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New York City Panel on Climate Change 2015 Report Chapter 3: Static Coastal Flood Mapping

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Introduction

The objective of this chapter is to describe the coastal flood-mapping methods used by the second New York City Panel on Climate Change (NPCC2) and the coastal flood-mapping products. The chapter illustrates the technical approach used to create the NPCC2 maps of projected future flood extents. Uncertainties in the coastal flood-mapping process are explained and associated caveats are presented. See Box 3.1 for key definitions and terms.

3.1 Mapping risk, hazards, and uncertainty

Risk and hazard mapping has a long and rich tradition, and presenting spatial risks and hazards has been applied in a wide range of contexts. The strength of the map as an information tool depends on the quality of data and the techniques used to translate the data onto a flat surface. Flood-hazard mapping has its roots in 1930s conservation-era watershed and flood-hazard management (Mileti, 1999). The most significant advance since that time, besides the dynamic growth of computational mapping and geographic information systems (GIS) (Clarke, 1997), has been the application of model-based projections of flood extents and periodicity (recurrence intervals) to the empirically based data on flood extents and elevation (see Chapters 2 and 4, NPCC, 2015).

New York City hazards and climate risks

Mapping natural hazards and climate risks is an essential part of an overall emergency management strategy for densely populated urban areas such as New York City and can be an effective part of an overall risk reduction plan. In 2009, the New York City Office of Emergency Management (OEM) developed the first FEMA-approved hazard mitigation plan (HMP) for the City, a document designed to serve as a guideline for protecting New York City from the effects of natural hazards. The HMP assesses hazard vulnerabilities including those related to climate, identifies risk reduction opportunities, and helps to secure funding for hazard mitigation; it is updated every five years.

The most current plan (NYCHMP, 2014) contains maps and tables that depict a broad range of both physical hazards and social vulnerabilities. The maps of potential flood inundation are used to illustrate the City's Hurricane Evacuation Zones and to inform the general public about their risk from individual flood hazard events. These are worst-case scenario maps based on the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model[b] and are

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[b]The 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 by taking into account atmospheric pressure, size, forward speed, and storm track data. These parameters are used to create a model of the wind field that drives storm surge.

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Box 3.1. Definitions and terms

Base flood elevation (BFE)
FEMA term for the 100-year flood elevation that specifically includes the elevation of wave crests above the stillwater elevation as well as estimated effects of wave runup and overtopping of sea walls.

Dynamic coastal flood modeling
Physics-based computer simulation techniques that include the effects of factors such as wind, atmospheric pressure, and friction in calculation of coastal flood elevations (also known as *hydrodynamic modeling*).

Extratropical cyclone
Coastal storms existing or occurring outside of the tropical latitudes, displaying poleward displacement and conversion of the primary energy source from the release of latent heat of condensation to baroclinic (temperature contrast between warm and cold air masses) processes. Cyclones can become extratropical and still retain winds of hurricane or tropical storm force.

Flood exceedance curves
Relationship between flood intensity and different levels of frequency; each curve represents the flood intensity that will be equaled or exceeded once in a certain number of years, indicated as the frequency of that curve.

Flood hazard assessment
Statistical evaluation of the annual likelihood of a given flood event for a range of different flood elevations.

Flood zone and floodplain
A flood zone is statistically-defined region whereby each point within is subject to a flooding at a given annual probability. A floodplain is a geologic term that refers to a broad, relatively flat land area subject to flooding from a river, lake, ocean, or other water body.

Return period/recurrence
The average interval, in years, between occurrences of two floods of equal or greater magnitude. It is based on the probability that the given flood event will be equaled or exceeded in any given year.

Static coastal flood modeling
A common technique for mapping flood extents whereby a flood elevation is extrapolated landward until it reaches the equivalent contour height on land (see Chapter 4 for further discussion of the static approach). Topographic elevations at or lower than this height are considered flooded. This approach—also referred to as a "bathtub" model—is commonly used for sea level inundation scenarios applied to surfaces of constant elevation such as a tidal datum, but it has also been applied to SLOSH model output.

Stillwater elevation
FEMA terminology for combined storm surge and tide, that is, total water elevation during a storm. It is the water elevation in the absence of waves. NPCC2 utilizes stillwater elevation to create its 500-year map products.

