Nat Hazards (2012) 60:727–745
DOI 10.1007/s11069-011-0046-8

ORIGINAL PAPER

Assessing future risk: quantifying the effects of sea level rise on storm surge risk for the southern shores of Long Island, New York

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Received: 2 June 2011 / Accepted: 8 November 2011 / Published online: 4 December 2011

Abstract Sea level rise threatens to increase the impacts of future storms and hurricanes on coastal communities. However, many coastal hazard mitigation plans do not consider sea level rise when assessing storm surge risk. Here we apply a GIS-based approach to quantify potential changes in storm surge risk due to sea level rise on Long Island, New York. We demonstrate a method for combining hazard exposure and community vulnerability to spatially characterize risk for both present and future sea level conditions using commonly available national data sets. Our results show that sea level rise will likely increase risk in many coastal areas and will potentially create risk where it was not before. We find that even modest and probable sea level rise (.5 m by 2080) vastly increases the numbers of people (47% increase) and property loss (73% increase) impacted by storm surge. In addition, the resulting maps of hazard exposure and community vulnerability provide a clear and useful example of the visual representation of the spatial distribution of the components of risk that can be helpful for developing targeted hazard mitigation and climate change adaptation strategies. Our results suggest that coastal agencies tasked with managing storm surge risk must consider the effects of sea level rise if they are to ensure safe and sustainable coastal communities in the future.

Keywords Storm surge · Risk · Social vulnerability · Sea level rise

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1 Introduction

Coastal areas face multiple storm-related hazards including floods, storm surge, and erosion. Densely populated coastal areas are particularly vulnerable to these hazards as increasing coastal development has positioned large numbers of people and infrastructure in close proximity to the coast. While planning and mitigation for these hazards is an ongoing and continuous process, significant challenges lie ahead for managers tasked with planning for the potential impacts of climate change on the magnitude and frequency of coastal hazards. Sea level rise is the most significant impact of climate change in coastal areas (Nicholls et al. 2007) and is a particularly important factor to include when assessing future hazard risk. Scientists estimate that thermal expansion of sea water due to ocean warming along with water mass input from melting ice will lead to an increase in global sea levels between .3 and 1.8 m by 2100 (Rahmstorf 2007; Vermeer and Rahmstorf 2009; Grinsted et al. 2010; Nicholls and Cazenave 2010). Additionally, the globally averaged intensity of tropical cyclones is projected to shift toward stronger storms, with intensity increases of 2–11% by 2100 (Knutson et al. 2010). These predicted changes threaten to exacerbate storm surge risk by increasing the inland penetration of storm surge.

Despite evidence suggesting that coastal areas are highly susceptible to even small shifts in sea level caused by climate change (Nicholls et al. 2007), most state and local coastal hazard risk assessments in the United States evaluate only current hazard risk (e.g., Batten et al. 2008; Jelesnianski and Shaffer 1992; Mercado 1994) and do not take into account enhanced risks due to climate change (Frazier et al. 2010). This is partly a reflection of a lack of communication and integrated approaches between the disaster risk reduction and climate change communities (Thomalla et al. 2006), which challenges our ability to effectively minimize risk in coastal areas; this likely results from the two communities perceiving the nature and timescale of the hazard threat differently, with the disaster risk management community concentrating on fairly distinct shorter-term hazardous conditions and the climate change community focusing on hazards that are slowly increasing over the long term and more difficult to predict and measure (Thomalla et al. 2006).

Another challenge is the lack of a standardized approach and terminology employed in hazard risk assessments. Significant variation exists in the scope and process, and an array of definitions for risk and vulnerability can be found throughout the literature (e.g., Cutter et al. 2003; Adger 2006), making it difficult to compare risk levels between regions. For example, the terms “vulnerability assessment”, “hazard assessment,” and “risk assessment” have all been used to describe the physical exposure and/or social vulnerability of a particular place to hazards. In this study, we characterize vulnerability, hazard, and risk as follows: “vulnerability” is the susceptibility of both biophysical and social systems to a “hazard,” which is an event or occurrence that has the potential to cause harm to people and/or property. “Risk” is the likelihood or probability of such harm.

An evaluation of who and what are physically exposed to the hazard is often the first and only step in assessing risk. However, risk depends on both the level of exposure to the hazard and the vulnerability of the community. The physical exposure of a community to a hazard is a straightforward concept and can often be precisely measured. Measurements of hazard events commonly include the magnitude, spatial extent, and frequency. More sophisticated risk assessments also include some measurement of “community vulnerability,” which is usually harder to measure (Cutter et al. 2003). The major drivers of vulnerability (e.g., lack of access to informational and financial resources; physical condition or dependence of individuals; and type and condition of building stock and infrastructure) are often used to represent vulnerability (Adger 2006; Cutter et al. 2003). A clear example of the importance of accounting for social vulnerability to hazards is the Hurricane Katrina disaster, where pre-existing social vulnerabilities gave rise to disproportionate impacts (Cutter and Emrich 2006). Most residents with resources such as their own vehicle left before the hurricane made landfall. However, those without the resources necessary to do so stayed behind and many (mostly poor and elderly) were trapped in the floodwaters (Cutter and Emrich 2006).

If risk is defined as the outcome of the interaction between the *hazard* impact, the level of *exposure* of the elements at risk to the hazard, and the *vulnerability* of the elements at risk (Chrichton 1999; Granger 2003), one can assess risk by measuring the hazard, vulnerability, and exposure. Granger (2003) expressed this relationship as:

$$\text{Risk }(i) = \text{Hazard }(i) \times \text{Elements at Risk }(i) \times \text{Vulnerability}$$

where (i) is a particular hazard scenario

Understanding and characterizing both current and future risk are essential for mitigating coastal hazards and managing adaptation to climate change. There is a clear need for managers to have access to methodologies that can generate risk assessments that account for potential increases in hazards (for example, as a result of climate change), allow for easy visualization of the components of risk (hazard, exposure, and vulnerability), and provide a transparent method for identifying high-risk areas. To address this need, we developed a storm surge risk assessment approach that integrates and expands the functionality of readily available, low cost, or free, frequently used hazards analysis tools such as FEMA's HAZUS tool, USGS's dasymetric mapping tool, and builds upon NOAA's Community Vulnerability Assessment Tool (CVAT) methodology. Though others have documented the effects of sea level rise on storm surge (Wu et al. 2002; Kleinosky et al. 2007; Frazier et al. 2010), to our knowledge, no studies have integrated these typically separate, commonly used tools and approaches to provide a combined transferrable and transparent technique for quantifying both current and future storm surge risk.

The framework for our approach is based largely on Granger's conceptualization of risk (2003), yet we modify and expand Granger's methodology to allow for the incorporation of more widely available data sets that can be found in coastal communities throughout the United States and include future storm surge risk related to sea level rise. As an example of this approach, here we outline steps for measuring and mapping exposure, vulnerability, and overall risk from a category 3 storm surge in Suffolk County on Long Island, New York. From this initial evaluation, we examine how risk changes when a 2080 sea level projection is incorporated into the analysis. We finish with a discussion of how this approach can provide direction for hazard managers tasked with minimizing storm surge risk, despite predicted increases in risk associated with sea level rise.

