Assessment of Inundation Risk from Sea Level Rise and Storm Surge in Northeastern Coastal National Parks

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ABSTRACT

Murdukhayeva, A.; August, P.; Bradley, M.; LaBash, C., and Shaw, N., 0000. Assessment of inundation risk from sea level rise and storm surge in northeastern coastal national parks. Journal of Coastal Research, 00(0), 000–000. Coconut Creek (Florida), ISSN 0749-0208.

Sea level rise and an increase in storm frequency and intensity are two major impacts expected to result from climate change in coastal ecosystems. Coastal national parks have many low-lying areas that are at risk from inundation resulting from these impacts. To help park managers meet their goal of preserving resources, we developed a methodology to evaluate risk of inundation from sea level rise and storm surge at sentinel sites, areas of importance for natural, cultural, and infrastructural resources. We selected the most recent, readily available, and appropriate geospatial tools, models, and data sets to conduct case studies of our coastal inundation risk assessments in two northeastern coastal national parks—Cape Cod National Seashore, MA, and Assateague Island National Seashore, MD/VA. We collected elevation data at sentinel sites using real-time kinematic global positioning system (RTK GPS) technology. We used three modeling approaches: modified bathtub modeling; the Sea Level Affecting Marshes Model (SLAMM); and the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model to assess the likelihood of inundation at sentinel sites. Cape Cod's sentinel sites, which in many cases occurred in high-elevation settings, were found to be less vulnerable to inundation than were Assateague Island's sentinel sites, which were distributed in low-lying areas along the barrier beach island. This inundation risk assessment methodology can be applied to other coastal areas and to the same coastal parks at different times as more accurate elevation data sets and updated sea level rise projections become available.

ADDITIONAL INDEX WORDS: Coastal elevations, LIDAR, GPS, modeling, climate change.

INTRODUCTION

In coastal ecosystems, accelerated sea level rise and an increase in storm frequency and intensity are two major impacts expected to result from climate change (Ashton, Donnelly, and Evans, 2008; Bender et al., 2010; Harvey and Nicholls, 2008). In the next century, the rate of global sea level rise is anticipated to be several times higher than that measured over the past century (Cazenave and Nerem, 2004; Church and White, 2006; Overpeck and Weiss, 2009; Pfeffer, Harper, and O’Neel, 2008; Rahmstorf, 2007). The U.S. northeast coast experiences a rate of relative sea level rise greater than the global average because of substantial regional variations in glacial isostatic adjustment effects and oceanographic processes (Sallenger, Doran, and Howd, 2012; Tamisiea and Mitrovica, 2011). Along the U.S. Atlantic coast, the highest rates of subsidence occur from southern Massachusetts to Virginia (Engelhart, Peltier, and Horton, 2011), and predicted changes in ocean circulation, driven by climate change, could potentially add meters of dynamic sea level rise along the northeast coast during the next century (Hu et al., 2009; Yin, Schlesinger, and Stouffer, 2009). Furthermore, the frequency and extent of severe coastal storms are expected to increase (Bender et al., 2010), and large surge levels may cause significant damage to coastal infrastructure and alteration of ecosystems (Irish et al., 2010; Kirshen et al., 2008; Lin et al., 2010; McInnes et al., 2003).

Our objective was to explore how widely accessible data and tools can be used for highly localized assessments of inundation risk. As case studies, we modeled inundation risk from predicted sea level rise and storm surge at 97 sentinel sites in two coastal, northeastern U.S. national parks—Cape Cod National Seashore (CACO), and Assateague Island National Seashore (ASIS)—using a variety of data sources, predicted scenarios, and physical models.

The definitions of two terms used throughout this article are essential to understanding the project. Sentinel sites are
locations of natural or cultural resources or critical infrastructure of special importance to the National Park Service (NPS). Examples include piping plover habitat, historic buildings, and bridges. At risk refers to the likelihood of inundation because of sea level rise or storm surge. However, some sites and associated resources predicted to be at risk of inundation would not necessarily be negatively affected by it. For example, a building may be unaffected by a brief period of inundation from storm surge. In other cases, natural or cultural resources or infrastructure may be severely affected if inundated. Therefore, risk (of inundation) does not equate to “impact” in our study. In either case, however, an understanding of the vulnerability of each sentinel site to inundation will allow park resource managers to develop appropriate management and mitigation strategies for these sites and areas of concern.

Coastal zone scientists have used a variety of quantitative models to assess the effect of sea level rise and storm surge on coastal inundation and flooding. Several hydrodynamic models are used to model inundation from rising sea levels. Examples include MIKE 21 and MIKE FLOOD (Sto. Domingo et al., 2010), ADCIRC (Lin et al., 2010), LISFLOOD-FP (Lewis et al., 2011), and ANUGA (Van Drie, Milevski, and Simon, 2010). The U.S. Federal Emergency Management Agency (FEMA) relies on a Geographic Information Systems (GIS) model, HAZUS-MH, to estimate the physical, economic, and social impacts of large-scale flooding events (Scawthorn et al., 2006a,b). Other GIS-based methods have been applied as well (Brown, 2006; Hennecke and Cowell, 2000). A thorough review of sea level and storm surge inundation models is provided in Murdukhayeva et al. (2012).

