Using High Accuracy Geodesy to Assess Risk from Climate Change in Coastal National Parks

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Abstract

The projected effects of global climate change threaten habitats, infrastructure and resources. In coastal ecosystems, sea level rise and an increase in storm frequency and intensity are two major impacts expected to result from climate change. In the northeastern United States, many coastal national parks are vulnerable to these impacts. To plan future land use and management activities, park managers require information about potential climate change-induced threats to coastal resources. Currently, inundation risk assessments are limited by the accuracy of the best available elevation data. We address this limitation by using geodetic-grade GPS technology to obtain accurate elevation data for "sentinel sites," areas of important natural, cultural, and infrastructural resources in the national parks. We assess the inundation risk to the parks' sentinel sites from coastal climate change impacts using global and local sea level rise predictions and modeled storm surge elevations.

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Introduction

An increase in the rate of sea level rise is one of the most serious potential impacts of climate change (IPCC 2007). Globally, sea level rise has accelerated since the nineteenth century due to the expansion of warmer waters and melting glaciers. Around the world, sea level rise has not been uniform due to regional factors such as land subsidence and isostatic rebound (upward movement of land after being pressed down, e.g., when a glacier melts). In the Northeast, as much as 2.4 mm/yr of additional sea level rise is due to land subsidence (Kirshen et al. 2007). The Fourth Assessment of the Intergovernmental Panel on Climate Change projected 0.26 to 0.59 m of sea level rise by 2100 under the "business as usual" greenhouse gas emissions scenario (IPCC 2007). This represents a conservative estimate because it does not consider sea level rise caused by rapid increases in the melting of Greenland and Antarctic ice (Overpeck and Weiss 2009). A less conservative approach is the semi-empirical method proposed by Rahmstorf (2007) which links global sea-level variations to global mean temperature, on time scales of decades to centuries. Using the semi-empirical method to model sea level under the same IPCC "business as usual" scenario, Vermeer and Rahmstorf (2009) projected a global sea level rise of 1.13 to 1.79 m by 2100.

Another coastal impact to expect from climate change is an increase in the extent and frequency of severe coastal storms and flooding. Using an ensemble mean of 18 global climate models, the frequency of Saffir-Simpson Category 4 and 5 hurricanes is expected to double by the end of the twenty-first century (Bender et al. 2010). During intense storms, surge is produced when water is forced onto the shore by strong winds moving cyclonically around the storm. Storm surge can cause extreme flooding in coastal areas, especially when it coincides with a high tide. During Hurricane Katrina, surge levels reached 9 m (Fritz et al. 2007) and caused significant damage to the coastal infrastructure and ecosystems on the Louisiana and Mississippi coasts. In the coming century, storm surge will be exacerbated by sea level rise.

Coastal national parks in the northeastern United States are extremely vulnerable to sea level rise and storm events. They feature many low-lying areas susceptible to flooding. For example, every park in our study area, except two (Cape Cod National Seashore and Acadia National Park), are located entirely below the 15 m (NAVD88) contour interval (Figure 1). The purpose of our analysis is to determine inundation risk of park assets (ecological, cultural, infrastructure) from sea level rise and storm-induced flooding. To help focus the study, park managers have identified "sentinel sites," or locations of importance near the coast, where assessing risk is extremely important. Sentinel sites include natural resources (e.g., species of concern habitats), cultural resources (e.g., archaeological sites), and infrastructure (e.g., visitor centers). We are using the best available elevation data, and sea level rise and storm surge models to estimate the probability of inundation from sea level rise and storm surge at sentinel sites in coastal national parks in the northeast region of the United States.

Digital elevation data

In order to initially evaluate resources at risk in coastal areas, we created detailed maps to determine which areas fall within elevations that would be inundated under various risk scenarios from sea level rise and storm surge. We found however, that the elevation data available for coastal parks are not accurate enough to conduct map-based assessments where critical elevations for inundation fall within the range of vertical accuracy of the digital elevation model (Figure 2). The United States Geological Survey (USGS) National Elevation Dataset for the entire country is accurate to within 2.4 m (Gesch 2009). A more recent source of elevation data is from LiDAR (light detection and ranging) acquired from a plane-mounted laser sensor that emits pulses of light energy at the ground, and is accurate to 0.15 to 1 m (Gao 2007).