2 Methods

The study area was delineated to encompass the southern shores of Suffolk County Long Island, NY, and their watershed drainage basins (Fig. 1). Suffolk County (6,146 km^2) is an excellent site to illustrate a risk assessment approach, as it is one of the most populous counties in the United States with large portions of the coastal zone highly developed. This area includes the towns of Babylon, Islip, Southampton, East Hampton, and most of Brookhaven. Much of this property is only slightly above sea level, which puts millions of dollars in public and private funds at great risk. Titus et al. (2009) estimated that under the

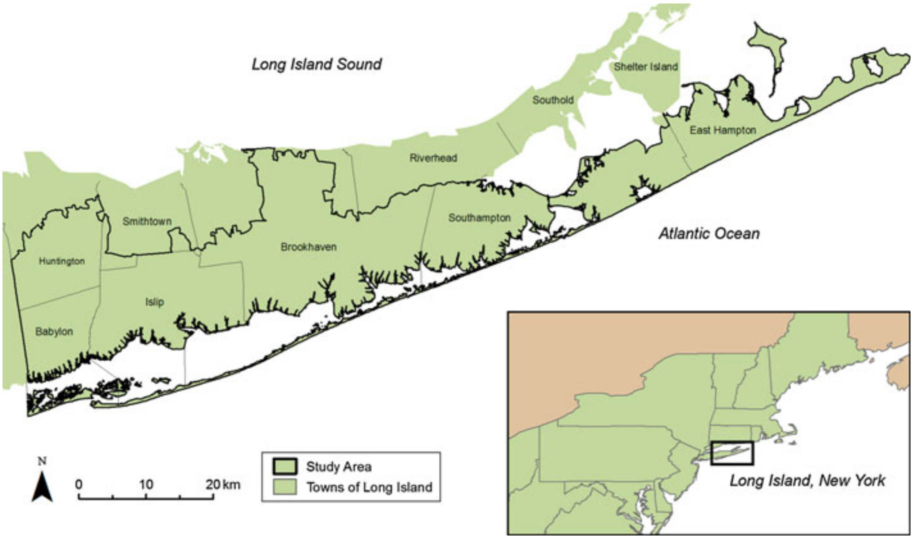

Fig. 1 Study area boundary encompassing the southern shores and drainage basins of Suffolk County, Long Island, New York

current "business as usual" development policies, close to 90% of the land below 1 m of elevation in New York (approximately 149 km^2) will become developed. Even moderate sea level rise will result in a significant increase in the likelihood of flooding. We focus on a category 3 Hurricane to illustrate our process for evaluating overall risk. In 1938, a category 3 hurricane known as "the Long Island Express" killed nearly 100 people and caused millions of dollars of damage (1938$) on Long Island (Longshore 2008; Pielke and Landsea 1998). Given the amount of development that has taken place since then (Jackson 1985), a similar powerful storm combined with higher predicted sea levels could result in a catastrophic natural disaster.

We evaluated overall risk from a category 3 hurricane at the census block group scale, the smallest geographic unit for which the census provides detailed demographic data, using an index based approach. We chose this scale as it would allow us to base our analysis on information in its least aggregated form. The overall risk index is a measure of relative risk for each block group in relation to all block groups within the study area. The overall risk index is the product of an exposure index and a community vulnerability index, each representing different social and infrastructure components (Fig. 2). To highlight the differences between present and future storm surge risk, we generated one overall risk index for storm surge and another for storm surge with projected 2080 sea level rise. Although, in reality, there will be demographic and infrastructure changes over the next 80 years, it was beyond the scope of this project to model future demographic characteristics or development. As in other studies (e.g., Frazier et al. 2010; Hallegatte et al. 2011; Zhang 2011), our approach uses the best available demographic and infrastructure data to quantify how future SLR will enhance present storm surge risk. To do this, we generate one community vulnerability index that was used to assess both current and future risk.

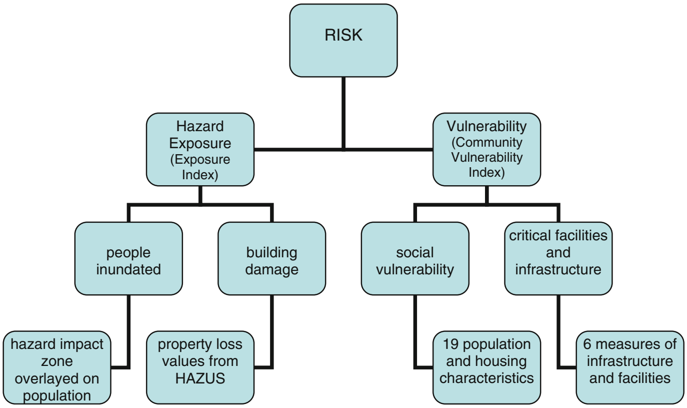

Fig. 2 Components of the Overall Risk Index

2.1 Measuring exposure

Exposure is represented by the *Hazard X Elements at Risk* portion of Granger's (2003) risk equation. We measured exposure by determining both the number of people affected by inundation and the property losses incurred per census block group for a given simulated storm surge inundation scenario. This method of measuring exposure departs from Granger's exposure assessment as he defined exposure based on the percentage of buildings inundated above floor level per census district. Because this requires a geospatial database of floor elevations, many communities will be unable to replicate Granger's risk assessment method due to the lack of a detailed building elevation database. Thus, we created an exposure index that ranks census block groups based upon human and economic exposure rather than building exposure.

The first step in measuring exposure is to delineate the hazard zone. Communities have flexibility in choosing which specific hazards to evaluate based on historically high impact hazards or future likelihoods of occurrence. Communities may also choose to evaluate a range of magnitudes for a given hazard, such as a range of hurricane categories. For our case study, we chose to evaluate the hazard zone for a category 3 hurricane storm surge and changes to the hazard zone and exposure resulting from a sea level projection for the year 2080.

2.1.1 Hazard zones—storm surge inundation with and without sea level rise

The category 3 hurricane storm surge impact zone was developed via the National Hurricane Center's Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model (Jelesnianski and Shaffer 1992). These data sets were provided to us by the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center (CSC) and were developed specifically for Long Island, New York, to evaluate storm surge inundation and flooding. SLOSH models determine inundation zones for storm surge via a series of hundreds of hypothetical hurricanes in each category with various forward wind speeds, landfall directions, and landfall locations (Jelesnianski and Shaffer 1992). At the end of each model run, an envelope of water is generated, reflecting the maximum surge height obtained by each grid cell for a given category of storm. The category 3 SLOSH output represents the potential surge inundation under current sea level conditions (see Fig. 3).