Parkwide and regional-scale assessments of sea level rise and storm surge risk have been conducted previously in these two national parks (CACO, ASIS). The Coastal Vulnerability Index (CVI) technique was applied at Cape Cod National Seashore (Hammar-Klose et al., 2003) and at Assateague Island National Seashore (Pendleton, Williams, and Thieler, 2004). The CVI method combines a number of physical variables to classify the relative vulnerability of 1.5-km shoreline segments to sea level rise effects. Gutierrez, Williams, and Thieler (2007) studied potential shoreline changes from sea level rise along the United States. Mid-Atlantic coast. The CVI and shoreline-change assessments provide a useful and robust overview of coastal vulnerability at landscape scales (1.5 km stretches of coast). Our study assesses risk at specific locations, thus provides a more-resolute evaluation of inundation.

All vulnerability models and methods rely on elevation data, which are often limited in their vertical accuracy and cause large ranges of uncertainty in the results (Gesch, 2009). The National Elevation Dataset (NED) is the largest-scale, readily available, topographic data set for the entire United States, but with a vertical accuracy (root mean square error [RMSE]) of 2.44 m (Gesch, 2007), it is of little value in assessing inundation risk at specific sites. Our study relied on two sources of high-accuracy elevation data for sentinel sites: Light Detection and Ranging (LIDAR) data and real-time kinematic global positioning system (RTK GPS) data. Our assessment also integrated output for three sea level rise scenarios and four storm surge scenarios from several modeling approaches. For sea level rise, we used a “bathtub inundation” model with tidal-orthometric datum conversion and the Sea Level Affecting Marshes Model (SLAMM). For storm surge, we used the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model. The probabilities of inundation at sentinel sites were calculated for each modeled scenario, and an index was developed to estimate overall inundation likelihood at each sentinel site. This overall index of inundation likelihood was an additional tool for prioritizing long-term management and climate change adaptation plans in the national parks.

## METHODS

A goal of this research was to develop a process to assess sea level rise and storm surge inundation risk at specific locations in coastal environments. We endeavored to use off-the-shelf data and technology and readily available models, so the process could be used by other coastal resource managers in other locations in the United States. A synopsis of the data and tools we chose and the sources of additional information for them are presented in Table 1.

### Table 1. Data, tools, and models used in this study and references for further information.

<table>
<thead>
<tr>
<th>Data/Tool</th>
<th>Source</th>
<th>Citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>Experimental Advanced Airborne Research Lidar (EAARL); the 3di Technologies, Inc. Digital Airborne Topographic Imaging System II (DATIS II), RTK GPS Surveys</td>
<td>Bonisteel et al., 2009; Bonisteel-Cormier et al., 2010; Brock et al., 2007; MassGIS, 2005, performed by Neil Winn (NPS ASIS), Mark Adams (NPS CACO), Michael Bradley (URI), and Angelica Murdukhayeva (URI)</td>
</tr>
<tr>
<td>Tidal and orthometric datum values</td>
<td>NOAA CO-OPS, NOAA VDatum 3.0 beta</td>
<td>NOAA, 2007; NOAA, 2011</td>
</tr>
<tr>
<td>SLOSH (Sea, Lake, and Overland Surges from Hurricanes model)</td>
<td>NOAA NWS Display Version 1.64a (release date: June 2011)</td>
<td>FEMA, 2003; Jarvinen and Lawrence, 1985; Jelesnianski, Chen, and Shaffer, 1992</td>
</tr>
<tr>
<td>Wetlands</td>
<td>U.S. Fish and Wildlife Service National Wetlands Inventory</td>
<td>USFWS, 2010</td>
</tr>
<tr>
<td>Upland land cover</td>
<td>NOAA Coastal Change Analysis Program</td>
<td>NOAA, 2006</td>
</tr>
<tr>
<td>Local accretion rates</td>
<td></td>
<td>J. Lynch, personal communication; NPS, 2009</td>
</tr>
</tbody>
</table>

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Study Areas

We worked in two coastal parks (Figure 1): Cape Cod National Seashore (CACO) and the Assateague Island National Seashore (ASIS). The CACO is located on the outer (eastern) portion of Cape Cod, Massachusetts. It encompasses 123 km of ocean, marsh, and inner bay shorelines and contains a variety of marine, estuarine, and upland, terrestrial ecosystems with relatively varied topography for the coastal zone. The ASIS is located on the Delmarva Peninsula and lies within the boundaries of two states, Maryland and Virginia. It has 60
km of shoreline on an undeveloped barrier island with long stretches of dunes, beaches, and marshes. These study areas represented two different types of coastal ecosystem landscapes: a peninsular glacial moraine (CACO) and a barrier island (ASIS).

Data Sources
Sentinel sites are locations of natural, cultural, and infrastructural resources of special importance to the NPS and were identified by park managers. At CACO, the 63 sentinel site locations included groundwater-monitoring wells, lighthouses, visitor centers, and historical monuments and sites, e.g., the Marconi Site and historic Marindin shoreline survey markers (Marindin, 1891). At ASIS, sentinel sites were locations of 34 newly installed or frequently used geodetic survey markers, which are critical for ongoing research on the island geomorphology. We measured the elevation of sentinel sites using RTK GPS (Trimble R8 GNSS), which provided elevation estimates with average vertical RMSE values of 3.5 cm for CACO and 0.7 cm for ASIS.