Storm surge/storm tide
Storm surge is a wind-driven and atmospheric pressure-driven increase in water level and combines with tides to form the total water elevation during a storm, also known as the storm tide.

Tropical cyclone
A warm-core, non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters with organized deep convection and a closed surface wind circulation about a well-defined center.

Wave setup
The rise in stillwater elevation that is driven by the unidirectional effect of waves breaking, thus pushing water onshore.

utilized by city agencies and stakeholders to develop plans to protect their at-risk infrastructure. FEMA Flood Insurance Rate Maps (FIRMs) are represented in the HMP. New York City's comprehensive climate resiliency plan, *A Stronger, More Resilient New York* (City of New York, 2013), also uses flood mapping to assess risks and plan for the future.

FEMA Flood Insurance Rate Maps and Hurricane Sandy

A Flood Insurance Study (FIS) is a document developed by FEMA that contains information about flooding in a community and is produced in conjunction with a flood rate insurance map (FIRM). Both coastal flooding and riverine flooding are included (the NPCC2 only considered coastal flooding). A FIS describes the flooding history of a community, explains the engineering methods and data sources used to develop the FIRMs, and provides flood heights and profiles for various recurrence probabilities.

FIRMs display flood hazard boundaries and base flood elevation (BFE) information essential to setting insurance rates and building design standards, and for the implementation of floodplain management and regulation practices. They are used by federal agencies, state and local governments, lending institutions, insurance agencies, surveyors, and the National Flood Insurance Program (Crowell *et al.*, 2007).

The initial Flood Insurance Study for the City of New York became effective in 1983 and then, in 1991, 1992, 1994, 2001, and 2007, underwent a series of revisions such as redelineations, and the incorporation of approved amendments requested by property owners. Despite these updates, the original coastal flood-hazard analysis for New York City was not fully revised until 2013.

FEMA was in the process of updating the FIS and FIRMs for New York City when Hurricane Sandy struck on October 29, 2012. The Hurricane Sandy field-verified inundation area (Fig. 3.1), a surface interpolated using field-verified high-water marks and storm-sensor data from the U.S. Geological Survey, clearly equaled and exceeded the 1983 100- and 500-year floodplains, most strikingly along the southern coasts of Brooklyn and Queens and along the eastern and southern shores of Staten Island. Northern Queens and the Bronx experienced less flooding relative to the other boroughs in part because the Long Island Sound was at low tide when Sandy made landfall (Georgas *et al.*, 2014).

It is critical that coastal flood maps are updated regularly. As a result of not having updated maps, many people were caught unaware and without flood insurance during Hurricane Sandy. The flood maps from the 2010 NPCC Report, *Climate Change Adaptation in New York City*, were based on the 1983 FEMA FIS, thus making them less useful than they were intended to be.

In December 2013, FEMA released Preliminary Flood Insurance Rate Maps for New York City based on their 2013 Flood Insurance Study. These maps were a significant update from the first FEMA Flood Insurance Study conducted in 1983. They incorporated changes that included:

- Revised flood hazard analysis and mapping for the 520 miles of coastal shoreline of New York City
- Base map updated to 2008 aerial photography
- Incorporation of 2010 digital topographic data provided by New York City
- Incorporation of validated Letters of Map Change (LOMCs), which are FEMA-issued documents that reflect official revisions/amendments to FIRMs
- Conversion of the geodetic datum from the National Geodetic Vertical Datum of 1929 (NAVD29) to the North American Vertical Datum of 1988 (NAVD88).

In comparison to the 1983 FIRMs, the revised preliminary FIRMs delineate a larger 100-year flood zone, extending the zone of flooding further inland in nearly all areas of the city and encompassing 50 square miles of land relative to the 100-year flood zone of 1983 that covered 33 square miles (Fig. 3.2).

3.2 GIS flood-mapping approach

In the first NPCC Report and in the post–Hurricane Sandy NPCC Climate Risk Information 2013 that followed (NPCC, 2010; 2013), the NPCC provided future flood maps for New York City depicting projected flood areas under the NPCC sea level rise scenarios. The sea level rise scenarios were an essential component of the future flood-mapping exercise because, as sea levels rise through the 21st century, a coastal flood of a given volume will reach higher elevations and greater aerial extents than previously experienced.