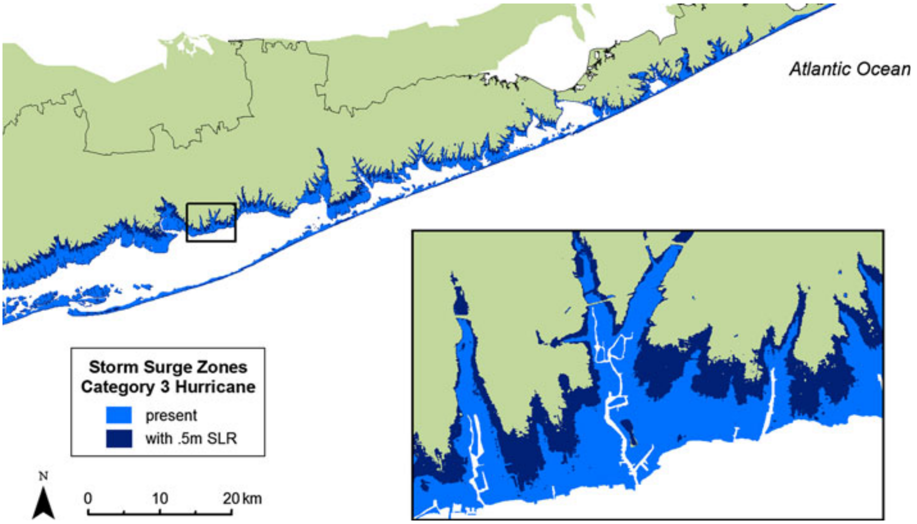

Fig. 3 Storm surge hazard zones. The .5-m SLR is based on the projection of the A2 emissions scenario for the year 2080

The second hazard zone, representing a category 3 hurricane storm surge under potential future sea level conditions, was generated by combining the category 3 SLOSH surge zone output with a SLR projection for the year 2080. The 2080 SLR projection used in this study was provided to the Nature Conservancy of Long Island by the Columbia University Center for Climate Systems Research (CCSR) for an ongoing study. The CCSR used the average of seven Global Circulation Models (GCMs) approved by the Intergovernmental Panel on Climate Change (IPCC). These same models were used in the New York City Panel on Climate Change (NPCC); the methodology is explained in NPCC, 2010, App. A. The projection used for our study is a ten-year average estimate centered on 2080 (NPCC 2009). Though many SLR estimates have been used in previous studies in the United States (see (Gesch et al. 2009) for review), the SLR scenario used in this study was selected to illustrate the risks posed by long-term sea level rise using the best available, locally relevant SLR estimate. The 2080 SLR projection was generated using the A2 IPCC emission scenario that assumes relatively rapid population growth and high and growing greenhouse emissions. The A2 scenario projected an increase in sea level of .5 m, which is at the lower end of the spectrum of recently published sea level projections (between .3 and 1.8 m by 2100) (Rahmstorf 2007; Vermeer and Rahmstorf 2009; Grinsted et al. 2010; Nicholls and Cazenave 2010; Nicholls et al. 2011).

The GCM data for the A2 scenario were refined for the New York region by CCSR. The GCM data were downscaled to include local variables such as historic tide data, land subsidence, and local differences in mean ocean density, circulation changes, and thermal expansion of sea water. We further tailored the 2080 SLR projection to our study area's digital elevation model (DEM) by calibrating the DEM's vertical datum to mean high tide using local tide gauge data. The lidar-based DEM used in this study has a vertical accuracy of 13 cm and horizontal grid resolution of 1.5 m (provided by Suffolk County). The calibrated sea level rise impact was mapped onto the DEM using a "bathtub fill" approach (Poulter and Halpin 2008). Although this SLR mapping approach has several documented limitations (Poulter and Halpin 2008; see Gesch 2009 for review), it was found to be a satisfactory approach for our study area, because our project focused on identifying low-lying areas most vulnerable to sea level rise rather than predicting where inundation might occur at the parcel scale. For parcel-specific inundation maps developed for local planning purposes, we are in agreement with others that the hydrological connectivity of the ocean to vulnerable lands should be considered (Gesch 2009). However, for our risk assessment at the block group scale, a bathtub fill model was deemed sufficient. The hazard zone for the category 3 storm surge plus the 2080 SLR projection of .5 m is also shown in Fig. 3.

2.1.2 *Elements at risk—people and property*

To accurately assess exposure of human populations, we first created a population distribution map at a finer resolution than the currently best available data set from the US Census Bureau. While the US Census Bureau collects household-level population counts, for reasons of anonymity, they aggregate household-level demographic data to larger enumeration units such as the census tract and block group scales. However, these boundaries rarely reflect the natural distribution of human populations within the aggregated geographic units (Sleeter 2008). For example, a census block group might have 500 people residing in it, but it is impossible to know where within these coarse units those 500 people reside. Dasymetric mapping techniques can more accurately reflect the distribution of residential populations by introducing ancillary information (i.e., residential land use data) and redistributing population based on varying densities of residential development within the enumeration unit (i.e., census units). The transfer of population data from the census units to residential land use classes is performed by areal interpolation (Mennis and Hultgren 2006). Following Sleeter (2008), we used the USGS dasymetric mapping tool to map residential population data from the census block scale to people per 10-m square grid cell via areal interpolation. Input data sets included the following :

- Suffolk County, NY parcel data (2008)
- NOAA landcover data (2005)
- US Census block data (2000)
- Transportation data (2000)

Parcel data were reclassified into high-, medium-, and low-density residential development based on the land use type and parcel size. Parcel classification was based on Suffolk County Planning Department zoning guidelines. Parcels greater than or equal to one acre were classified as low density; parcels less than 1 acre (.4 hectares) and greater than .2 acres (.08 hectares) were classified as medium density; and parcels less than or equal to .2 acres were classified as high density. Approximately 7% of Suffolk County's parcel database did not contain a land use attribute. We, therefore, used the 2005 landcover data set (NOAA-CSC 2005) to fill in missing land use attributes where possible within the parcel database. Parcels that intersected major roads or railroads were deleted, as these parcels would likely be labeled high-density residential development due to the high degree of impervious surface within each parcel, although these parcels would likely be classified as commercial or transportation, not residential. There are potentially cases where the parcels without attributes were misclassified through this process, but given that only 7% of the parcels in our study area had to be reclassified, any misclassification would have very little impact on the resulting population map. A zonal function was employed to calculate the composition of LULC within each parcel. Parcels that contained a majority of high-density development LULC were classified as high density; parcels comprised of medium-density development were classified as medium density and so forth.

Non-residential parcels were used as an exclusionary class in the dasymetric calculation (i.e., the exclusionary class prevents census block population data from being distributed to these parcels). We then used the USGS dasymetric mapping Extension to redistribute census block population to each residential parcel. The resulting map of human population distributions at the 10-m sq scale provides critical baseline information for assessing exposure. We determined how many people were affected for each scenario by overlaying each inundation scenario over the population distribution map and tallying the number of persons per block group that are located within the surge impact zone.