Digital elevation models (DEMs) were derived from LIDAR data obtained by the U.S. Geological Survey (USGS) and the NPS from aircraft-mounted laser sensors. LIDAR data are typically accurate to 0.15–1 m (Gao, 2007). The horizontal resolutions of CACO’s and ASIS’s DEMs were 1 m and 2.5 m, respectively. The reported vertical accuracy of the DEMs for CACO and ASIS was 15 cm RMSE. To validate these accuracy estimates, we calculated the vertical RMSE using high-accuracy (<2 cm vertical and horizontal error) ground-control points that were available in each park. For CACO, the vertical RMSE of the DEM was 0.53 m using 35 existing geodetic control points. For ASIS, the vertical RMSE was 0.33 m using 1179 control points.

The SLAMM model requires a DEM layer, a slope layer (derived from the DEM), a detailed land-use layer, parameters for tidal ranges (National Oceanic and Atmospheric Administration [NOAA], 2007), and if known, accrretion rates for marshes. The land-use layer was created by merging the Coastal Change Analysis Program (C-CAP) data (NOAA, 2006) and the National Wetlands Inventory (NWI) data (USFWS, 2010) and recoding them to SLAMM categories, as specified by the SLAMM 6.0.1 Beta Users Manual (Warren Pinnacle Consulting, 2010). The source data for NWI were aerial photography (CACO in 1993 and ASIS in 1988), and the source data for C-CAP were 2006 Landsat imagery. Some model parameters, such as marsh accretion rates, were obtained from Surface Elevation Table (SET) data (J. Lynch, personal communication; NPS, 2009). When these and other parameters (i.e., beach sedimentation rate, frequency overwash) were unknown or unavailable, SLAMM’s default settings were used. Using default parameter settings could strongly sway the rates of inundation predicted by SLAMM (Scarborough, 2009), but we were limited by data availability for our case study sites.

Sea Level Rise Scenarios and Models
Three scenarios were selected to represent the current range of sea level rise predictions for the year 2100: rises of 0.6 m (IPCC, 2007), 1 m (Vermeer and Rahmstorf, 2009), and 2 m (Pfeiffer, Harper, and O’Neel, 2008). The scenarios represent reasonable estimates of low, medium, and high predictions of sea level rise for this region. For example, the Rhode Island Coastal Resources Management Council has adopted sea level rise scenarios in the range of 1–2 m to guide their planning policies (Gregg, 2010).
features that might prevent inundation of inland areas, only raster cells adjacent to the ocean or contiguous with other inundated cells were included in the risk maps.

ArcGIS 10 software was used for all geospatial data processing (ESRI, 2011).

**Statistical Procedures**

Probabilities of inundation for sentinel sites were calculated for each of the sea level rise scenarios (0.6 m, 1 m, and 2 m) and storm surge scenarios (Category 1–4 hurricanes). The land surface elevation and modeled water surface were compared, and probabilities of inundation at sentinel sites were calculated using the z-score inundation uncertainty technique described by NOAA Coastal Services Center (2010a). The standard normal cumulative-distribution function was used to calculate probabilities of inundation and the certainty of the prediction given errors associated with the data and models (Ott and Longnecker, 2010). Standard scores, or z-scores, were calculated at each sentinel site using the formula:

\[
    z-score = \frac{\text{Inundation level} - \text{Elevation}}{\text{RMSE}_{Total}},
\]

where \(\text{RMSE}_{Total}\) is calculated as follows:

\[
    \text{RMSE}_{Total} = \sqrt{(\text{RMSE}_{Elevation})^2 + (\text{RMSE}_{WaterSurface})^2}.
\]

The \(\text{RMSE}\) for LIDAR DEMs is calculated as follows:

\[
    \text{RMSE}_{Elevation} = \sqrt{\frac{i = 1}{n} (x_{\text{LIDAR},i} - x_{\text{GPS},i})^2},
\]

where \(x_{\text{LIDAR}}\) is the elevation from LIDAR at a single location, and \(x_{\text{GPS}}\) is the elevation as determined by GPS in the same location. The RMSEs for the GPS survey elevations were reported by Trimble Software. The RMSEs for water surfaces were reported by VDatum. An area was considered at risk from inundation if it had an elevation less than or equal to the water surface elevation predicted for that location and was contiguous with other inundated pixels. Because high topographic

Figure 2. Sea level rise scenarios at Cape Cod, Massachusetts. The blue areas represent areas at risk from inundation in 1-m and 2-m sea level rise scenarios. The areas in orange represent areas whose elevations are under the 1-m and 2-m water surfaces but are unconnected to the ocean or other areas expected to be inundated. (Color for this figure is available in the online version of this paper.)
features might prevent inundation of low-elevation areas further inland, we retained inundated locations that were contiguous with flooded areas but did not retain inland sites that were low elevation but were separated from the coast by a landscape feature higher than the inundation elevation (see Figure 2).

Descriptive statistics were calculated for each risk estimate variable (e.g. probability of inundation with 1 m sea level rise, inundation depth at 2 m sea level rise), and the variables were tested for normality using the Shapiro-Wilk normality test. Because data were usually nonnormally distributed, we performed pairwise comparisons using the nonparametric Wilcoxon signed rank test, and where there were three or more groups in a comparison, we used the Kruskal-Wallis rank sum test. A principal components analysis (PCA) was used to reduce the large number of risk measures to a smaller number of variables to develop a composite measure of inundation risk at sentinel sites. All analyses were conducted using the statistical software package R (R Development Core Team, 2011).

RESULTS

Inundation Mapping

Estimates of the extent of sea level rise using the bathtub model are shown for selected parts of CACO (Figure 2) and ASIS (Figure 3). Expected storm surge heights from Category 1–4 storms were modeled for CACO and ASIS (Table 2). Figure 4 demonstrates how differences in expected surge heights translate to inundation-zone mapping in the northern extent of the CACO. Total areas at risk from sea level rise and storm surge inundation scenarios are presented in Table 3.

