**New Jersey Coastal Flood Exposure Assessment**

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## Goals and Objectives

Through land use planning, development and coastal management decisions, local decision-makers play a key role in influencing the resilience of coastal communities to climate-change related sea level rise and storm surge. As both the exposure to hazards and the underlying system vulnerability are spatially varying, any adaptation response will also be a locally varying decision-making challenge. Faced with a variety of conflicting mandates and uncertainty as to the appropriate responses, local land use planners and managers are increasingly relying upon place-based decision support system tools that outline a range of geographically targeted management options. A necessary first step is a better understanding of the scope of potential hazards and the exposure of key infrastructure and vulnerable populations to inundation, whether due to sea level rise alone or to the combined effects of storm-related flooding. To help inform coastal resiliency planning in the state of New Jersey, we undertook an assessment of coastal areas most exposed to coastal flooding, storm surge and sea level rise.

In assessing the risks posed by sea level rise in combination with storm-related flooding, we have adopted the following general framework:

Flooding Risk = Hazard x Exposure x Vulnerability

1$^{st}$ step: Model hazards → 2$^{nd}$ step: Map resulting exposure →3$^{rd}$ step: Assess vulnerability

Thus as part of our ongoing work to promote enhanced resiliency for New Jersey's coastal zone, we have been separately characterizing hazard vs. exposure vs. vulnerability for various systems. The objective for this report is a mapping of coastal flooding exposure (Step 2 above) and a limited assessment of the vulnerability of human population and built infrastructure (Step 3 above). We caution that due to limitations in the spatial detail and accuracy of the underlying data, the modelling and mapping employed in this assessment is intended for use as a screening/planning tool and not for site-specific decisions. Additionally, our intent is to use this assessment to inform ongoing discussions in New Jersey with regard to coastal resiliency and we welcome opportunities to enhance and revise these methods based on input from coastal resilience experts and practitioners.

## Methods

Through consultation with a panel of coastal hazard experts[1], we identified criteria for a New Jersey coastal flooding exposure assessment protocol and ranking scheme. The New Jersey assessment protocol shares some similarities to that adopted by New York Department of State, in consultation with the NOAA Coastal Services Center (CSC) (NYS Department of State, 2013). The assessment distinguishes at least three classes of geographic areas based on variation in exposure to coastal hazards: Moderate, High and Extreme exposure (Table 1). The logic was such that areas exposed to flooding on a more frequent basis were given a higher ranking. Thus the ranking incorporates the probability or likelihood of the area being flooded. For example, even though a Category 3 storm surge has higher flooding elevations, the likelihood of occurrence is lower than a Category 1 storm surge and therefore the Category 3 flood area was given a lower exposure ranking. Extreme exposure areas are those that are exposed to relatively frequent flooding. In addition, the Extreme exposure areas also include those areas subject to the most powerful wave impacts. Both current and future exposure are considered, the latter through incorporation of projected sea level rise at 2050 and 2100.

Before Hurricane Sandy, Federal Emergency Management Agency (FEMA) had begun a coastal flood study to update Flood Insurance Rate Maps (FIRMs) and Flood Insurance Study (FIS) reports for portions of New York and New Jersey using improved methods and data to better reflect coastal flood risk. The resulting Special Flood Hazard Area (SFHA) maps are used to document coastal flooding exposure and were released first as Advisory Base Flood Elevation (ABFE) maps and then later superseded by Preliminary FIRM (P-FIRMS) work maps. The P-FIRM work maps are subject to a public comment period after which final maps are adopted by FEMA as Digital Firms or D-FIRMS. The SFHA or the area on the D-FIRMS depicting the 1% chance

[1] The technical expert panel consisted of Douglass Marcy and William Brooks of the NOAA Coastal Services Center; Mark Mauriello, former Commissioner of the New Jersey Department of Environmental Protection, currently Director of Environmental Affairs and Planning, Edgewood Properties; Dr. Norbert Psuty, Rutgers University; Dr. Karl Nordstrom, Rutgers University; Dr. Danielle Kreeger and Sari Rothrock, Partnership for the Delaware Estuary; Martha Maxwell-Doyle, Barnegat Bay Partnership; Dr. Tracy Quirk, Drexel University; and, Steve Jandoli, New Jersey Department of Environmental Protection.

flood zone, is the area where the National Flood Insurance Program's (NFIP's) floodplain management regulations must be enforced and the area where the mandatory purchase of flood insurance applies. Until the P-FIRM work maps become D-FIRMs, they are considered "the best available information" by FEMA, and thus, were used in this assessment.

For this assessment, we extracted the 1% base flood zone (i.e., a one percent chance of being equaled or exceeded in any given year). This is the regulatory standard also referred to as the "100-year flood" (mapped as A Zone). We ranked the 1% base flood (A Zone) as High Exposure. V Zones represent areas along the coast subject to inundation by the 1% with additional hazards associated with storm-induced waves. Due to the additional hazards posed by high energy waves, we ranked V zones as Extreme Exposure. The 0.2% (or 500-year flood, mapped as X Zone) were included as lower probability flooding events and therefore ranked as a Moderate Exposure. The P-FIRMs were downloaded from the FEMA website (http://fema.maps.arcgis.com/home) for the following counties: Atlantic, Bergen, Burlington, Camden, Cape May, Cumberland, Essex, Gloucester, Hudson, Middlesex, Monmouth, Ocean, and Salem Counties. Where P-FIRMS were unavailable (i.e. Union County), Advisory Base Flood Elevation (ABFE) maps were used.