Estimated economic loss per census block was calculated using the Federal Emergency Management Agency's (FEMA) Hazus-MH Flood Model software. Hazus is a risk assessment tool that is used for estimating potential property losses from disasters and, in our case, flooding from storm surge and sea level rise. A Hazus Level 1 analysis estimates flood losses based on default data sets provided with the Hazus application software. Default data includes a General Building Stock inventory and demographic data aggregated at the census block level for the entire United States. The General Building Stock economic exposure data provide the building valuation for each Hazus occupancy classification (e.g., residential, commercial, industrial, government, etc.) developed from the 2000 US Census and 2002 data from Dun & Bradstreet. This data set was developed by applying RSMeans replacement values for typical building floor areas and construction for each specific occupancy. All processing and analysis for this research were accomplished using Hazus-MH MR5, Patch 1.

For this study, the economic flood losses are estimated by Hazus as part of Level 2 analysis scenario. For a Level 2 analysis, the Hazus flood model has the ability to incorporate improved flood hazard data sets and building inventory information. In our case, the default building inventory data was used along with modeled storm surge and sea level rise flood depths to arrive at estimated building damages per census block. Economic loss is the value of estimated building damage (replacement value) by census block based on different storm and sea level rise conditions. All scenarios assume estimated current (2006 $) replacement value or building values for all building occupancy types. The Hazus-generated building damage values were then aggregated from census blocks to block groups to match the mapping unit of the demographic and persons inundated per block group data sets.

2.1.3 Exposure index

For each inundation scenario, we created a composite exposure index based on both the number of persons inundated and the total economic loss per block group. First, we scaled the raw inundated population counts per block group and the raw building damage values per block group for the category 3 storm surge scenario to each range from 1 to 100. Next, we added the affected population and building damage values for each block group together and scaled the resulting exposure index to range from 1 to 100, with higher values indicating higher exposure. We repeated this process to create an exposure index for a category 3 storm surge with SLR.

2.2 Measuring community vulnerability

We measured community vulnerability as it relates to storm surge flooding by assessing characteristics of the population and the built environment, and generating a community vulnerability index (CVI) that reflects the relative contribution of each block group to overall community vulnerability (Granger 2003). Granger described the CVI, which can be easily mapped, as “the game board across which the hazard impacts are played.” Because the measured vulnerability characteristics do not depend upon the magnitude of the hazard in question, the *vulnerability* portion of the risk equation is independent of the hazard event.

To assess community vulnerability, we collected information relating to the demographic, housing, and infrastructure characteristics of the community based on year 2000 US Census SF3 block group data. Limited census data have been released to date from the 2010 US Census. As 2010 data reflecting the total suite of information used in this study have yet to be released, we used data from the 2000 census for this study. We created two indices, a social vulnerability index and a critical facilities and infrastructure index, to evaluate these two aspects of vulnerability separately. These two separate indices can help managers easily identify block groups that could benefit most from vulnerability reduction strategies focusing primarily on either social programs or the built environment. To characterize overall community vulnerability, we combined the two indices to create the community vulnerability index (CVI). The CVI is important for identifying block groups that are most vulnerable to coastal hazards impacts irrespective of the magnitude or extent of the hazard event. The steps for creating each index follow below.

2.2.1 Social vulnerability index

A suite of variables for measuring social vulnerability have been identified in the risk and vulnerability literature. We reviewed literature related to the Community Vulnerability Assessment Tool (Flax et al. 2002), the storm tide risk assessment for Cairns, Australia (Granger 2003), and the social vulnerability index for the United States (Cutter et al. 2003). From these, we identified 19 variables related to population and housing characteristics (Table 1) to characterize social vulnerability for use in this case study. We chose the following social variables related to population characteristics: population and population density, age, education, race, single-parent status, median income, poverty level, and public assistance status. For housing characteristics, we chose housing unit density, housing units without vehicles, rentals and seasonal units, new residents, and build date of residence. We retrieved data for these variables from the US Census SF3 data tables and mapped each variable at the census block group scale. For each variable, the block groups were ranked from most vulnerable to least vulnerable for inclusion in the social vulnerability index.

To generate the social vulnerability index, the ranks for each variable were added together to generate a total rank sum per block group. The values were then standardized by expressing each value as a percentage of the maximum total rank sum.

2.2.2 Critical infrastructure and facilities index

The critical infrastructure and facilities index ranks census block groups based on the amount of critical infrastructure and facilities located within each block group. Extensive infrastructure increases a block group’s vulnerability as communities within and adjacent to the block groups are likely highly dependent on the services provided by the infrastructure. Infrastructure and services related to transportation, communications and utilities, community facilities, and critical facilities were counted and measured for each block group (Table 2). These variables were used to rank each block group from most to least

Table 1 Social variables included in the social vulnerability index

Variable	Measure of variable per block group	Reason
Population	Ranked from most people to least people	Likely require extra considerations related to disaster preparations and evacuations
Population density	Ranked from highest population density to lowest population density	May need special planning for evacuations and transportation
Housing unit density	Ranked from highest housing unit density to lowest	Many housing units within a small area likely require additional evacuation support and shelter assistance
Age under 5	Percentage of population 5 years of age or younger	Dependent upon others in emergency situations and may require special assistance
Age over 65	Percentage of population 65 years of age or older	May be dependent upon others in emergency situations and may also require mobility assistance
No diploma	Percentage of population over age 25 lacking a high school diploma	May have limited access to preparation and recovery resources and may need face-to-face contact in lieu of print
Non-english-speaking	Percentage of population whose primary language is not English	May need assistance with information dissemination related to preparedness and evacuations
Non-white	The percentage of population who listed a race other than white	May be more vulnerable due to social and political marginalization in communities with racial disparities
Single female parent	Percentage of households run by a single female parent	May be more vulnerable because of childcare responsibilities and being the sole financial provider.
Without vehicle	The percentage of housing units without a vehicle	Occupied housing units without access to a vehicle may indicate mobility limitations during an evacuation
Median income	To assess wealth, we ranked BGs by median 1999 household income	Wealthy communities have more financial resources available for preparedness and recovery
Below poverty	Percentage of population living below the poverty line	May have limited or no access to financial resources for disaster planning and recovery
Public assistance	Percentage of block group households supported by public assistance	May require additional public disaster aid before, during, and after a disaster
Renter occupied units	Percentage of occupied housing units designated as rental units	Least likely to be insured, renters may have limited information about flood zones
Seasonal housing units	Percentage of housing units designated as seasonal	May be vacant or occupied by vacationers unfamiliar with evacuation routes and shelter locations
Length of residency	Percentage of population residing in home less than 5 years	Less likely to have experienced a disaster in current location and are less familiar with local resources
Housing unit year built	Ranked from oldest median build date to newest median build date	Older housing units typically are more vulnerable due to older, less-stringent building specifications

vulnerable. The critical infrastructure and facilities index was created by summing the block group ranks for each indicator and standardized by expressing them as a percentage of the maximum total rank sum.