Table 2. Storm surge heights (above MHHW) predicted by SLOSH.

<table>
<thead>
<tr>
<th>Storm Class</th>
<th>Surge Height (m) CACO</th>
<th>Surge Height (m) ASIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 1</td>
<td>0.34–1.52</td>
<td>0.43–1.77</td>
</tr>
<tr>
<td>Category 2</td>
<td>0.91–3.20</td>
<td>0.73–3.02</td>
</tr>
<tr>
<td>Category 3</td>
<td>1.34–5.33</td>
<td>2.56–4.30</td>
</tr>
<tr>
<td>Category 4</td>
<td>1.80–8.07</td>
<td>4.15–5.55</td>
</tr>
</tbody>
</table>

Figure 3. Sea level rise scenarios near Verrazano Bridge, Assateague Island: (A) 0.6 m, (B) 1 m, and (C) 2 m. (Color for this figure is available in the online version of this paper.)

Elevations of Sentinel Sites

The elevations of sentinel sites that were obtained from RTK GPS and those from LIDAR-derived DEMs were significantly different (Table 4). At CACO, the LIDAR elevations were lower than RTK GPS elevations and had a mean difference of 1.19 ± 0.10 m (mean ± 1 standard error [SE]). At ASIS, the LIDAR elevations were often higher than RTK GPS elevations and had a mean (± SE) difference of 0.29 ± 0.04 m. For all of our probability calculations, we used the RTK GPS–derived elevations for sentinel sites.

Probabilities of Inundation

Mean probabilities of inundation for each park’s set of sentinel sites are reported in Tables 5 and 6. The complete list of sentinel sites and their individual probabilities of inundation can be found in Murdukhayeva (2012). As expected, inundation risk increased as sea level rise height and storm intensity increased. The mean probabilities of inundation at CACO were significantly different for the two sea level rise scenarios (Wilcoxon signed rank, $V = 0$, $p < 0.001$). Similarly, for ASIS, the mean probabilities of inundation are significantly different for the three sea level rise scenarios ($H = 66.02$, df = 2, $p < 0.0001$). The mean probabilities of inundation for the four storm surge scenarios are significantly different for both CACO ($H = 44.51$, df = 3, $p < 0.0001$) and ASIS ($H = 96.52$, df = 3, $p < 0.0001$).

Storm surge inundation risk increased dramatically with increasing Category storms. Sentinel sites at Provincetown Airport, Pleasant Bay Marsh, and Wellfleet Harbor,
Massachusetts, are at risk under Category 3 and 4 hurricane scenarios. Along the entire length of Assateague Island, sentinel sites are at high risk. Under the Category 2 storm surge scenario, 22 sentinel sites have $>75\%$ probability of inundation, and under the Category 3 and 4 scenarios, all 34 sentinel sites have $>75\%$ chance of inundation (Table 6).

Habitat Changes Predicted by SLAMM

The SLAMM model predicted habitat classes under selected scenarios of sea level rise by 2100. Change matrices (Tables 7 and 8) show the number of sentinel sites in each habitat class initially and their expected conversions because of sea level rise. At CACO, only two scenarios were modeled because the vertical accuracy of the LIDAR data (the primary...
input driving the model) was inadequate to support the 0.6-m scenario. In the Undeveloped dry land category, 10 sentinel sites experienced conversions to the Transitional marsh category, one sentinel site converted to Estuarine beach, and one sentinel site converted to Open ocean after 2 m of sea level rise (Table 7). In ASIS, many sentinel sites were in the Undeveloped dry land class (24 of 34 total sites [71%]) and experienced conversions to Transitional marsh (n = 9; 38%), Estuarine beach (n = 1; 4%), Ocean beach (n = 3; 13%), and Open ocean (n = 11; 46%) with 2 m of sea level rise. Four sentinel sites that started in the Irregularly flooded marsh category converted to Salt marsh after 2 m of sea level rise (Table 8).

Following the recommendation of Scarborough (2009), similar land cover classes were aggregated for ease of interpretability. The 11 possible SLAMM categories were

<table>
<thead>
<tr>
<th>Study Area (n)</th>
<th>RTK GPS (mean ± SE m)</th>
<th>LIDAR (mean ± SE m)</th>
<th>Absolute Difference (pairwise mean ± SE m)</th>
<th>Test of Mean Pairwise Differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>CACO (63)</td>
<td>13.20 ± 1.45</td>
<td>12.02 ± 1.46</td>
<td>1.19 ± 0.10</td>
<td>1999</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>ASIS (34)</td>
<td>1.39 ± 0.07</td>
<td>1.65 ± 0.07</td>
<td>0.29 ± 0.04</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

Table 6. Mean (±SE) probabilities of inundation at sentinel sites using the SLOSH storm scenarios. The number of sites where the probability of inundation exceeds 0.75 is shown in parentheses.