Storm surge results from severe storms such as hurricanes and nor'easter whose strong winds, combined with low pressure drive water onshore (NOAA NWS 2013). The **S**ea, **L**ake and **O**verland **S**urges from **H**urricanes (SLOSH) model is a computerized numerical model developed by the National Weather Service (NWS) to estimate storm surge heights resulting from historical, hypothetical, or predicted hurricanes (NOAA NWS, 1992). The SLOSH model is applied to a specific locale's shoreline, incorporating the unique bay and river configurations, water depths, bridges, roads, levees and other physical features. A composite approach that predicts surge by running SLOSH several thousand times with hypothetical hurricanes under different storm conditions is recommended for this application. More specifically, a Maximum of the Maximum (MOMs) is regarded by National Hurricane Center as the best approach for determining storm surge vulnerability for an area since it takes into account forecast uncertainty. The MOMs provides a worst cast snapshot for a particular storm category under "perfect" storm conditions. It is highly unlikely that a single hurricane will produce the regional flooding depicted in the MOMs. Instead, the product is intended to capture the worst case high water value at a particular location for hurricane evacuation planning. The US Army Corps of Engineers (USACE) provided Rutgers CRSSA with a seamless coverage of SLOSH MOMs model outputs for New Jersey. The New Jersey study area includes three SLOSH model basins: New York, Atlantic City and Delaware Bay. SLOSH MOM outputs were generated for Category 1, 2, 3 and 4 hurricanes/storms at Mean Higher High Water (datum NAVD88).

Shallow coastal flooding (SCF) represents land areas along the coast that are periodically flooded by higher than average high tide (i.e. spring or 'king' tides) and worsened by heavy rainfall and onshore winds (i.e., wind blowing landward from the ocean). NOAA mapped areas inundated by shallow coastal flooding on a regular basis over the past 3 years. This data set was provided by NOAA CSC to Rutgers CRSSA for use in this project.

To inform an assessment of coastal vulnerability and future flooding exposure of New Jersey's coastal zone, a panel of sea level rise (SLR) experts was convened to assist in developing "best available" values for Year 2050 and 2100 sea level rise scenarios. Two independent analyses formed the basis for the subsequent development of a series 'consensus' SLR values: 1) Doug Marcy of NOAA's Coastal Services Center provided NJ-specific estimates based on NOAA Global Scenarios (Parris et al., 2012) and the NOAA/USACE SLR Calculator; and, 2) Drs. Ken Miller and Robert Kopp provided NJ-specific estimates based on their research (Miller et al., 2013) (Appendix A). Our 'Present Day' baseline year is 2000. For the years 2050 and 2100, the range in SLR estimates was synthesized to develop low, high and higher scenarios. Further information on the Consensus SLR estimates is provided in Appendix A.

As a 'first-cut' approximation of scope of potential future flooding exposure, the SFHA, SLOSH and SCF base flood elevations were projected to account for future sea level rise using standard NOAA Coastal Services Center (CSC) protocols (D. Marcy and W. Brooks, personal communication). The baseline digital elevation model (DEM) was developed from the most recent LiDAR-derived elevation data (depending on location collected between 2006 and 2010; tidally corrected to NAVD88 datum using V-DATUM software) and provided by the NOAA CSC. Due to the specialized modeling needed to derive the SFHA V Zones, these could not be projected to account for future sea level rise; the Present Day V Zones were used 'as is' for the 2050 and 2100 scenarios. Due to the absence of base flood elevation data (i.e. no Preliminary work or ABFE maps were available at the time of the analysis) for the counties of Gloucester, Camden and the Delaware River portion of Burlington County, this area was not projected for future sea level rise and thus excluded from the 2050 and 2100 assessment.

The CFE mapped inputs were adjusted based on the following logic. Using a precautionary principle of wanting to factor in a high margin of protection, a High SLR estimate was used to 'adjust' the FEMA SFHA and the SLOSH mapping. Based on Kopp et al. (2014), there is only an 8-10% chance that sea level rise will exceed 2.0 ft by 2050 and 5 ft by 2100. The SCF maps were adjusted in the following fashion with the SLR scenarios that have a higher likelihood of being exceeded being ranked as a higher risk. Accordingly, as the Low SLR depth estimate has an 80-85% chance of being exceeded, the SCF + Low SLR category was given an Extreme exposure risk ranking. While at the other extreme, the Higher SLR depth estimate has a < 1% chance of being exceeded and therefore the SCF + the Higher SLR category given a Moderate exposure risk ranking.