Table 2 Infrastructure and facilities variables included in the critical infrastructure and facilities index

Variable	Measure of variable per block group	Reason
Transportation terminals	Ranked from greatest number of airports, bus, and train terminals to least	Vital both for transit within the community and as important connection points to the surrounding communities
Cable lifeline length	Total road length used as a surrogate for cable line, ranked from greatest to least	Utility lines are generally found near or adjacent to roads and block groups with most lifelines are likely most vulnerable
Road density	Ranked from lowest road density (road length per hectare) to greatest	Indicates the number of route options during an evacuation and low road density likely means fewer evacuation routes
Critical facilities	Ranked from greatest number of fire, police, medical facilities, etc. to least	Provide crucial services to communities and are important resources before, during, and after natural disasters
Community facilities	Ranked from greatest number of schools, government offices, etc. to least	Provide social and logistical support to communities and useful for information dissemination and supply distribution
Utility facilities	Ranked from greatest number of gas, power, water, etc. facilities to least	Utility facilities support the gas, electricity, and water supply systems that communities depend upon.

2.2.3 *Overall community vulnerability index*

The overall community vulnerability index (CVI) represents the combined vulnerability of the people, property, and resources within a community. To create the CVI, we combined the social vulnerability index and the critical facilities and infrastructure index. We added the two indices together and scaled the values to 1–100, with higher values indicating the most vulnerable block groups.

2.3 Bringing exposure and vulnerability together: measuring risk

While the individual exposure and vulnerability indices are helpful for understanding the community context of a natural hazard event, an integrated index that measures overall risk of storm surge inundation is essential for guiding preparation and mitigation. To create the overall risk index, we multiplied each hazard scenario's exposure index with the community vulnerability index and scaled the resulting values from 1 to 100.

3 Results

3.1 Hazard exposure

A projected sea level rise of .5 m increases inundation extent, the number of persons affected, and projected property losses versus present-day storm surge impacts (Table 3). A 33% increase in total area inundated results in disproportionate increases in persons affected (47% increase) and property losses (73% increase). The exposure index values are divided into quartiles with the top 25% of values indicating those areas with the greatest amounts of people inundated and greatest building damage losses. To compare the results of the future exposure index incorporating SLR, we applied the quartile cut-offs from the

Table 3 Comparison of hazard zones and exposure for entire study area

Exposure measure	Storm surge	Storm surge and SLR
Inundated block groups	214	263
Total area inundated (ha)	18,399	24,174
Total persons affected	88,885	130,718
Total property losses ($1000)	4,299,336	7,424,455

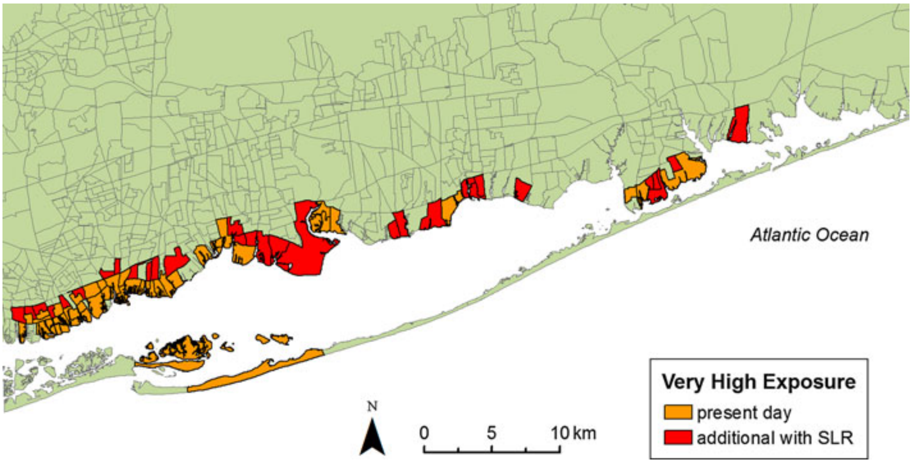

Fig. 4 High-exposure block groups identified through the exposure index. Very high exposure areas are those block groups with the greatest amounts of people inundated and greatest building damage losses

present-day scenario to the new exposure index. This allows easy identification of changes in exposure attributable to climate change (Wu et al. 2002). Figure 4 shows the block groups identified as very high exposure and those block groups that in the future will be very high exposure. For both hazard scenarios, all very high exposure areas are located in the westernmost portion of the study area where population densities are highest and the majority of buildings are located.

3.2 Community vulnerability

The community vulnerability index (CVI) ranged from 1 to 100 with a median score of 54. We divided the CVI values into quartiles and identified those blocks groups in the top 25% of CVI vales as “Very High” vulnerability areas. The spatial distribution of the CVI is shown in Fig. 5. The majority of the most vulnerable block groups are located in the western portion of the study area. Many of the block groups in this area have high percentages of socially vulnerable populations along with high housing unit densities.

3.3 Overall risk

The spatial representation of overall risk for category 3 storm surge (present day) is shown in Fig. 6 (top). The overall risk index values are divided into quartiles with the top 25% of values indicating those areas most at risk. Similar to the exposure index, we applied the

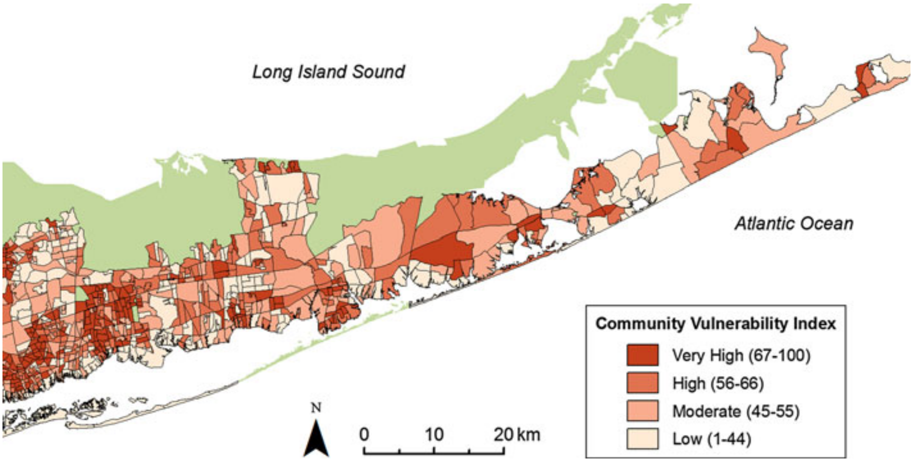

Fig. 5 Community vulnerability index (CVI) for the southern shores of Suffolk County, Long Island. The CVI helps identify block groups that are most vulnerable to coastal hazards impacts due to social vulnerability and infrastructure circumstances

quartile cut-offs from the present-day scenario to allow easy identification of changes in the future risk index attributable to climate change (Wu et al. 2002). The spatial distribution of overall risk is also shown in Fig. 6 (bottom). Figure 6 shows that overall risk will increase with a sea level rise of .5 m and that the majority of very high-risk areas are located in the western portion of the study area for both the present and future scenarios.