<table>
<thead>
<tr>
<th>Study Area (n)</th>
<th>Category 1</th>
<th>Category 2</th>
<th>Category 3</th>
<th>Category 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>CACO (63)</td>
<td>0.000 ± 0.000 (0)</td>
<td>0.013 ± 0.012 (1)</td>
<td>0.051 ± 0.022 (1)</td>
<td>0.114 ± 0.034 (5)</td>
</tr>
<tr>
<td>ASIS (34)</td>
<td>0.162 ± 0.047 (2)</td>
<td>0.700 ± 0.066 (22)</td>
<td>0.980 ± 0.009 (34)</td>
<td>0.999 ± 0.001 (34)</td>
</tr>
</tbody>
</table>

input driving the model) was inadequate to support the 0.6-m scenario. In the Undeveloped dry land category, 10 sentinel sites experienced conversions to the Transitional marsh category, one sentinel site converted to Estuarine beach, and one sentinel site converted to Open ocean after 2 m of sea level rise (Table 7). In ASIS, many sentinel sites were in the Undeveloped dry land class (24 of 34 total sites [71%]) and experienced conversions to Transitional marsh (n = 9; 38%), Estuarine beach (n = 1; 4%), Ocean beach (n = 3; 13%), and Open ocean (n = 11; 46%) with 2 m of sea level rise. Four sentinel sites that started in the Irregularly flooded marsh category converted to Salt marsh after 2 m of sea level rise (Table 8).

Following the recommendation of Scarborough (2009), similar land cover classes were aggregated for ease of interpretability. The 11 possible SLAMM categories were

<table>
<thead>
<tr>
<th>Initial Category (No. of sentinel sites)</th>
<th>Predicted Category (1 m, 2 m sea level scenarios)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry land developed (12)</td>
<td>Dry Land Developed (12)</td>
</tr>
<tr>
<td>Dry land undeveloped (46)</td>
<td>Dry Land Undeveloped (40, 34)</td>
</tr>
<tr>
<td>Nontidal swamp (1)</td>
<td>Nontidal Swamp (1, 0)</td>
</tr>
<tr>
<td>Transitional marsh (0)</td>
<td>Transitional Marsh (5, 10)</td>
</tr>
<tr>
<td>Salt marsh (0)</td>
<td>Salt Marsh (0, 1)</td>
</tr>
<tr>
<td>Estuarine beach (0)</td>
<td>Estuarine Beach (1, 1)</td>
</tr>
<tr>
<td>Rocky intertidal (2)</td>
<td>Rocky Intertidal (1, 0)</td>
</tr>
<tr>
<td>Irregularly flooded marsh (2)</td>
<td>Irregularly Flooded Marsh (1, 2)</td>
</tr>
<tr>
<td>Open ocean (0)</td>
<td>Open Ocean (0, 0)</td>
</tr>
</tbody>
</table>
Table 8. ASIS SLAMM conversion matrix. Numbers in parentheses indicate sentinel sites converted to each class in each inundation scenario (0.6 m, 1 m, 2 m).

<table>
<thead>
<tr>
<th>Initial Category (No. of sentinel sites)</th>
<th>Dry Land Developed</th>
<th>Dry Land Undeveloped</th>
<th>Inland Fresh Marsh</th>
<th>Transitional Marsh</th>
<th>Salt Marsh</th>
<th>Estuarine Beach</th>
<th>Tidal Flat</th>
<th>Ocean Beach</th>
<th>Irregularly Flooded Marsh</th>
<th>Estuarine Open Water</th>
<th>Open Ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry land developed (1)</td>
<td>(1, 1, 1)</td>
<td>(8, 2, 0)</td>
<td>(7, 7, 9)</td>
<td>(0, 1, 1)</td>
<td>(8, 11, 3)</td>
<td>(1, 3, 11)</td>
<td></td>
<td></td>
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<tr>
<td>Dry land undeveloped (24)</td>
<td></td>
<td>(1, 1, 0)</td>
<td>(0, 0, 1)</td>
<td>(1, 1, 0)</td>
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<td>(1, 1, 0)</td>
<td>(0, 0, 1)</td>
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<tr>
<td>Inland fresh marsh (1)</td>
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<tr>
<td>Transitional marsh (1)</td>
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<td>(0, 0, 1)</td>
<td>(0, 0, 1)</td>
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<tr>
<td>Salt marsh (1)</td>
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<td>(1, 1, 0)</td>
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<td>(0, 0, 1)</td>
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<tr>
<td>Estuarine beach (1)</td>
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<td>(1, 1, 0)</td>
<td>(0, 0, 1)</td>
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<tr>
<td>Tidal flat (0)</td>
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<td>(0, 0, 1)</td>
<td>(0, 0, 1)</td>
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<tr>
<td>Ocean beach (1)</td>
<td></td>
<td>(1, 1, 0)</td>
<td>(0, 0, 1)</td>
<td>(1, 1, 0)</td>
<td>(0, 0, 1)</td>
<td>(0, 0, 1)</td>
<td></td>
<td></td>
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<tr>
<td>Irregularly flooded marsh (4)</td>
<td></td>
<td>(1, 1, 0)</td>
<td>(0, 0, 1)</td>
<td>(1, 1, 0)</td>
<td>(0, 0, 1)</td>
<td>(0, 0, 1)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Estuarine open water (0)</td>
<td></td>
<td>(1, 1, 0)</td>
<td>(0, 0, 1)</td>
<td>(1, 1, 0)</td>
<td>(0, 0, 1)</td>
<td>(0, 0, 1)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Open ocean (0)</td>
<td></td>
<td>(1, 1, 0)</td>
<td>(0, 0, 1)</td>
<td>(1, 1, 0)</td>
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</table>

Figure 5. The SLAMM initial conditions and model output at Assateague Island. Eleven possible land-use classes in the study area (top panels), and land-use classes aggregated into five broad groups (bottom panels). (Color for this figure is available in the online version of this paper.)
reclassified into five land-cover categories for mapping applications: Upland, Forested wetland, Marsh, Beach, and Open water. Figure 5 shows initial conditions and a 1-m sea level rise output with the original classification scheme (top panels) and with the aggregated classification scheme (bottom panels). Figure 6 shows an area east of Calfpen Bay, Virginia (ASIS), which showed great changes over the modeled scenarios; there was a large increase in Marsh, Transitional marsh, and Open water.
water areas. This area showed some of the greatest changes in the two parks studied.