Table 1. New Jersey Coastal Flooding Exposure Assessment Protocol

| Flooding Hazard | Present | 2050 | 2100 |
|---|---|---|---|
| FEMA Special Flood Hazard Areas (SFHA) | Extreme: V zone<br>High: 1% A zone<br>Moderate: 0.2% (X) zone | Extreme: V zone<br>High: 1% A zone + 2’<br>Moderate: 0.2% (X) zone + 2’ | Extreme: V zone<br>High: 1% A zone + 5’<br>Moderate: 0.2% (X) zone + 5’ |
| SLOSH Storm Surge | Extreme: N/A<br>High: SLOSH Cat 1<br>Moderate: SLOSH Cat 3 | Extreme: N/A<br>High: SLOSH Cat 1 + 2’<br>Moderate: SLOSH Cat 3 + 2’ | Extreme: N/A<br>High: SLOSH Cat 1 + 5’<br>Moderate: SLOSH Cat 3 + 5’ |
| NOAA/NWS Shallow coastal flooding (SCF) | Extreme: SCF<br>High: N/A<br>Moderate: N/A | Extreme: SCF + 1’<br>High: SCF + 2’<br>Moderate: SCF + 2.5’ | Extreme: SCF + 2.5’<br>High: SCF + 5’<br>Moderate: SCF + 7’ |

The three flooding hazard maps were gridded using a cell resolution of 10 meters and then composited using a Maximum option (i.e., the highest category ranking for the three inputs was output for each grid cell). For example, at a selected grid cell if SFHA = High, SLOSH = High and SCF = Extreme, the output cell value = Extreme. The resulting composite flood exposure maps were cross-tabulated with several other geographic information system (GIS) data sets (Table 2) to characterize the human population and built infrastructure potentially exposed to coastal flooding. The facilities and infrastructure GIS data produced by FEMA HAZUS-MH and the New Jersey Office of Information Technology (NJOIT) were quality controlled by project staff at CRSSA. However, for FEMA themes where NJOIT state-produced data exist, the NJOIT data have been used, due to higher resolution content and spatial accuracy. The New Jersey Department of Transportation and the North Jersey Transportation Planning Authority provided GIS data on other critical infrastructure, including: causeways, evacuation routes and all roadways by road type. The human population and socio-demographic data were derived from 2010 U.S. Census data and mapped to the tract level. The 2050 and 2100 assessment is based on 2010 census numbers and did not factor in population growth. Several socio-demographic variables indicative of a limited capacity to prepare for or recover from extreme flooding events were extracted including: Zero Vehicle households; Limited English Proficiency; and, Population over 65 years in age.  The Known Contaminated Sites List data was provided by the NJ Department of Environmental Protection (released May 28, 2014). The number of parcels and estimated land value exposed to flooding (i.e., if a parcel was completely or partially exposed to flooding the parcel was counted as affected and the entire value of the parcel was included) was derived from NJOIT digital parcel data and the Mod-IV tax data from the NJ Department of Treasury and only includes present day (Year 2013) values.

Table 2. Summary of the geographic information systems (GIS) data.

| Data Type | Source |
|---|---|
| Coastal Evacuation Routes | NJ Department of Transportation |
| Critical Facilities | FEMA HAZUS and NJOIT |
| Known Contaminated Site List | NJ Department of Environmental Protection |
| Population | US Census Factfinder2 |
| Parcel and land value | NJOIT and Department of Treasury |

**Results**

The results for the Present Day (baseline without future sea level rise) assessment are displayed below in both map (Figure 1) and tabular form (Table 3). Extreme exposure is limited to tidal marshes, low-lying areas exposed to shallow coastal flooding and the most wave-exposed shorelines. Much of New Jersey's heavily developed Atlantic barrier islands/back bay, Cape May, Delaware Bayshore, Raritan/Newark Bay and Hackensack Meadowlands communities are exposed to Moderate to High levels of flooding exposure. In addition, there are approximately 38,000 acres exposed to coastal flooding (Extreme, High and Moderate categories combined) in the tidally-influenced portions of the Delaware River basin in Gloucester, Camden, and Burlington Counties (shown in Figure 1). Due to the absence of base flood elevation data (at the time of this assessment), the Delaware River area of these three counties could not be projected under sea level rise. To be consistent across all three time periods, the acreage values for the Delaware River area are excluded from Table 3. Therefore, these values underestimate the total acreage of NJ's coastal flood exposed area.

Due to sea level rise, the total area subject to coastal flooding (i.e., Extreme, High and Moderate categories combined) is expected to increase 7% by 2050 and 14% by 2100 (Table 3). Areas ranked as High levels of exposure are expected to increase 12% by 2050 and 25% by 2100 (Table 3) due to the expected expansion of coastal flood zones into the mainland interior. Areas ranked as Extreme level of exposure are also expected to increase 17% by 2050 and 33% by 2100 (Table 3). This is primarily due to expected expansion of areas susceptible to chronic shallow coastal flooding. The overall amount of area ranked as Moderate exposure actually decreases due to the fact that many locations ranked as Moderate under Present conditions convert to a High or Extreme exposure ranking with continued sea level rise.