To highlight the differences between present day and future risk, we mapped the changes in risk at the block group scale (Fig. 7). Nearly 30% of the areas identified experienced an increase in risk as a result of sea level rise with 9,572 hectares identified as “newly at risk”. These “newly at risk” areas are presently not at risk from a category 3 storm surge, but will be at risk in the year 2080. Figure 8 complements the risk change map by summarizing changes in exposure and risk associated with sea level rise for each of the affected towns located within our study area. The exposure of people and properties generally decreases by town from west to east for both the present-day and future scenarios. Changes in high-risk areas do not follow the west to east pattern with both Islip and Southampton experiencing considerable increases in very high-risk areas. Southampton, which under present conditions has no very high-risk areas, will have 1362 hectares of land classified as very high risk with a .5 m SLR.

4 Discussion

In this study, we demonstrate how to effectively integrate commonly used tools and approaches used by separate management communities to provide a combined transferrable and transparent technique for quantifying risk from storm surge and SLR. Our results demonstrate that sea level rise will likely increase future risk; these risks can and should be incorporated into these types of assessments. This study highlights the importance of increased collaboration within the disaster risk reduction and climate change adaptation research and planning communities, as it demonstrates the power of bringing together information that is usually evaluated separately by each of these communities. Although

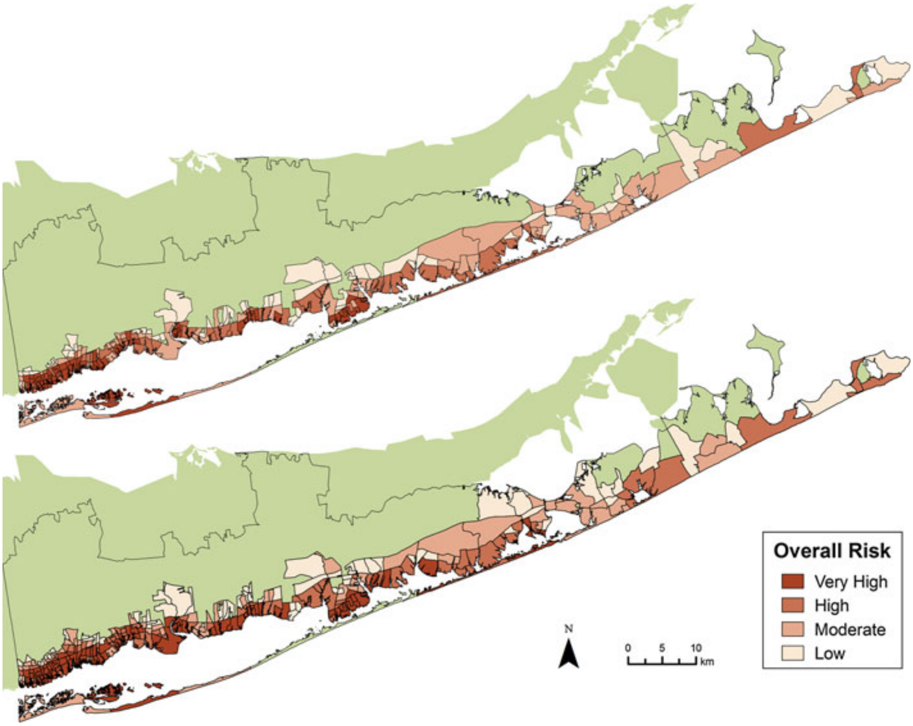

Fig. 6 Overall risk from category 3 storm surge in Southern Suffolk County, New York (*top*: present; *bottom*: with .5 m SLR) The .5-m SLR is based on the projection of the A2 emissions scenario for the year 2080

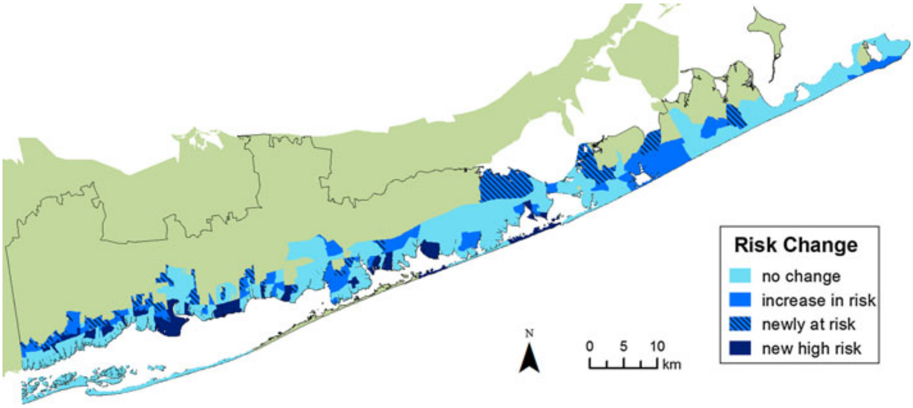

Fig. 7 Changes in storm surge risk with a .5-m rise in sea level. The .5-m SLR is based on the projection of the A2 emissions scenario for the year 2080

the natural disaster and climate change communities have some intersecting objectives, many of their differences in approach are related to differences in perceptions of the magnitude and timescale of hazards (Thomalla et al. 2006). Disasters caused by extreme coastal

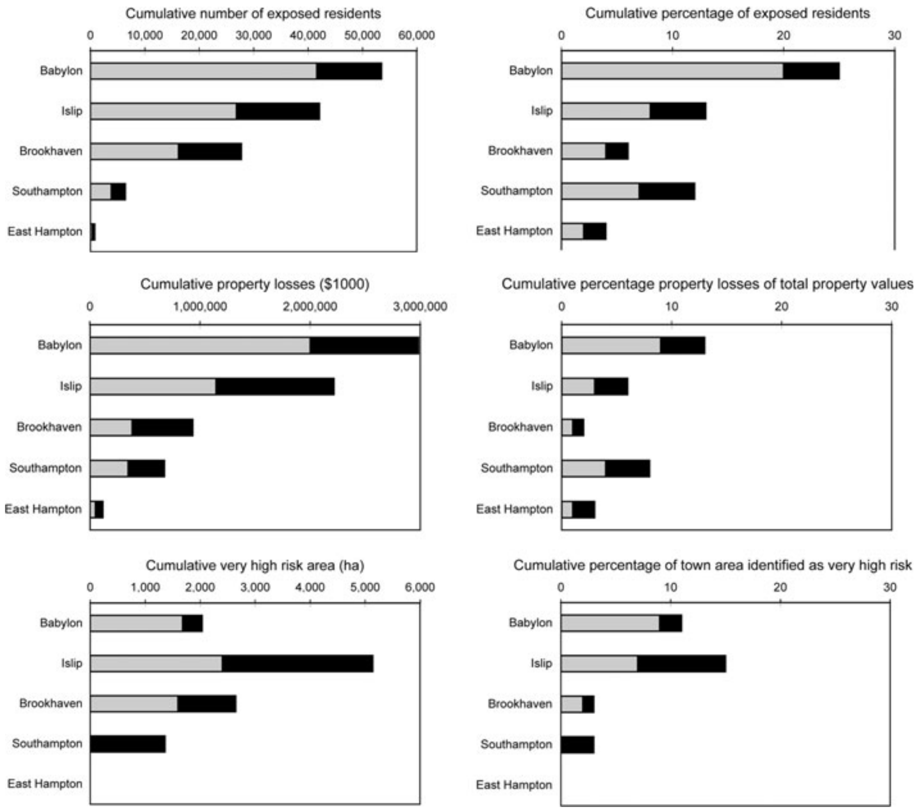

Fig. 8 The effects of sea level rise on storm surge impacts by town, listed from west to east. Cumulative amount and percentage of exposed residents, property losses, and very high-risk areas for a category 3 hurricane storm surge (*gray*) and additional impacts with a .5-m sea level rise (*black*). The .5-m SLR is based on the projection of the A2 emissions scenario for the year 2080