Maps with park-scale views of initial land-cover classes and model-output land-cover classes for each sea level rise scenario are found in Murdukhayeva et al. (2012).

Overall Inundation Index

The three models yielded several measures of inundation risk. We used PCA to reduce the large set of correlated risk variables to a set of uncorrelated variables or principal components (Table 9). The first principal component (PC1) explained 63% of the total variation in risk measures at CACO and 58% of the total variation in risk measures at ASIS. In all cases, inundation probabilities had a negative loading, and RTK GPS elevations had a positive loading on PC1 (Table 9). Nearly all variables had similar loading values on PC1, thus PC1 represents a “size” effect (August, 1983) and can be used as an index of the overall risk of inundation. The other principal components had high loadings on only one or two variables and reflected specific risk factors. Furthermore, they did not predict overall variation well and, therefore, were not candidates for an overall risk index. The range of PC1 values for each park was separated into five quintiles. Large, positive PC1 scores for sentinel sites indicated that inundation was very unlikely; large, negative PC1 scores indicated that inundation was very likely (Table 10). Overall inundation index classification at sentinel sites was mapped for CACO and ASIS (Figure 7).

<table>
<thead>
<tr>
<th>Variable</th>
<th>CACO</th>
<th>ASIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS elevation</td>
<td>0.37</td>
<td>0.23</td>
</tr>
<tr>
<td>C1_depth</td>
<td>-0.37</td>
<td>-0.23</td>
</tr>
<tr>
<td>C2_depth</td>
<td>-0.37</td>
<td>-0.23</td>
</tr>
<tr>
<td>C3_depth</td>
<td>-0.37</td>
<td>-0.23</td>
</tr>
<tr>
<td>C4_depth</td>
<td>-0.37</td>
<td>-0.23</td>
</tr>
<tr>
<td>Prob_60cm</td>
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<td>0.47</td>
</tr>
<tr>
<td>Prob_1m</td>
<td>-0.23</td>
<td>0.49</td>
</tr>
<tr>
<td>Prob_2m</td>
<td>-0.27</td>
<td>0.30</td>
</tr>
<tr>
<td>Slamm_60cm</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Slamm_1m</td>
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<td>0.39</td>
</tr>
<tr>
<td>Slamm_2m</td>
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<td>0.17</td>
</tr>
<tr>
<td>% Variation explained</td>
<td>62.7</td>
<td>62.7</td>
</tr>
<tr>
<td>Cumulative variation (%)</td>
<td>62.7</td>
<td>86.3</td>
</tr>
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</table>

Table 9. Principal components analysis of risk variables. Class loadings for the first three principal components are provided for each variable. The GPS elevation refers to site elevation as surveyed by GPS; C1_depth to C4_depth refer to the depth of inundation from Category 1-4 storms; Prob_60cm, Prob_1m, and Prob_2m refer to probabilities of inundation given sea level rise scenarios of 60 cm, 1 m, and 2 m; SLAMM_60cm, SLAMM_1m, and SLAMM_2m refer to conversion predictions (yes or no) by SLAMM given sea level rise scenarios of 60 cm, 1 m, and 2 m.

DISCUSSION

Quality of the LIDAR Data

The best LIDAR data that were available to us were not as accurate as expected and this affected how they could be used in the models. The metadata for each of the two LIDAR-derived DEMs reported a 15 cm vertical RMSE. To validate these accuracy estimates, we calculated the vertical RMSE using ground control points of high quality and accuracy (<2 cm vertical and horizontal accuracy) collected using survey-grade GPS. Our estimates of the RMSE of the LIDAR data were two to three times larger than the RMSE values reported in the metadata. This result had many implications in our study. We were unable to reliably model the 0.6-m sea level rise scenario at CACO based on the uncertainty of the LIDAR DEM used in the modeling (NOAA, 2010). These results suggest that it is prudent to independently test the accuracy of DEMs used in inundation modeling.

Quality of the RTK GPS Data

The high accuracy of the elevations measured with RTK GPS was an important asset for this project. The GPS field surveys allowed us to collect accurate elevations of sentinel sites that were hidden from LIDAR signals and sensors (NOAA CSC, 2010b). For example, we surveyed elevations of groundwater monitoring wells located in forests with heavy canopy cover. Furthermore, because these elevations were measured with great accuracy using the RTK GPS (RMSE values of 0.6–8.7 cm), inundation probabilities could be calculated with greater certainty. The application of RTK GPS is a promising solution to elevation uncertainty issues in sea level rise inundation risk assessments. It is important to note, however, that RTK GPS protocols require operating a GPS base station at a location that has been surveyed to within a few millimeters. For this reason, a network of accurate geodetic control sites within 5 km is a requirement for RTK GPS measurement at sentinel sites (Murdukhayeva 2012).