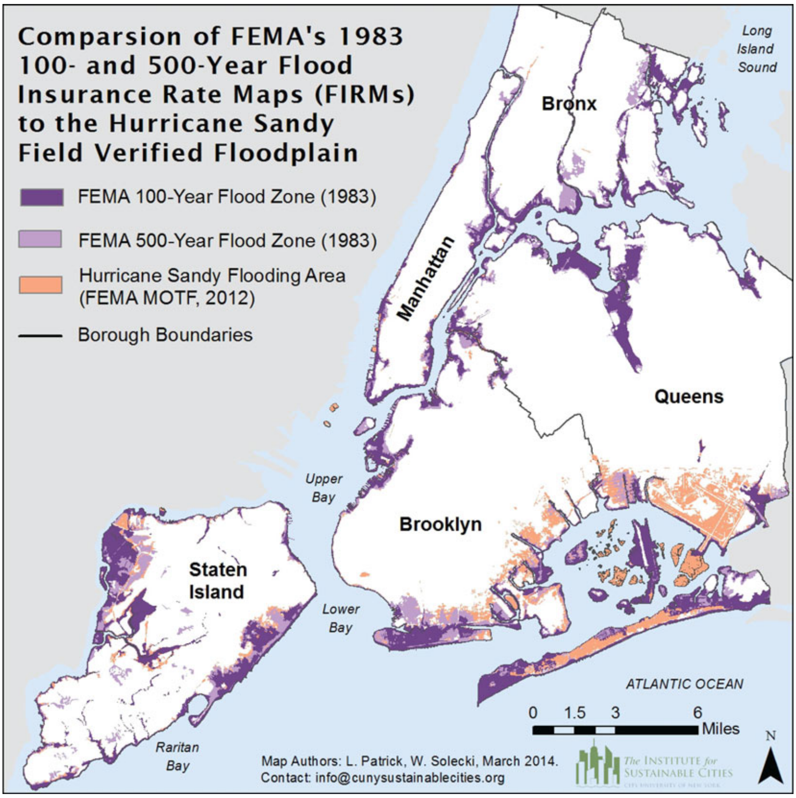

Figure 3.1. FEMA's 1983 projections of the 100-year and 500-year flood zones[c] in New York City compared to the field-verified post–Hurricane Sandy flooding area. Source: FEMA.

The projected flood areas created by the NPCC2 for the 100- and 500-year flood events in the 2020s, 2050s, 2080s, and 2100 were developed using a static coastal flood-modeling technique that uses outputs from FEMA's hydrologic and hydraulic models and modifies these outputs in a GIS by adding the NPCC sea level rise projections (see Appendix IIC NPCC, 2015 for further details). This static "bathtub" approach to mapping sea level effects on coastal flood zones is simple in logic. It assumes that floodwaters will continue to move landward until they reach an equivalent topographic elevation (see Chapter 4, NPCC, 2015, for further discussion of the static approach) (Titus and Richman, 2001; Wu *et al.*, 2002; Kleinosky *et al.*, 2006; Poulter and Halpin, 2008; Gesch, 2009; Li *et al.*, 2009).

The FEMA FIRMs were chosen as the base dataset (and not the hurricane storm-surge inundation areas derived from SLOSH) because the FIRMs are used for New York City Building Code regulations and floodplain management. Selection of the FIRMs produces maps that are compatible and comparable for stakeholder and planner use. However, the FEMA Regional 2 Coastal Storm Surge Study (FEMA, 2014) suggests the 2013 FIRM flood elevations and extents may be on the high end of previous estimates (see Chapter 4 of NPCC, 2015 for further discussion).

Following on from this approach, the NPCC2 has also conducted analyses and created maps that combine sea level rise directly with dynamic coastal flood models that include wave effects (see Chapter 4). Despite its limitations (discussed below), the static approach is a useful tool for planners and stakeholders and can be used to inform decisions on infrastructure investments and land use policy. The static approach is relatively simple, requires less

[c]The 100-year coastal flood event refers to the flood with a 1% annual chance of occurence. The 500-year coastal flood event refers to the flood with a 0.2% annual chance of occurrence.