hazards typically take place in a distinct time frame with impacts that are easy to detect, while the impacts of climate change occur slowly over timescales that are often difficult to perceive (Thomalla et al. 2006). However, as our study has demonstrated over time these "slow moving" climate change impacts can considerably increase the magnitude of a hazard event and cause a number of people and structures to be newly at risk in the future.

Designing systems that help planners and stakeholders integrate and access the type of information we generated in this study should be a priority. The Coastal Resilience project (www.coastalresilience.org) provides an example of how this can be done effectively. The Coastal Resilience project, spearheaded by multiple non-profits and governmental agencies, developed an interactive web mapping application to allow users to explore flooding scenarios resulting from sea level rise and storm surge for the south shore of Long Island, the resulting impacts on people and natural resources, and potential planning and regulatory strategies for local governments that are beginning to consider the effects of climate change.

In developing the risk assessment presented in this paper, our aim was to develop a transferrable methodology for assessing overall risk to communities from storm surge and sea level rise using commonly available data sets that local governments can use to better understand the risks they face now and in the future. This methodology integrates and expands the functionality of readily available, low cost, or free, frequently used hazards analysis tools such as FEMA's HAZUS tool, USGS's dasymetric mapping tool, and builds upon NOAA's Community Vulnerability Assessment Tool (CVAT) methodology. Although we have demonstrated our approach in a coastal community with extensive and detailed spatial information, we believe this approach can also be scaled down for coastal communities without existing spatial information. For example, if data and models to generate flooding extent are lacking, an exposure index could be created to reflect the distribution of only people or dwellings within a defined hazard zone. If hazard zones have not been delineated for an area, historic or anecdotal mapping could be used to generate a rough outline of hazard extent. A range of buffer zones could be added to the hazard zones to account for various sea level rise scenarios. If census and infrastructure data are lacking, community vulnerability could be assessed by surveying structure types or developing data sets characterizing one or two key demographic indicators of social vulnerability. Regardless of amount of available information, the important concept to strive to retain is that the components of risk (Fig. 2) should be considered both separately and in combination to best determine how to reduce the impacts of coastal hazards and climate change. Which hazards and indicators are used to create the indices is dependent upon community objectives and data availability. Accordingly, there is a significant amount of flexibility for adapting this risk assessment method to a particular community's needs, access to information, and technical capacity. Just as we adapted methods developed for other geographies (e.g., the Granger method for Australia) to suit our local needs and access to information, similar modifications could be made elsewhere. Involving stakeholders that reflect the varied social, environmental, and political interests of a community is paramount to this process (Berke and Campanella 2006) and is considered to be a critical element in vulnerability assessments and adaptation planning (Cronin et al. 2004; Moser 2005; Frazier et al. 2010) Though much can be understood through scientific literature and technical experts, a community's design, priorities, and limitations need to be gauged by interacting with individuals from within the community (Frazier et al. 2010).

Although this risk assessment does demonstrate increased storm surge risk from sea level rise, our study is only part of an emerging body of literature related to hazards and climate change. Further studies are needed to fully characterize uncertainty related to climate change impacts on hazard frequencies and magnitudes. Our goal was to emphasize the importance of assessing future risk; therefore, we chose to consider only one (category 3 hurricane) storm surge to allow for a straightforward comparison of hazard zones with and without sea level rise. However, counties or states undertaking a comprehensive hazard assessment should include multiple storm intensities when evaluating overall risk (Frazier et al. 2010; Wu et al. 2002; Kleinosky et al. 2007). Risk assessment would also benefit from research projecting future population and development growth in coastal areas subject to sea level rise. Because we were unable to model future demographic characteristics and development, the amount of people and property newly at risk in the future are likely underestimated. This lack of reliable population projections for the future was a significant limitation on our capacity to characterize the number of people exposed to increased risk. Finally, our risk assessment did not take into consideration the effects of increased storm surge on coastal ecosystems and the consequential impacts to human populations (e.g., reductions in available ecosystem services such as water quality regulation). Future work should evaluate increases in human exposure and vulnerability attributable to loss of coastal ecosystems and the vital benefits they provide, such as fisheries production and coastal protection.

5 Conclusion

The Long Island case study shows that sea level rise will likely increase risk in many coastal areas and potentially create risk where it was not likely before. In addition, our results show that an increase in inundated area can result in amplified impacts in terms of people affected and overall costs. Comparable case studies along the US east coast have reported similar increases in flooding risk due to sea level rise (Wu et al. 2002; Kleinosky et al. 2007; Frazier et al. 2010).

To date, most coastal hazard mitigation plans do not consider sea level rise, including the most recent hazard mitigation plan covering our study area published by Suffolk County (2009). Though planners at the local, state, and federal levels are starting to see the value of land use planning as a tool for risk reduction (Burby 2006), the inclusion of climate change scenarios, such as sea level rise, in these planning efforts is in its infancy (Frazier et al. 2010). Among the reasons for not including sea level rise projections is the notion that the risks and impacts of sea level rise will be minor relative to the impacts of storms. However, our results show that even modest and probable sea level rise increases impacts of storms both in terms of people affected and property losses. It is also important to note that these considerations do not include the reasonable likelihood that the severity of storms could increase, further increasing risk. Our results suggest that coastal agencies tasked with managing storm surge risk must consider the effects of climate change if they are to ensure safe and sustainable coastal communities in the future. It is our hope that the approach we outline here will help coastal managers effectively and transparently incorporate the effects of sea level rise in their planning efforts.

Acknowledgments We thank Columbia University Center for Climate Systems Research (CCSR) for the provision of data sets. This work was supported by the David and Lucile Packard Foundation and The Nature Conservancy.

