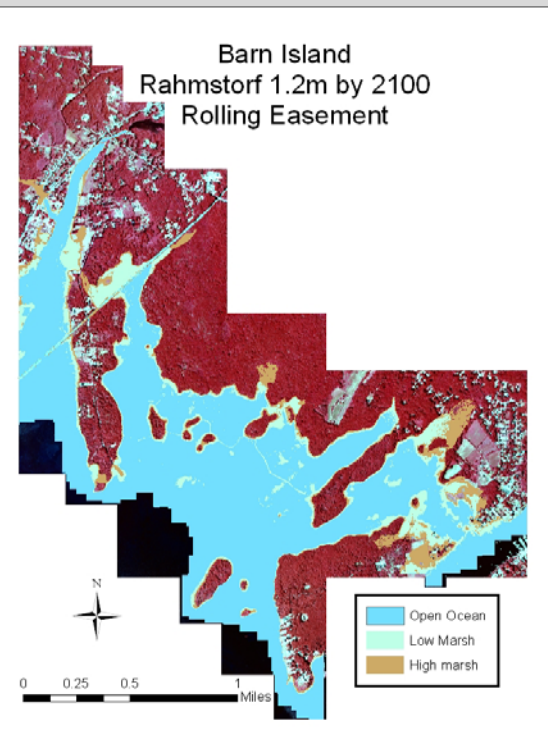
(a)

Figure 5. The (a) Current Marsh Conditions and (b) Results from the Salt Marsh Migration Tools for Barn Island.
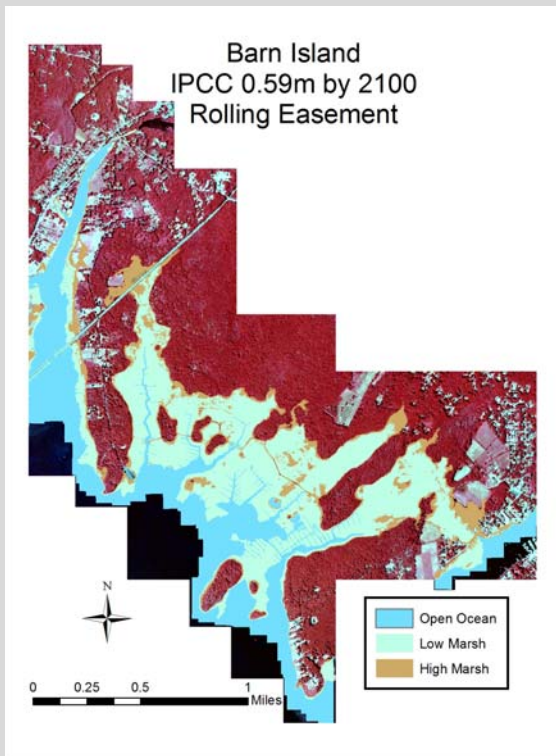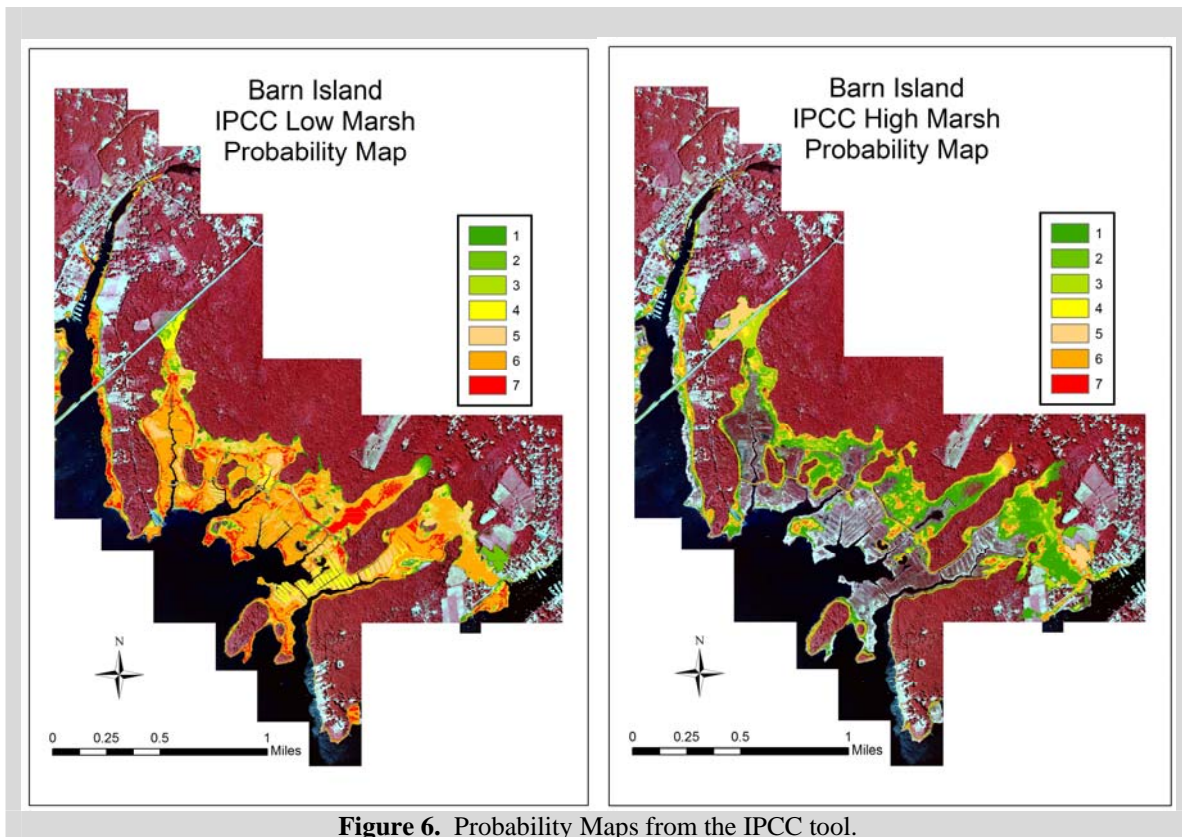

(b)

Figure 6. Probability Maps from the IPCC tool.

Currently the salt marsh migration tool is being used to assess the future conditions of salt marshes surrounding Long Island Sound. This heavily populated, often steep coastline offers limited area for future marsh migration. Use of this tool will allow agencies such as The Nature Conservancy and The Connecticut Department of Environmental Protection, to best utilize their limited resources to mitigate the effects of sea level rise on salt marshes.

ACKNOWLEDGMENTS

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