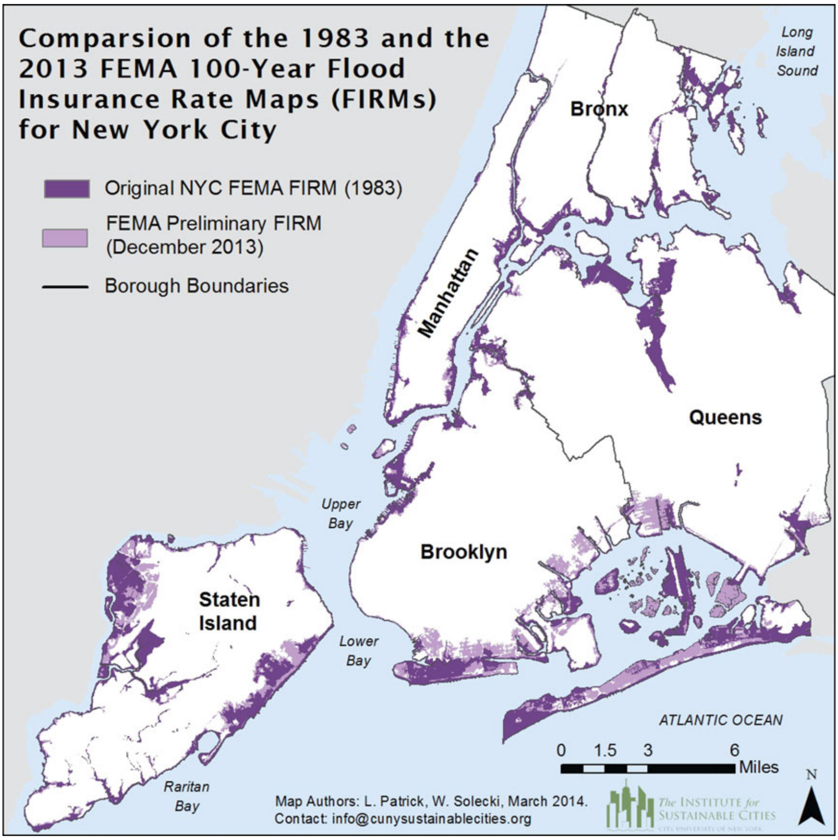

Figure 3.2. Comparison of FEMA's 100-year floodplains for New York City as first developed in 1983 and revised in 2013.

time, and is less computer-intensive than dynamic approaches.

The methodology for developing the static GIS maps described in the NPCC 2010 Report has been revised slightly for the NPCC2 mapping products that have followed. The following section details the GIS mapping approach, methodology and limitations regarding data use and map interpretation, and describes the vertical accuracy of the topographic data. It notes where current data-sets and methods differ from previous mapping efforts.

Data sets used for mapping

The following data sets were used to develop the NPCC2 flood maps:

1. The 90th-percentile value projections of sea level rise elevations for the 2020s, 2050s, 2080s, and 2100 developed by NPCC2.
   - 2020s, 10 inches; 2050s, 30 inches; 2080s, 58 inches; 2100, 75 inches
   - Prepared February–December 2013
2. Preliminary 2013 FIRMs derived from the FEMA 2013 Preliminary Flood Insurance Study for the City of New York, NY.
   - Flood extent and base flood elevation (BFE) information (relative to the North American Vertical Datum of 1988 [NAVD88]) for the 100-year floodplain
   - Release date: December 5, 2013
3. The 0.2% (500-year) Annual Chance Flood Hazard Area Stillwater Elevation Raster, derived from the FEMA Preliminary Flood Insurance Study and FIRMs for the City of New York, NY.
   - Flood extent and stillwater elevation (SWEL) information (relative to NAVD88) for the 500-year floodplain
   - Release date: December 5, 2013
4. Digital Elevation Model (DEM), 2010 for New York City.
   - Surface developed from LiDAR data collected in spring 2010 over New York City

- Nominal pulse spacing (NPS) of LiDAR: < 1 meter (>1 pulse/m^2)
- LiDAR points interpolated to create a 1-foot resolution surface with cell values corresponding to ground-elevation values in feet above NAVD88
- Horizontal positional accuracy: root mean square error (RMSE) of LiDAR data 33.08 cm
- Horizontal datum: North American 1983
- Vertical positional accuracy: root mean square error (RMSE) of LiDAR data 9.5 cm
- Vertical datum: NAVD88[d]