References

Adger WN (2006) Vulnerability. Glob Environ Change 16(3):268–281. doi:10.1016/j.gloenvcha.2006.02.006

Batten BK, Weberg P, Mampara, Xu L (2008) Evaluation of sea level rise for FEMA Flood Insurance Studies: magnitude and time-frames of relevance. American society of civil engineers conference proceedings. doi:10.1061/40968(312)6

Berke PR, Campanella TJ (2006) Planning for post disaster resiliency. Annal Am Acad 604:192–207

Burby RJ (2006) Hurricane Katrina and the paradoxes of government disaster policy: bringing about wise governmental decisions for hazardous areas. Annal Am Acad 60:171–191

Chrichton D (1999) The risk triangle. In: Ingleton J (ed) Natural disaster management. Tudor Rose, London, pp 102–103

Cronin S, Petterson M, Taylor P, Biliki R (2004) Maximising multi-stakeholder participation in government and community volcanic hazard management programs; a case study from Savo, Solomon Islands. Nat Hazard 33(1):105–136. doi:10.1023/b:nhaz.0000035021.09838.27

Cutter SL, Emrich CT (2006) Moral hazard, social catastrophe: the changing face of vulnerability along the hurricane coasts. Annal Am Acad Polit Soc Sci 604:102–112 (Shelter from the storm: repairing the national emergency management system after Hurricane Katrina)

Cutter SL, Boruff BJ, Shirley WL (2003) Social vulnerability to environmental hazards. Soc Sci Quart 84(2):242–261. doi:10.1111/1540-6237.8402002

Flax LK, Jackson RW, Stein DN (2002) Community vulnerability assessment tool methodology. Nat Hazard Rev 3(4):163–176. doi:10.1061/(asce)1527-6988(2002)3:4(163)

Frazier TG, Wood N, Yarnal B, Bauer DH (2010) Influence of potential sea level rise on societal vulnerability to hurricane storm-surge hazards, Sarasota County, Florida. Appl Geogr (In Press, Corrected Proof). doi:10.1016/j.apgeog.2010.05.005

Gesch DB (2009) Analysis of lidar elevation data for improved identification and delineation of lands vulnerable to sea-level rise. J Coast Res 49–58. doi:10.2112/SI53-006.1

Gesch DB, Gutierrez BT, Gill SK (2009) Coastal elevations. In: Titus JG, Anderson KE, Cahoon DR et al (eds) Coastal sensitivity to sea-level rise: a focus on the mid-atlantic region. A report by the U.S. climate change science program and the subcommittee on global change research. U.S. Environmental Protection Agency, Washington, pp 25–42

Granger K (2003) Quantifying storm tide risk in cairns. Nat Hazard 30(2):165–185. doi:10.1023/a:1026166300914

Grinsted A, Moore J, Jevrejeva S (2010) Reconstructing sea level from paleo and projected temperatures 200–2100 Clim Dynam 34(4):461–472. doi:10.1007/s00382-008-0507-2

Hallegatte S, Ranger N, Mestre O, Dumas P, Corfee-Morlot J, Herweijer C, Wood R (2011) Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen. Clim Change 104(1):113–137. doi:10.1007/s10584-010-9978-3

Jackson KT (1985) Crabgrass frontier: the suburbanization of the United States. Oxford University Press, Oxford

Jelesnianski CP, Shaffer JWA (1992) SLOSH (sea, lake, and overland surges from Hurricanes). NOAA Technical Report, National Weather Service, p 48

Kleinosky L, Yarnal B, Fisher A (2007) Vulnerability of Hampton Roads, Virginia to storm-surge flooding and sea-level rise. Nat Hazards 40(1):43–70. doi:10.1007/s11069-006-0004-z

Knutson TR, McBride JL, Chan J, Emanuel K, Holland G, Landsea C, Held I, Kossin JP, Srivastava AK, Sugi M (2010) Tropical cyclones and climate change. Nat Geosci 3(3):157–163. http://www.nature.com/ngeo/journal/v3/n3/suppinfo/ngeo779_S1.html

Longshore D (2008) Encyclopedia of hurricanes, typhoons, and cyclones. Infobase Publishing, New York

Mennis J, Hultgren T (2006) Intelligent dasymetric mapping and its application to areal interpolation. Cartogr Geogr Inf Sci 33(3):179

Mercado A (1994) On the use of NOAA's storm surge model, SLOSH, in managing coastal hazards—the experience in Puerto Rico. Nat Hazard 10(3):235–246. doi:10.1007/bf00596144

Moser SC (2005) Impact assessments and policy responses to sea-level raise in three US states: an exploration of human-dimension uncertainties. Glob Environ Change Part A 15(4):353–369. doi:10.1016/j.gloenvcha.2005.08.002

Nicholls RJ, Cazenave A (2010) Sea-level rise and its impact on coastal zones. Science 328(5985):1517–1520. doi:10.1126/science.1185782

Nicholls RJ, Wong PP, Burkett V, Codignotto J, Hay J, McLean R, Ragoonaden S, Woodroffe CD, Abuodha PAO, Arblaster J, Brown B, Forbes D, Hall J, Kovats S, Lowe J, McInnes K, Moser S, Rupp-Armstrong S, Saito Y (2007) Coastal systems and low-lying areas. In: Parry OFC ML, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 315–356

Nicholls RJ, Marinova N, Lowe JA, Brown S, Vellinga P, de Gusmão D, Hinkel J, Tol RSJ (2011) Sea-level rise and its possible impacts given a 'beyond 4°C world' in the twenty-first century. Philos Trans R Soc A Math Phys Eng Sci 369(1934):161–181. doi:10.1098/rsta.2010.0291

NPCC (2009) Climate risk information. New York City Panel on Climate Change, New York

Pielke RA, Landsea CW (1998) Normalized Hurricane damages in the United States: 1925–1995. Weather Forecast 13(3):621–631. doi:10.1175/1520-0434(1998)013<0621:nhditu>2.0.co;2

Poulter B, Halpin PN (2008) Raster modelling of coastal flooding from sea-level rise. Int J Geogr Inf Sci 22(2):167–182. doi:10.1080/13658810701371858

Rahmstorf S (2007) A semi-empirical approach to projecting future sea-level rise. Science 315(5810):368–370. doi:10.1126/science.1135456

Sleeter R (2008) A new method for mapping population distribution. U.S.G.S., U.S. Geological Survey Fact Sheet 2008–3010, p 2

Thomalla F, Downing T, Spanger-Siegfried E, Han G, Rockström J (2006) Reducing hazard vulnerability: towards a common approach between disaster risk reduction and climate adaptation. Disasters 30(1):39–48. doi:10.1111/j.1467-9523.2006.00305.x

Titus JG, Hudgens DE, Trescott DL, Craghan M, Nuckols WH, Hershner CH, Kassakian JM, Linn CJ, Merritt PG, McCue TM, O'Connell JF, Tanski J, Wang J (2009) State and local governments plan for development of most land vulnerable to rising sea level along the US Atlantic coast. Environ Res Lett 4(4):044008

Vermeer M, Rahmstorf S (2009) Global sea level linked to global temperature. Proc Natl Acad Sci 106(51):21527–21532. doi:10.1073/pnas.0907765106

Wu SY, Yarnal B, Fisher A (2002) Vulnerability of coastal communities to sealevel rise: a case study of Cape May County, New Jersey, USA. Clim Res 22(3):255

Zhang K (2011) Analysis of non-linear inundation from sea-level rise using LIDAR data: a case study for South Florida. Clim Change 106(4):537–565. doi:10.1007/s10584-010-9987-2