The use of high accuracy RTK GPS data helped minimize the error in estimating inundation risk. Because the error associated with each sentinel site elevation was low, there...
was less uncertainty associated with each modeled scenario. Many of the sentinel sites had probabilities of inundation of either 0 (very unlikely) or 1 (very likely) when the RTK GPS elevation values for the sentinel sites were used. Murdukhayeva et al. (2012) found that this was not the case with probabilities of inundation calculated using elevations at sentinel sites based on LIDAR data, rather than the more accurate RTK GPS; many probabilities of inundation were in the range of 0.25 to 0.75 (rather than 0 or 1). Using higher-accuracy elevation data for sentinel sites resulted in greater certainty regarding the likelihood of inundation.

**Habitat-Change Modeling**

The SLAMM maps with aggregated land-cover classes can provide useful information for assessing habitat transition under various sea level rise scenarios. In presenting the SLAMM output in maps, however, it is important to recognize the uncertainty of habitat predictions because of uncertainty in input elevation and land cover. The SLAMM model is constrained by the quality of the data driving it (e.g., LIDAR-derived DEMs). It was not possible to integrate high-accuracy RTK GPS elevations into the model to enhance the results.
Another important baseline data set for the SLAMM model is initial land-use classification. In this study, initial land-use conditions were obtained, in part, from National Wetlands Inventory maps created using aerial photography from 1988 (ASIS) and 1993 (CACO). Those maps did not reflect changes during the past two decades. Furthermore, there is no way to quantitatively determine the uncertainty associated with a SLAMM prediction. These factors and others limit the utility of the output results (Kirwan and Guntenspergen, 2009; Scarborough, 2009), particularly for park managers developing mitigation strategies. Higher-resolution elevation data and current land use data sets are becoming more widely available and should address these deficits.

For the risk assessment, we were first interested in predicting changes from land to open water (i.e. inundation). The SLAMM results indicated that CACO had one site (1-m scenario) and three sites (2-m scenario) convert to open water, whereas, at ASIS, four sites (1-m scenario) and 12 sites (2-m scenario) are predicted to convert to open water. The bathtub model predicts greater amounts of inundation (Table 6). At CACO, three (1-m scenario) and 11 sites (2-m scenario) have probabilities of inundation >75%, and at ASIS, 11 (1-m scenario) and 32 (2-m scenario) sites have probabilities of inundation >75%. This difference in results supports the argument for bathtub models over estimate inundation (McLeod et al., 2010; NOAA, 2010), but it may also indicate that SLAMM underestimated inundation. An important finding of our study was that the use of multiple methods provided us a robust range of inundation possibilities across plausible sea level scenarios.

Inundation Modeling

Bathtub modeling is a relatively straightforward technique that can be used with off-the-shelf geospatial data, but the resulting inundation surfaces can be inaccurate (McLeod et al., 2010; Poulter and Halpin, 2008). Typically, that inaccuracy derives from subtle land barriers that are not discerned in the DEM and can impede inland water flow. Similarly, structures that permit water flow under the topographic surface, such as culverts below roads, can contribute to error in modeled inundation surfaces. Future human modifications of the landscape as adaptation measures to sea level rise are not included in simple bathtub models nor are changes to coastal geophysical processes because of sea level rise, for example breaching of barrier beaches that would significantly change tidal dynamics of lagoon systems behind the barrier (Anthony et al., 2009). By using high-quality LIDAR data for our DEMs and by excluding pixels that were not connected to the coast, our bathtub model results can serve as a preliminary assessment of potential inundation regions in these study areas.

One of the most valuable products of this assessment is the range of storm surge heights modeled by SLOSH (Table 4). Those surge heights can be used for predictions of hurricane impacts in the near future. For example, the SLOSH model predicted extensive inundation in Provincetown, Massachusetts, and the salt marsh sites in Cape Cod, Massachusetts. The potential damage to a sentinel-site resource under conditions of storm surge inundation varies depending on the nature of the site. Buildings or historical artifacts could face extensive damage, whereas certain habitats or hard infrastructure (roads, geodetic monuments) might not be damaged at all during a brief period of inundation. Therefore, it is important that the NPS evaluate risk for each site and develop mitigation plans accordingly.

Implications for Sentinel Sites

For the most part, Cape Cod’s sentinel sites were located inland, on relatively high elevations; 39 of the 63 sentinel sites (62%) had elevations >5 m above the MHHW, and, as a result, many sites are not at risk from sea level rise or storm surge inundation. For example, the base of Highland Lighthouse (Truro, Massachusetts) is located at 39.34 m NAVD88 or 38.41 m above MHHW (Figure 8). Although we understand that inundation modeling does not identify those sites >5 m above the MHHW as at risk, they could face other impacts of changing coastal patterns (erosion, etc.). Several sites that were found to be at risk are very close to current tide levels. For example, one sentinel site at CACO, a culvert near Wellfleet Harbor, was almost submerged at high tide on our survey trip (Figure 8). One polynvinyl chloride (PVC) survey marker in Pleasant Bay and National Geodetic Survey (NGS) monuments at the Provincetown airport are at risk as well. These findings agree closely with the results of the Hammar-Klose et al. (2003) Coastal Vulnerability Index assessment. In their study, 1.5-km segments of shoreline were ranked as being of low to high vulnerability, using an index that combined geological and physical variables. The high-vulnerability sentinel sites, as ranked by the composite Inundation Index we derived from the PCA, tend to appear immediately inland of those shoreline segments with a high CVI vulnerability rank.