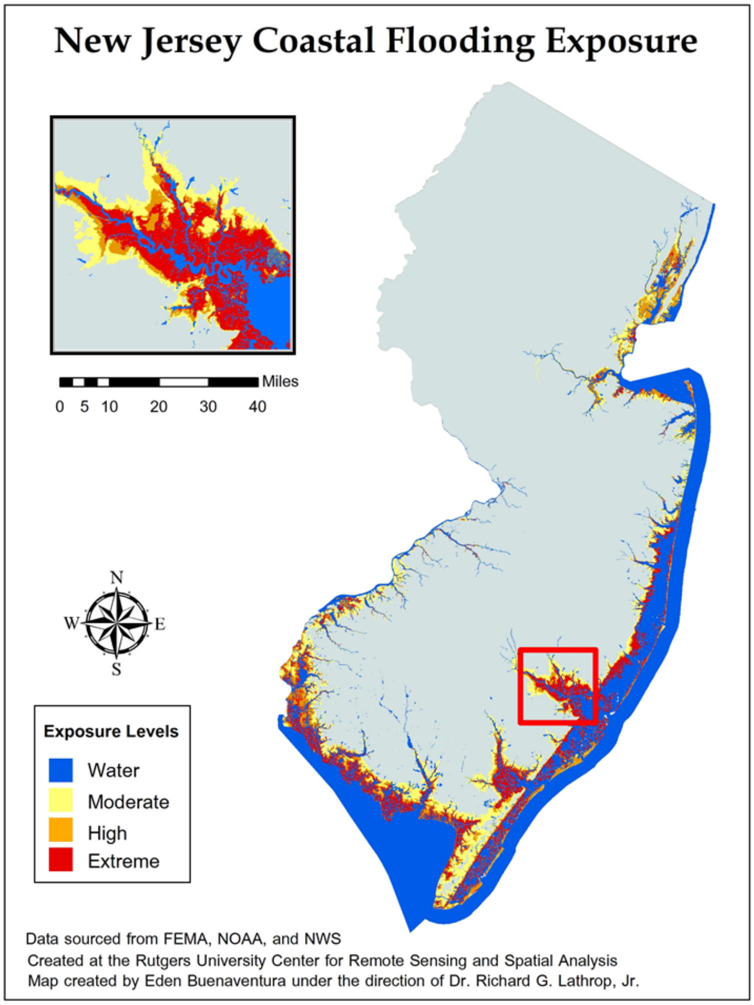


Figure 1. Map of Coastal Flooding Exposure under present day conditions. Note: map includes Delaware River basin portions of Gloucester, Camden, and Burlington Counties.

Table 3. NJ Coastal Flood Exposure: Area by category (in acres and as % change from baseline Year 2000). Note that this analysis does not include the potentially exposed areas in the tidally-influenced portions of the Delaware River basin in Gloucester, Camden, and Burlington Counties due to lack of data; therefore, these values underestimate the total acreage of NJ's coastal flood exposed area.

| Category | 2000 | 2050 | | 2100 | |
|---|---|---|---|---|---|
| | Area (ac) | Area (ac) | % change | Area (ac) | % Change |
| Moderate | 197,433 | 183,329 | -7.1 | 165,833 | -16.0 |
| High | 148,060 | 165,272 | +11.6 | 185,489 | +25.3 |
| Extreme | 234,224 | 271,784 | +16.6 | 310,608 | +32.6 |
| Total | 579,717 | 620,385 | +7.0 | 661,930 | +14.2 |

In planning for enhanced coastal resiliency, it is vital to consider the populations, facilities and resources at risk of exposure which can be evaluated for options such as flood-proofing, elevating, relocation, property buy-outs or other adaptation options. Within these areas exposed to coastal flooding, there is a noteworthy amount of infrastructure in terms of major roads/evacuation routes, critical facilities, contaminated sites and property values (Table 4). Also affected are segments of society that may have limited capacity to prepare for or recover from extreme flooding events (Table 4).

Table 4. Built infrastructure and socially vulnerable populations exposed to coastal flooding by exposure category under baseline Present day conditions. Note: excludes Delaware River basin portions of Gloucester, Camden, and Burlington Counties.