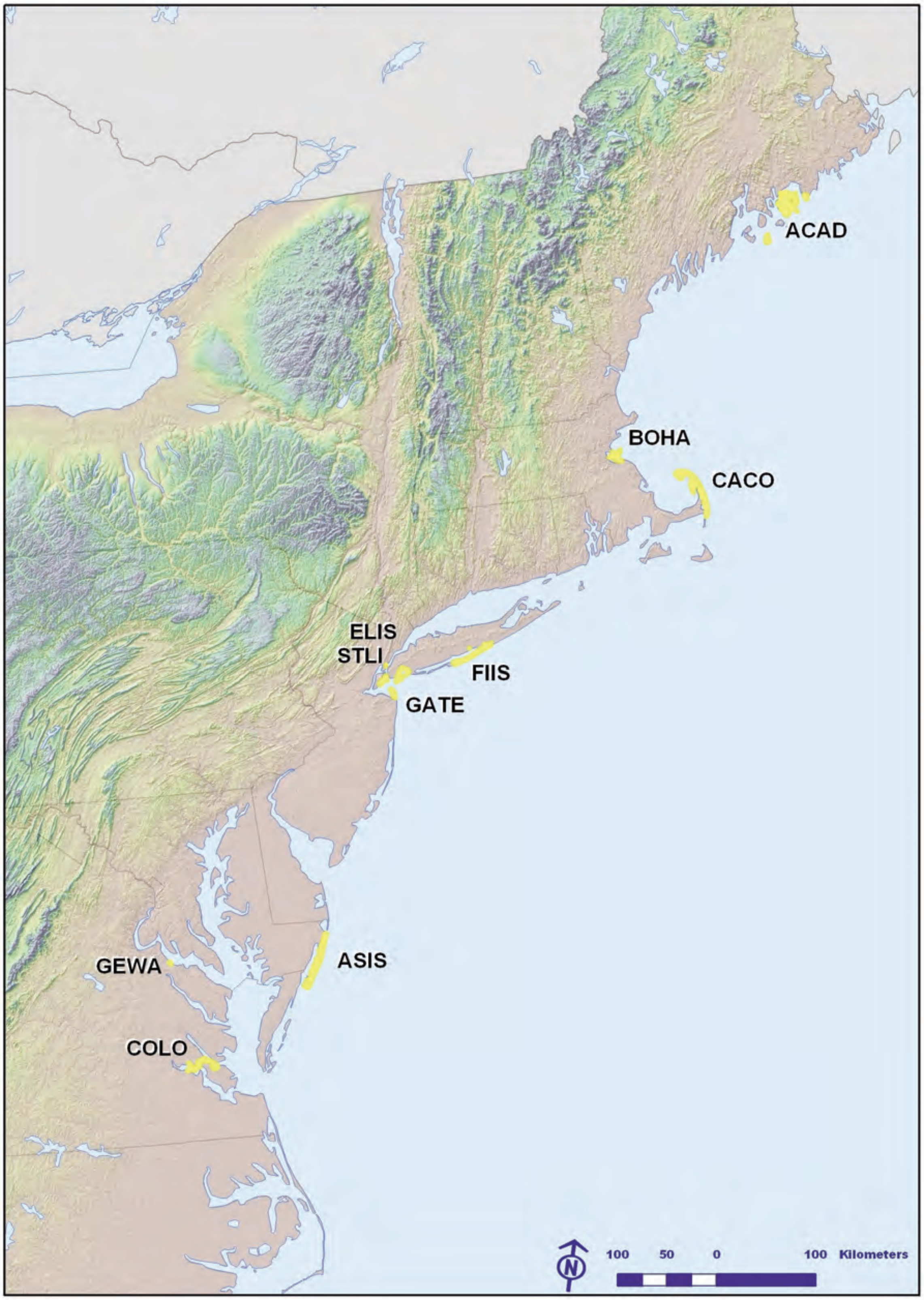


Figure 1. Study area. Acadia National Park in Maine, Boston Harbor Islands National Recreational Area in Massachusetts, Cape Cod National Seashore in Massachusetts, Ellis Island and Statue of Liberty National Monument in New York and New Jersey, Fire Island National Seashore in New York, Gateway National Recreational Area in New York and New Jersey, Assateague Island National Seashore in Maryland and Virginia, George Washington Birthplace National Monument in Virginia, and Colonial National Historical Park in Virginia.