5. New York City borough boundaries (New York City Department of City Planning).
   - Release date: September 2008

Static coastal flood mapping methodology

Vector shapefiles and maps of areas that could be impacted by future 100- and 500-year floods were created using spatial processing techniques in ESRI ArcGIS software.[e] In 2010 and again in 2013, the NPCC developed a GIS-based methodology to map projected flood scenarios based on given increments of sea level rise. That work was based on the following assumptions:

1. Sea level rise will result in greater 100- and 500-year flood extents and higher flood elevations than are currently modeled in the FEMA FIRMs.
2. Floodwaters will continue to move onshore until they reach an equivalent topographic elevation.
3. Low-elevation land areas must have direct connectivity to the open water in order to flood (i.e., they are not surrounded by areas of higher elevation).[f]
4. Wave contributions to flood elevations will remain unchanged from those found in the FEMA FIRMs.

Flood-elevation values change as floodwaters move inland, most often but not always decreasing in elevation as they move from the coast to areas onshore. NPCC2 projections of the 90th percentile of sea level rise elevations of 10 inches for the 2020s, 30 inches for the 2050s, 58 inches for the 2080s, and 75 inches for 2100 were added to the BFE and SWEL elevation values at the most landward locations of flooding to show how a rise in sea level could increase those values and extend the 100- and 500-year floodplains further inland.

FEMA's BFE and SWEL elevations vary both parallel and perpendicular to the shoreline and thus are not at a constant elevation. The transitions in flood elevation values along the coasts should be reflected in the landward movement of floodwaters, such that the inland shape and extent of the flood zone reflect the changing base flood elevation values nearer to shore. The NPCC2 static approach incorporates these lateral variations in flood elevation values by assuming that landward values of floodwater elevation are likely to be more similar to neighboring flood-elevation values and less similar to more distant values (see Appendix IIC, NPCC, 2015).

3.3 Future flood map products

The NPCC2 maps illustrate the estimated potential inundation extent associated with projected sea level rise elevations for four time slices (see Figs. 3.3 and 3.4). Using the static approach, the NPCC2 created two specific map products:

1. GIS shape files of the future 100-year flood extent for the 2020s, 2050s, 2080s, and 2100 based on FEMA's Preliminary FIRMs (December 2013) for New York City and the NPCC2 high-estimate (90th percentile) sea level rise projections of 10 inches for the 2020s, 30 inches for the 2050s, 58 inches for the 2080s, and 75 inches for 2100.
2. GIS shape files of the future 500-year flood extent for the 2020s, 2050s, 2080s, and 2100 based on stillwater elevation (SWEL) raster data for New York City (December 2013) and

[d]The NAVD88 is an orthometric datum that is approximately 2.5 inches above mean sea level at the Battery, NY tide gauge station.

[e]ESRI's ArcGIS software is a platform that is used for creating maps and geographic information products.

[f]It is possible that areas not hydrologically connected to open water can flood via subterranean tunnels or pipes or via a storm surge–induced increase in hydrostatic pressure that raises water tables relatively distant from shoreline. However, this flooding is not indicated on the NPCC maps.