| **Infrastructure** | **Moderate (M)** | **High (H)** | **Extreme (E)** | **Total** |
|---|---|---|---|---|
| ***Miles of road affected*** | | | | |
| Major Roads (miles) | 382 | 270 | 45 | 697 |
| Evacuation Routes (miles) | 297 | 249 | 58 | 604 |
| ***# of facilities affected*** | | | | |
| Wastewater Treatment | 10 | 17 | 4 | 31 |
| Coastal Energy Facilities | 12 | 15 | 1 | 28 |
| Schools | 180 | 119 | 2 | 301 |
| Fire Stations | 99 | 90 | 6 | 195 |
| Law Enforcement | 46 | 44 | 3 | 93 |
| Long Term Care / Assisted Living Facilities | 20 | 11 | 0 | 31 |
| Hospitals | 7 | 6 | 0 | 13 |
| ***Socially vulnerable populations*** | | | | |
| Total Population (in persons using 2010 Census) | 428,769 | 333,923 | 150,959 | 913,651 |
| Zero Vehicle Households (persons 2010 Census) | 26,642 | 29,549 | 6,007 | 62,198 |
| Limited English Proficiency (persons 2010 Census) | 69,262 | 50,513 | 10,192 | 129,967 |
| Over 65 years in age (persons 2010 Census) | 52,121 | 39,420 | 22,606 | 114,147 |
| ***Known Contaminated Sites (NJDEP)*** | | | | |
| Active Sites with Confirmed Contamination | 197 | 269 | 24 | 490 |
| Total (including pending sites) | 1261 | 1501 | 193 | 2955 |
| | **M-H-E categories combined** | | | |
| ***Property parcels affected*** | # affected | $ Land value (in 2013 $) | | |
| Commercial Properties | 20,154 | $26,555,293,664 | | |
| Industrial Properties | 3,934 | $8,960,318,156 | | |
| Residential Properties (includes Apartments) | 335,873 | $129,057,872,992 | | |
| Total Combined | 359,961 | $164,573,484,812 | | |

As sea level is expected to continue to rise, if not accelerate, over the coming decades, we projected the increase in exposure to existing critical facilities and populations that might be expected at 2050 (Table 5) and 2100 (Table 6). The miles of major roads exposed to flooding increases nearly 13% by 2100. The number of existing critical facilities exposed increases from 692 (Present day) to 781 (or 13%) by 2050 to 879 (or 27%) by 2100. The overall population potentially directly exposed to flooding increases from 913,651 (Present day) to 1,012,174 (11%) by 2050 to 1,116,294 (22%) by 2100. The socially vulnerable population, number of affected parcels and property values exposed to coastal flooding are also expected to increase.

Table 5. Infrastructure and socially vulnerable populations exposed to coastal flooding for 2050. Note: excludes Delaware River basin portions of Gloucester, Camden, and Burlington Counties.

| **Infrastructure** | **Moderate (M)** | **High (H)** | **Extreme (E)** | **Total** |
|---|---|---|---|---|
| ***Miles of road affected*** | | | | |
| Major Roads (miles) | 311 | 339 | 74 | 724 |
| Evacuation Routes (miles) | 263 | 289 | 89 | 641 |
| ***# of facilities affected*** | | | | |
| Wastewater Treatment | 8 | 18 | 7 | 33 |
| Coastal Energy Facilities | 9 | 19 | 2 | 30 |
| Schools | 186 | 157 | 6 | 349 |
| Fire Stations | 93 | 104 | 20 | 217 |
| Law Enforcement | 42 | 53 | 5 | 100 |
| Long Term Care / Assisted Living Facilities | 22 | 13 | 1 | 36 |
| Hospitals | 6 | 10 | 0 | 16 |
| ***Socially vulnerable populations*** | | | | |
| Total Population (in persons using 2010 Census) | 394,343 | 420,427 | 197,404 | 1,012,174 |
| Zero Vehicle Households (persons 2010 Census) | 23,223 | 35,195 | 9,430 | 67,848 |
| Limited English Proficiency (persons 2010 Census) | 61,705 | 67,123 | 15,306 | 144,134 |
| Over 65 years in age (persons 2010 Census) | 47,897 | 49,864 | 29,038 | 126,799 |
| ***Known Contaminated Sites (NJDEP)*** | | | | |
| Active Sites with Confirmed Contamination | 162 | 305 | 61 | 528 |
| Total (including pending sites) | 1009 | 1772 | 367 | 3148 |

| | **M-H-E categories combined** | | | |
|---|---|---|---|---|
| ***Property parcels affected*** | # affected | $ Land value (in 2013$) | | |
| Commercial Properties | 22,291 | $28,174,257,332 | | |
| Industrial Properties | 4,116 | $9,224,330,856 | | |
| Residential Properties (includes Apartments) | 366,241 | $138,423,061,359 | | |
| Total Combined | 392,648 | $175,821,649,547 | | |

Table 6. Infrastructure and socially vulnerable populations exposed to coastal flooding for 2100. Note: excludes Delaware River basin portions of Gloucester, Camden, and Burlington Counties.

| **Infrastructure** | **Moderate (M)** | **High (H)** | **Extreme (E)** | **Total** |
|---|---|---|---|---|
| ***Miles of road affected*** | | | | |
| Major Roads (miles) | 271 | 407 | 108 | 786 |
| Evacuation Routes (miles) | 228 | 325 | 140 | 693 |
| ***# of facilities affected*** | | | | |
| Wastewater Treatment | 4 | 20 | 10 | 34 |
| Coastal Energy Facilities | 9 | 16 | 6 | 31 |
| Schools | 196 | 181 | 34 | 411 |
| Fire Stations | 78 | 114 | 43 | 235 |
| Law Enforcement | 36 | 57 | 18 | 111 |
| Long Term Care / Assisted Living Facilities | 19 | 18 | 3 | 40 |
| Hospitals | 7 | 10 | 0 | 17 |
| ***Socially vulnerable populations*** | | | | |
| Total Population (in persons using 2010 Census) | 370,979 | 471,145 | 274,170 | 1,116,294 |
| Zero Vehicle Households (persons 2010 Census) | 20,858 | 36,615 | 16,157 | 73,630 |
| Limited English Proficiency (persons 2010 Census) | 57,116 | 78,077 | 25,376 | 160,569 |
| Over 65 years in age (persons 2010 Census) | 45,858 | 55,228 | 39,392 | 140,478 |
| ***Known Contaminated Sites (NJDEP)*** | | | | |
| Active Sites with Confirmed Contamination | 146 | 311 | 102 | 559 |
| Total (including pending sites) | 866 | 1795 | 683 | 3344 |