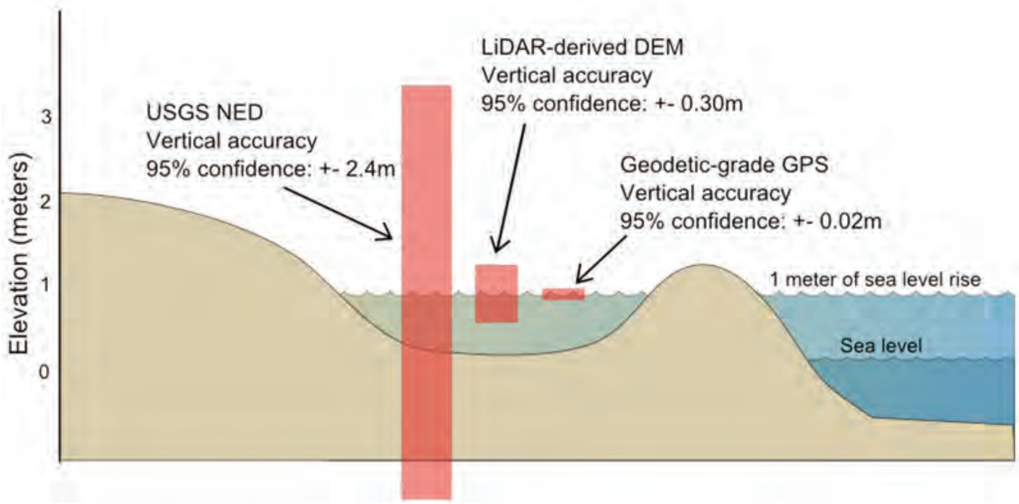


Figure 2. Mapping one meter of sea level rise on land. Digital elevation models with different vertical accuracies result in inundation zones with different ranges of uncertainty (adapted from Gesch 2009).

The most up-to-date elevation data for the coastal parks in the Northeast consists of LiDAR data, which are managed by the National Park Service Inventory and Monitoring Program. At present, there are LiDAR elevation data for every park in our study area, except Acadia. However, the coverage of these data is sometimes incomplete or in need of updating (Skidds 2011).

Given the inconsistencies and irregularities of park elevation data, an accurate measure of risk from sea level rise and storm surge inundation is problematic. Survey (geodetic) grade GPS devices are a promising tool in studying sea level rise and storm surge impacts. These devices are capable of measuring elevation at accuracies of up to 1 to 2 cm vertically, and have the ability to quickly calculate a reference position with highly accurate x, y, and z (longitude, latitude, and elevation) positional information (Trimble Engineering and Construction Group). When sea level rise and storm surge assessments are conducted using a network of many known, highly accurate reference positions (a geodetic control network), the ambiguity arising from error in the elevation data is reduced.