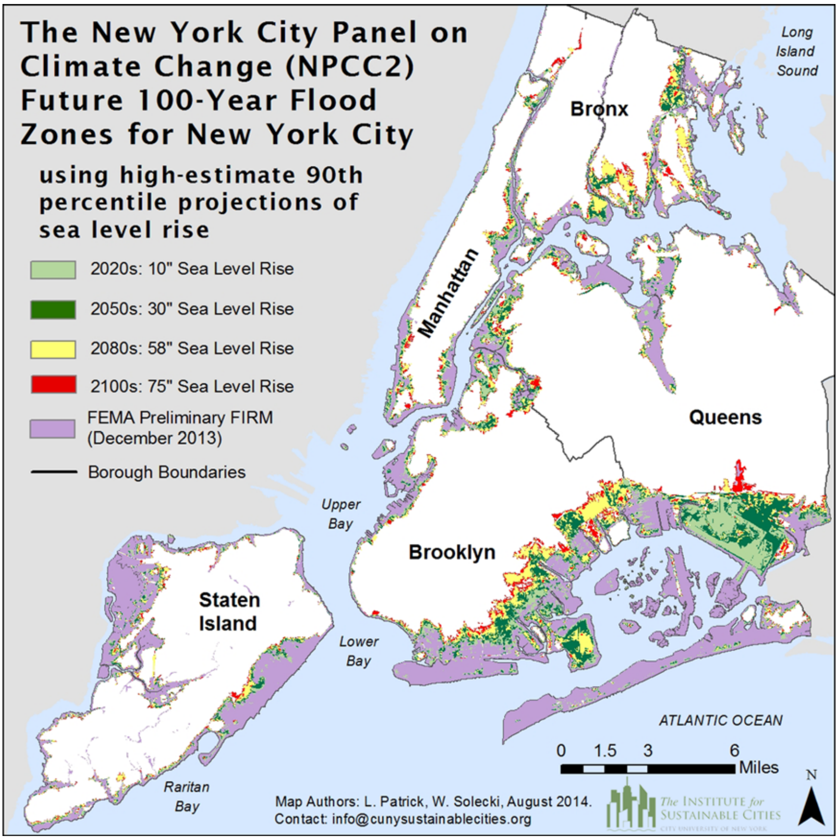

Figure 3.3. Potential areas that could be impacted by the 100-year flood in the 2020s, 2050s, 2080s, and 2100 based on NPCC2 projections of the high-estimate 90th-percentile sea level rise scenario.

Note: This map is subject to limitations in accuracy as a result of the quantitative models, datasets, and methodology used in its development. The map and data should not be used to assess actual coastal hazards, insurance requirements, or property values or be used in lieu of FIRMS issued by FEMA. The flood areas delineated above in no way represent precise flood boundaries but rather illustrate three distinct areas of interest: (1) areas currently subject to the 100-year flood that will continue to be subject to flooding in the future; (2) areas that do not currently flood but are expected to potentially experience the 100-year flood in the future; and (3) areas that do not currently flood and are unlikely to do so in the timeline of the climate scenarios used in this research (end of the current century).

the NPCC2 high-estimate (90th percentile) sea level rise projections of 10 inches for the 2020s, 30 inches for the 2050s, 58 inches for the 2080s, and 75 inches for 2100.

The GIS shape files were used to create the projected future 100- and 500-year flood zone maps for New York City shown in Figures 3.3 and 3.4. These maps illustrate that higher sea level elevations result in greater floodplain areas, with the extent of landward movement dictated by the elevation and slope of the land. In each scenario, Queens is the borough with the most affected land area, followed by Brooklyn, Staten Island, the Bronx, and Manhattan.

The relationship between sea level elevation and flood extent is illustrated by the calculations of flood area inundation in Table 3.1.

3.4 Mapping limitations

The maps contain numerous sources of uncertainty as a result of the datasets and methodologies used in their development and as such are limited in their accuracy. FEMA's methodology for creating coastal BFEs and SWEL data involves simulating the dynamic processes of flooding using detailed hydrologic and hydraulic models (FEMA, 2013). These models have a range of uncertainty associated with their output, even before sea level rise