| | **M-H-E categories combined** | | |
|---|---|---|---|
| ***Property parcels affected*** | # affected | $ Land value (in 2013 $) | |
| Commercial Properties | 24,192 | $29,593,101,475 | |
| Industrial Properties | 4,304 | $9,516,255,656 | |
| Residential Properties (includes Apartments) | 396,023 | $146,142,771,785 | |
| Total Combined | 424,519 | $185,252,128,916 | |

## Summary and Conclusions

We undertook this coastal flooding exposure assessment to inform state and local resiliency planning efforts across the state of New Jersey's extensive coastal zone. In enhancing future resilience, a necessary first step is a better understanding of the scope of potential hazards and the exposure of key infrastructure and vulnerable populations to inundation. As this assessment shows, New Jersey has a tremendous amount of infrastructure and a large vulnerable population exposed to coastal flooding. This assessment helps answer the question as to what areas of our coastal zone are most exposed and should be factored into deliberations concerning rebuilding, redesigning/redeveloping or buyouts and planned retreat in New Jersey's coastal zone.

Expected levels of sea level rise will only exacerbate the problem of coastal flooding over the coming century. This assessment represents a 'first cut' approximation of the geographic areas in New Jersey most exposed to potential future flooding hazards under predicted levels of sea level rise. Due to limitations in time and funding, we employed a 'back end' approach to adjusting the FEMA FIRMs and SLOSH surge maps by projected sea level rise, in that we added sea level rise to the existing modelled/mapped water surfaces. Ideally, a 'front end' approach should be employed where the sea level rise is added on to the base tidal datum first (i.e. at the 'front end') and then modeling of wave energies and base flood elevations is undertaken. We caution that the 'back end' approach employed in this assessment has the potential to underestimate the base flood elevation as well as the inland extent of surge-related flooding. However, without further analysis it is unclear to what extent 'back' vs. 'front end' approaches may differ in the areas mapped and the levels of exposure risk and further investigation of this question is warranted. We strongly recommend that more sophisticated 'front end' modeling of storm surge and other coastal flooding under future sea level rise and climate change be undertaken. In the meantime, our assessment provides a useful screening tool to highlight those areas that may be at even greater risk in the future. A further note of caution is warranted: If sea levels rise beyond the projected ranges used in this study, then exposure levels can be expected to increase and areas further inland (not mapped as such) will potentially be exposed to coastal flooding.

In addition to this report, the NJ coastal flooding exposure map products have been made available on the *NJDAPT* platform (http://www.njadapt.org/). This WebGIS tool was developed to help jump-start local community discussions about hazard impacts with municipal scale maps that show people, places, and natural resources exposed to coastal flooding. The mapped data and the discussions spurred from these maps are valuable and applicable to a variety of community planning processes—from comprehensive land-use to hazards mitigation and conservation planning. The *Getting to Reliance* online assessment tool (http://www.prepareyourcommunitynj.org) was developed to assist communities to reduce vulnerability and increase preparedness. Outputs provided at the completion of the questionnaire can strengthen local/county all-hazards and emergency operations plans as well as be worth valuable points through FEMA's Community Rating System and Sustainable Jersey.

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We gratefully acknowledge the contributions of the technical panel: Doug Marcy, William Brooks and Darlene Finch, NOAA Coastal Services Center; Jared Scott, US Army Corps of Engineers; Mark Mauriello, Edgewood Properties; Dr. Norbert Psuty, Rutgers University; Dr. Karl Nordstrom, Rutgers University; Dr. Danielle Kreeger and Sari Rothrock, Partnership for the Delaware Estuary; Martha Maxwell-Doyle, Barnegat Bay Partnership; Dr. Tracy Quirk, Drexel University; and, Steve Jandoli, New Jersey Department of Environmental Protection.

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**Appendix A. Consensus Sea Level Rise Scenarios for the NJ Coastal Flood Exposure (CFE) Assessment**

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Estimates of sea level rise (SLR) for New Jersey vary depending upon methods used by different scientists. A consensus set of estimates have been developed to inform the scenario analyses for the Coastal Flood Exposure (CFE) Assessment regarding future flooding exposure for New Jersey's coastal zone. In August 2013, a panel of sea level rise experts from Rutgers University, the National Oceanic and Atmospheric Administration, and the U.S. Global Climate Change Research Program was convened to assist in developing "best available" values for Year 2050 and 2100 SLR scenarios for this assessment. Additional discussions have occurred since August 2013 as the scientists have continued with their research and publications.