At Assateague Island, all of the sentinel sites were at low elevations <2.6 m. Many of them are at risk from sea level rise and storm surge from large hurricanes. The CVI assessment and spatial pattern of the overall Inundation Index at ASIS correspond with each other (Pendleton, Williams, and Thieler, 2004). Disagreement occurs at points near the Chincoteague Inlet, Virginia. The CVI rated that shoreline as low vulnerability because of high accretion rates, and the Inundation Index rated sentinel sites in that area as high vulnerability because of the low elevations.

It is inappropriate to compare the frequency of inundation at sentinel sites between the national parks in our study because resource managers at CACO and ASIS chose very different kinds of sites to serve as sentinel sites. The CACO sites consisted of a variety of historical and natural resources, as well as important infrastructure. The ASIS sentinel sites were monumented reference locations at low elevations. If the CACO resource managers had, like those at ASIS, selected only sentinel sites used to monitor sea level rise then those two sets of sentinel sites would have had more comparable landscape placement, and the frequency of inundation could have been quite similar despite the very different geomorphology of the two parks.

Conclusions and Directions for Future Work

This study assessed inundation risk at 97 sentinel sites located in two northeastern U.S. coastal national parks. Rigorous revalidation of the LIDAR-derived data inputs was
essential to making appropriate use of the models. The methodology we used can be applied at other coastal parks and can be repeated at the same parks with improved data, alternate scenarios, or additional sentinel sites. We used three different modeling approaches because we were interested in inundation and habitat changes under various sea level rise scenarios as well as inundation from storm surges. Each model provided unique information that served our management needs. Depending on the resource issues and management needs of other coastal sites, all three models may or may not be required.

Our choice of models was driven by the goal to make our methods transportable to other coastal settings and implementable using off-the-shelf data. Accurate elevation data, such as that provided by LiDAR technology, are an essential requisite for inundation modeling. These analyses could not be performed with coarse data, such as the NED. All the models suffer from the naive assumption that coastal geomorphology does not change as sea level rises or storm surge overwashes inland features. As coastal barrier/lagoon systems breach or dune systems wash away, inundation dynamics will change, and those changes are not accounted for in the models we have chosen.

Models of sea level rise and storm surge are continually being refined, and inundation probabilities can be recomputed as new models are developed. Scenarios for sea level rise are evolving as new data from satellite altimetry and ice-melt studies are acquired. The U.S. National Weather Service updates SLOSH’s storm-surge predictions for regional basins following large hurricane events. The LiDAR data are being acquired for large regions of the United States coast to evaluate sea level rise and storm-surge risk. For example, the USGS recently completed

Figure 8. (Top) Sentinel site with low relative likelihood of inundation. Highland Lighthouse in North Truro, Massachusetts. (Bottom) Low-lying sentinel site at Cape Cod National Seashore. A culvert near a bike path in Wellfleet, Massachusetts. (Color for this figure is available in the online version of this paper.)
an extensive LIDAR acquisition for coastal counties of the northeast United States. The use of RTK GPS technology to collect accurate elevations at sentinel sites is a promising undertaking that will improve predictions of inundation risk based on different possible scenarios and models. The growing network of stable, permanent, and accurate geodetic control sites to form a backbone of base station locations makes it possible to greatly expand the areas where rapid collection of high-resolution elevation data with RTK GPS are possible (Murdubkhayeva et al., 2012).

POSTSCRIPT

We visited 11 sentinel sites at ASIS immediately following Hurricane Sandy to determine the accuracy of our inundation modeling. Peak surge was 29 October 2012 at 1730. The Ocean City, Maryland, tide gauge (1.5 km from the closest sentinel site) recorded a surge elevation of 1.4 m NAVD88. We inspected each sentinel site for signs of inundation, such as sand scouring and evidence of wrack. Seven sites were at elevations above 1.4 m, and of those, five (71%) were not inundated. The two that did flood were very close to the surge elevation (1.5 m and 1.7 m). No sentinel sites above 1.9 m were inundated. Four sites were below the surge elevation, and of these, three (75%) were flooded. The site that did not flood was within a meter or two (horizontally) of the wrack line. The mean (±SE) PC1 inundation index score for flooded sentinel sites was 0.59 ± 0.48 (n = 5), and the mean (±SE) PC1 score for sites that did not flood was 2.97 ± 0.94 (n = 6). The flooded sites had a significantly lower inundation index (i.e. higher risk of inundation) than did nonflooded sites (Wilcoxon two-sample test, V = 26, p = 0.025).

ACKNOWLEDGMENTS

This research was supported by NPS Task Agreement J4531090800—Assessing Inundation Risk From Sea Level Rise and Storm Surge in Coastal National Parks Using High Accuracy Geodetic Control—administered by the North Atlantic Coast Cooperative Ecosystem Studies Unit at the University of Rhode Island Coastal Institute. We gratefully acknowledge the technical and logistic support we received from the Northeast Coastal and Barrier Network of the NPS Inventory and Monitoring Program. The project has benefited from the contributions and ideas of Tim Smith, Rob Thieler, Donald Cahoon, Kelly Knee (Applied Science Associates), Neil Winn, Marc Albert, Mark Adams, Charles Roman, YQ Wang, Chris Damon, Roland Duhaime, Sarah Stevens, Dennis Skidds, Galen Scott, Tiffany-Lane Davis, Heather Grybas, Doug Marcy, and many others. The thoughtful comments by three anonymous reviewers significantly improved the clarity of the paper.

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