Geodetic control network

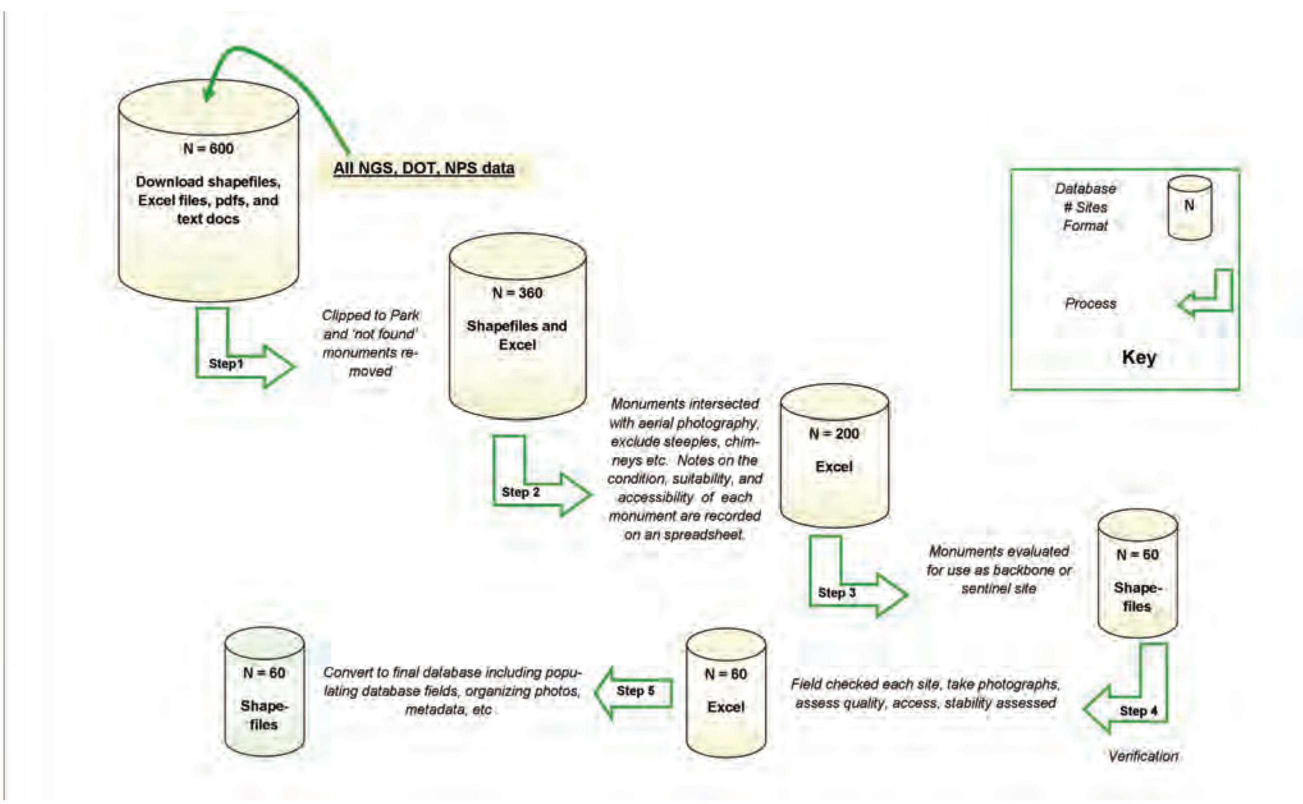
The coastal parks of the northeastern United States of America have had geodetic control monuments established inside the parks by various federal and state agencies. By "geodetic control monuments," we mean locations that are permanently marked with a brass disk, metal rod, cement or stone platform, or other permanent structure for which an accurate survey of location and elevation has been conducted (Smith 2007). Many of the monuments in national parks have been established by the National Oceanic and Atmospheric Administration's National Geodetic Survey (NGS). Additional geodetic control monuments have been added to the parks by the National Park Service (NPS) Denver Service Center for various projects over the decades. state department of transportation (DOT) offices have also been active in establishing geodetic control in and around coastal parks. Unfortunately, there is not a single database that identifies all geodetic control monuments in parks, and their current condition.

The initial phase of our project focused on taking an inventory of monumented geodetic control points in the parks. This included an extensive data mining exercise to download all readily available data from the NGS, NPS, and DOT offices. To be useful for our analysis, a control point must be accessible to park personnel and researchers (e.g., not on private property), be clearly marked and physically stable (e.g., marked with a steel rod driven to depth, or a brass disk mounted in bedrock), and accessible so GPS equipment can be used at the site. Inaccessible sites such as church steeples or water tanks were not used. Each potential control point's key information (e.g., date surveyed, location, monument ID, description of the site, navigation instructions) was encoded into a database and visited in the field. For each control point that we located, we photographed the site, ensured that the monument was intact and not damaged, prepared explicit descriptions of the monument, and developed instructions for navigating to the site. Any control point that was not found or which appeared to have been damaged or disturbed was so noted and indicated in the database. All of these points will be included in database of geodetic control monuments for each park (Figure 3).

Existing monuments that are highly stable and have long-term viability are eligible to be used as backbone monuments for a park. Backbone monuments are the network of monuments spaced at 10 km intervals that provide coverage of all coastal areas in a Park. The 10 km spacing among backbone sites represents the effective area for using geodetic-grade GPS systems that require an active GPS base station (Figure 4) established at a known location (backbone site), and a rover GPS that is used to measure elevations at sentinel sites. Using the database of existing monuments in the parks, as well as the spatial distribution of sentinel sites, we conducted a gap analysis to determine locations where existing monuments can be used, and where new backbone monuments must be installed. These backbone monuments will be surveyed following NGS protocols for benchmark establishment using survey (geodetic) grade GPS technology.