Initially, two independent analyses formed the basis for the subsequent development of a series "consensus" SLR values: 1) Doug Marcy of NOAA's Coastal Services Center provided NJ-specific estimates based on NOAA Global Scenarios (Parris et al., 2012) and the NOAA/USACE SLR Calculator; and, 2) Ken Miller and Robert Kopp provided NJ-specific estimates based on their research (Miller et al., 2013). The consensus sea level rise projections (labeled CFE values in Table 1) for the New Jersey coastal flood exposure were derived by averaging these two analyses and then rounding up to the nearest 0.5 foot.

Table 1. Consensus sea-level rise projections (in feet) for the New Jersey Coastal Flood Exposure (CFE) assessment. The baseline is year 2000 sea level.

| Year | Low | High | Higher |
|---|---|---|---|
| 2050 | 1.0’ | 2.0’ | 2.5’ |
| 2100 | 2.5’ | 5.0’ | 7.0’ |

The probabilistic framework of Kopp et al. (2014) provides guidance in interpreting the odds of the different sea-level rise projections used in the CFE model.

- There is about an 85% chance, an 8% chance, and a 1-in-200 (0.5%) chance that sea-level rise along the Jersey shore line will exceed the CFE values of 1.0 ft, 2.0 ft and 2.5 ft by 2050 under a Representative Concentration Pathway (RCP) 8.5 high emissions scenario. Reducing greenhouse gas emissions does not significantly affect these mid-century projections.

- Under the high-emissions RCP 8.5 scenario, there is about an 80% chance, a 10% chance, and a 1-in-125 (0.8%) chance that sea-level rise will exceed the CFE values of 2.5 ft, 5.0 ft and 7.0 ft by 2100. The moderate emissions RCP 4.5 scenario lowers these probabilities to 65%, 2% and 1-in-250. The extremely-low emissions RCP 2.6 scenario further lowers them to 40%, 1%, and 1-in-300.

Table 2 details the projections that contributed to the development of the consensus values used in the CFE analyses. In addition, recent research by Robert Kopp et al. (2014) is included.

Table 1. Sea-level rise projections underlying the consensus values. Note: All values are feet above baseline year 2000 sea level.

| **2050 Projection** | **Low** | **High** | **Higher** |
|---|---|---|---|
| NOAA Average* | 1.0 | 1.5 | 2.5 |
| Miller/Kopp (2013)** | 1.1 | 1.9 | 2.2 |
| Mean of NOAA and M/K | 1.0 | 1.7 | 2.4 |
| CFE Values*** | 1.0 | 2.0 | 2.5 |
| CFE Values: % Chance of SLR exceeding this value **** | 85% | 8% | 0.5% |
| **2100 Projection** | **Low** | **High** | **Higher** |
| NOAA Average* | 2.3 | 4.5 | 7.5 |
| Miller/Kopp (2013)** | 2.5 | 4.9 | 5.8 |
| Mean NOAA and M/K | 2.4 | 4.7 | 6.7 |
| CFE Values*** | 2.5 | 5.0 | 7.0 |
| CFE Values: % Chance of SLR exceeding this value **** | 80% | 10% | 0.8% |

** NOAA Intermediate Low projections included under Low category, NOAA Intermediate High included under High category and NOAA High values included as Higher category in Table. SLR Values are in FT and are provided by the NOAA/USACE calculator rounded to the nearest 0.5 FT*

*** Miller/Kopp Low projections, rounded to nearest 0.1 Ft*

**** Rounded up to nearest 0.5 FT*

***** Percentile projections based on Kopp et al., 2014*

Further information on these three analyses is provided below.

The Parris et al. (2012) global sea level rise projections, developed for the U.S. National Climate Assessment, are adjusted for local subsidence, as estimated from tide gauge data, using the U.S. Army Corps of Engineers calculator (http://www.corpsclimate.us/Sandy/curvesNJNY2_detailed_NOAA.asp). The 2050 calculated values were graciously provided for this assessment by the National Oceanic and Atmospheric Administration Coastal Services Center (Marcy 2013). Parris et al. (2012) present four alternative scenarios. For their lowest scenario (labelled as Low in the NOAA/ACE calculator), they linearly extrapolated historical 20$^{th}$ century tide gauge measurement. Their lowest scenario was not used in determining the consensus SLR estimates and not displayed in Table 1 above. Their Intermediate Low scenario (labelled as Low in Table 1 above) is based on the upper end of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, using the B1 emissions scenario (generally considered lowest expected increase in emissions) primarily from ocean warming. Their Intermediate High scenario (labelled as High in Table 1 above) is based on an average of the high end of ranges of global mean sea level rise reported by several studies using semi-empirical approaches including recent ice sheet loss. Their High scenario (labelled as Higher in Table 1 above) is derived from the IPCC Fourth Assessment Report global projections coupled with maximum possible glacier and ice sheet loss. As noted, in our adaptation of these projections, local subsidence is accounted for using estimates of flood projections for 5 year intervals based on local tide gauge data (Atlantic City, Cape May and Sandy Hook), assuming a linear trend based on the historical record.

Miller et al. (2013) modified the approach of the National Research Council (2012) to generate a Low, a Central, a High, and a Higher estimate. For each estimate, they consider the terms that contribute to global sea level rise, as well as the factors that cause the regional expression of these terms to differ from the global mean. Their Higher estimate employs the same estimates of individual contributing factors as the High estimate, but assumes that the uncertainties in the different factors are highly correlated. Their Central estimate was not used in determining the consensus SLR estimates as it did not correspond with any of the NOAA/ACE calculator categories (and is not displayed in Table 1 above).

To assess the contribution of thermal expansion to global sea level rise, Miller et al. (2013) follow NRC (2012) directly: their Central estimate is the middle of projections for the A1B (medium) emissions scenario, while their Low estimate is the 5$^{th}$ percentile of projections for the B2 (low) emissions scenario and their High and Higher estimates are the 95$^{th}$ percentile of projections for the A1F1 (high) emissions. They also adopted NRC (2012) projections of glacier and ice cap melt, using an extrapolation of observed changes for the Low and Central scenarios and incorporating an additional dynamic contribution for High and Higher cases. Adopting the framework of NRC (2012) but employing a more recent assessment of ice sheet changes (Shepherd et al., 2012), Miller et al. (2013) assume in the low estimate that Greenland and Antarctic ice sheets continue at the same average rate observed over the period 1992-2011; in their central estimate they assume the decadal acceleration between 1992-2000 and 2000-2011 continues; in their high estimate they assume acceleration observed from 2000-2010 in Greenland continues and that the Antarctic ice sheet makes a similar contribution to global sea level rise.

To regionalize their global projections, Miller et al. (2013) employ static-equilibrium sea-level fingerprints to account for net gravitational changes associated with melting polar ice sheets, as well as for associated changes in the flexure and rotation of the solid Earth. To incorporate the effects of changes in ocean circulation and winds, they employ projections from ten models included in the IPCC's Fourth Assessment Report (Yin et al., 2009). To incorporate glacial isostatic adjustment and local subsidence associated with sediment compaction and groundwater withdrawal, they use the last 10,000 years of geologic data (including 50 sea level index points that define continuously rising relative sea level in the NJ during the Holocene), as well as the historical record of tide gauge observations.

Kopp et al. (2014) develop probability distributions for sea-level rise at tide gauge sites throughout the world, including the Battery tide gauge at New York City and the Sandy Hook, Atlantic City and Cape May tide gauges in New Jersey. Their probability distributions account for all the major factors contributing to sea-level rise: land ice melt (and its local expression as mediated via static-equilibrium effects), thermal expansion, changes in ocean dynamics, glacial isostatic adjustment, and sediment compaction. Projected changes in the volumes of the Greenland and Antarctic ice sheets are based upon a combination of the IPCC's Fifth Assessment Report and an expert elicitation study of the 'tail' risk of extreme ice sheet melt. Changes in non-polar glaciers are based upon a distribution of climate models coupled to a glacier surface mass balance model. Thermal expansion and ocean dynamics are based upon the distribution of climate model projections, while glacial isostatic adjustment and sediment compaction are based upon the observational record.

In conclusion, although different approaches are used, the closeness of the estimates provides consensus by both groups of authors, who communicated together throughout 2013 and 2014 in the use of these values for New Jersey.

<u>Notes on Sea Level Rise Mapping</u>

As with any topographic mapping project, the underlying data contains error in both horizontal as well as vertical dimensions. High spatial resolution LiDAR imagery acquisition for the state of New Jersey has been a cooperative effort between the U.S. Geological Survey, the Federal Emergency Management Agency (FEMA) and the state government. LiDAR acquisition was completed in stages over a period of years from 2006 to 2010. The NOAA Coastal Services Center (CSC) provided the LiDAR-derived digital elevation model (DEM) corrected to a standard vertical datum of NAVD88 and a standard tidal datum of mean higher high water (MHHW; based on the National Tidal Datum Epoch for the years 1983 to 2001) with a grid cell resolution of 25 feet. All data sets produced for this project are consistent with NOAA methodology and using the National Geodetic Survey's vertical datum transformation software tool (VDatum) to determine tidal variability across geographic space. The VDatum software generates an ASCII file output with the same format (X, Y, Z). However, in the output, the Z value represents the difference/variability of the selected tidal datum. Most variation occurs in the immediate coastal and shoreline regions; little to no change is observed inland. The final MHHW surfaces were then used to generate sea level rise inundation water surface grids for 1.0 to 7.0 foot sea level rise scenarios.

The original elevation data has a vertical root mean square error between 2.4-5.3 inches (6 and 13.5 cm) (NOAA CSC, 2012). V-DATUM correction introduces additional (but unquantified) vertical errors. The difference in years between the LiDAR data acquisition dates, the National Tidal Datum Epoch and the baseline Yr 2000 for the sea level rise scenario generation may also introduce additional vertical discrepancies (on the order of up to several inches). Thus the difference between the modeled and mapped vs. the 'true' sea level height at any particular location may vary on the order of 6 inches to 1 foot or more.

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