NPS managers provided us locations of sentinel sites near the coast where assessing inundation risk is critical. Currently, we are measuring elevations of sentinel sites using survey (geodetic) grade GPS equipment. It is imperative that sentinel sites be fully documented and monumented so they can be revisited in the future. Depending on the sentinel site, nearby geodetic control might suffice for recording accurate measurements of position and elevation for the location.

Figure 3. Monumented geodetic control evaluation process for Cape Cod National Seashore.



Where sites consist of hard infrastructure (buildings, roads), positions and elevations can be obtained from fixed features (building foundations, utility platforms). When sentinel sites do not have stable, permanent reference features to work from (e.g., shorebird nesting sites, salt marsh edges), we will install stable monumentation that will allow revisiting the location in the future.

Figure 4. Field site showing geodetic-grade GPS base station. (Photo credit: Cheryl Hapke, USGS).

Inundation risk assessment

To assess vulnerability from severe storms, we use the NOAA Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model, a forecast model for hurricane-induced water levels (NOAA 2007). We obtained predicted elevations of storm surge for Saffir-Simpson Category 1 to 4 hurricanes in each northeastern U.S. storm basin. The SLOSH model predicts maximum potential storm surge elevation based on hurricane category, forward speed, landfall direction and landfall location for various locations around the USA. The maximum surge within each grid cell is defined as the maximum of the maximum envelope of water (MOMs) and represents the worst-case, localized surge that will occur for landfall in a given location. The results are location-specific, accounting for local water depths, proximity to bays and rivers, etc., and are accurate to within 20% of the calculated value (NOAA 2007).

For each park, we will compare the elevations from a LiDAR-derived digital elevation model to SLOSH surge elevations to create a generalized inundation risk map. The resulting map will show areas of the park which have a high likelihood of inundation. To supplement this, we will also compare the land elevations at sentinel sites (obtained from GPS) to the predicted surge elevations to give us a more accurate assessment of the vulnerability of sentinel sites during each storm event. Using these two methods we can make an informed assessment of probability of inundation risk at each site.

To assess vulnerability from accelerated sea level rise in coastal national parks, we use the Sea Level Affecting Marshes Model (SLAMM). The model simulates the dominant processes involved in wetland conversions and shoreline modifications during sea level rise (Clough et al. 2010). We will use the most recent LiDAR data and National Wetlands Inventory data as baseline inputs. We use historic relative sea level rise and projected eustatic sea level rise (i.e., global changes from changes in ocean, or net ocean basin, volume) rates to simulate processes that affect wetland fate during long-term sea level rise. The resulting maps show expected wetland conversions in each park. These results are used to assess risk to sentinel sites. For example, if a plover nesting beach is predicted to be converted to open water under a certain sea level rise scenario, then we assess that the habitat is at risk.

Storm surge and sea level rise models will be based on local tidal datums. To be conservative, we are using surge and sea level rises relative to mean higher high water (MHHW). MHHW is the average of the higher high water height of each tidal day observed over a national tidal datum epoch (i.e., 19-year measurement period adopted by the National Ocean Service, Hicks 1999). Standardizing surge and sea level heights relative to MHHW provides us the maximum extent of flooding during normal high tides.

Conclusion

Modern sea level rise and storm surge models give us the ability to identify coastal areas at risk in the coming century. They allow national park managers to develop proactive adaptation and mitigation strategies. However, we must be aware that the delineated inundation zones predicted by these models are limited by the vertical accuracy of elevation data. The use of geodetic grade GPS technology is extremely valuable for assessing risk to national park resources from sea level rise and storm surge. The technology gives us the most accurate point elevation data for the parks' sentinel sites. These elevation data can also be used as inputs for storm surge risk assessments, and serve as reference points for accuracy assessments of digital elevation models. By including the point elevation data in a National Park Sentinel Site Database, they are available for future use as baseline data for monitoring and vulnerability assessment efforts. As the field of sea level and storm surge modeling matures, more sophisticated methods of predicting inundation will certainly be developed. As models become refined, the accurate elevations at sentinel sites will always permit better assessment of risk inundation.

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