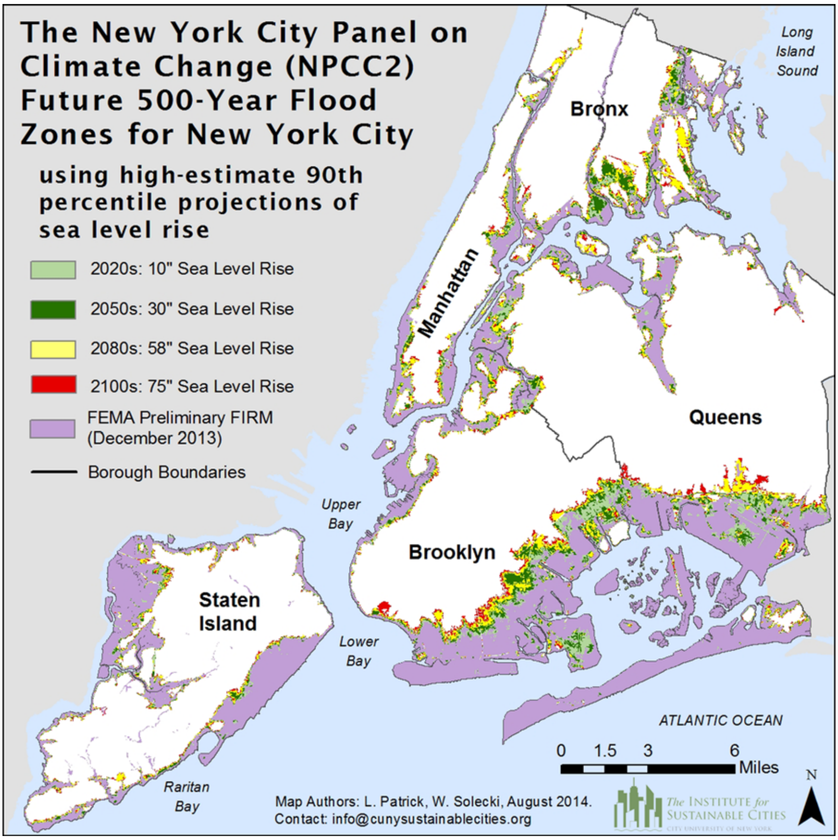

Figure 3.4. Potential areas that could be impacted by the 500-year flood in the 2020s, 2050s, 2080s, and 2100 based on NPCC2 projections of the high-estimate 90th-percentile sea level rise scenario.
Note: This map is subject to limitations in accuracy as a result of the quantitative models, datasets, and methodology used in its development. The map and data should not be used to assess actual coastal hazards, insurance requirements or property values or be used in lieu of FIRMS issued by FEMA. The flood areas delineated above in no way represent precise flood boundaries but rather illustrate three distinct areas of interest: (1) areas currently subject to the 1-in-500-year flood that will continue to be subject to flooding in the future; (2) areas that do not currently flood but are expected to potentially experience the 1-in-500-year flood in the future; and (3) areas that do not currently flood and are unlikely to do so in the timeline of the climate scenarios used in this research (end of the current century).

projections are added (see Box 3.2). As mentioned above, FEMA's 2013 Preliminary FIRMs and 500-year Flood Hazard Still Water Elevation Raster present flood elevations and extents that are on the high end of previous estimates (see Chapter 4 of NPCC, 2015 for further discussion). Projecting future sea level rise impacts on the 100- and 500-year flood areas also involves uncertainties regardless of the methodology. Uncertainty in the elevation data, the sea level rise projections, and FEMA model outputs (BFE and SWEL data) contribute to uncertainty that is difficult to quantify.

In addition, the static coastal flood-modeling methodology involves different uncertainties than those encountered in the dynamic modeling methodology. The static GIS-based methodology does not take into consideration the effects of soils, vegetation, surface permeability, infrastructure (e.g., drainage systems), structures, friction, and other factors that can act to limit or increase the extent of flooding at local scales (in most cases these factors will likely limit the extent of flooding). For example, the landward extents of FEMA's dynamically modeled 100- and 500-year flood areas do not simply follow topographic contours but are influenced by shoreline protection features (e.g., rip-rap, bulkheads), land use/land cover, and infrastructure obstructions. Because these are not taken

Box 3.2. NPCC2 mapping data limitations

Critical issues related to future coastal flood mapping are the vertical accuracy of the elevation data, the consistency of flood elevation data, and the inherent uncertainties in the information presented. (See Appendix IIC for further details.)

Vertical accuracy of elevation data

The absolute vertical accuracy of the topographic elevation dataset must be known in order to determine if the sea level rise increments used are supported by the underlying elevation data. Using sea level rise increments that are smaller than the bounds of the statistical uncertainty of the elevation data, defined as the linear error at 95% confidence, will yield questionable results. The 90th-percentile NPCC2 sea level rise projections of 10 inches (25.4 cm) for the 2020s, 30 inches (76.2 cm) for the 2050s, 58 inches (145.3 cm) for the 2080s, and 75 inches (190.5 cm) for 2100 all exceed the 95% error bounds of the elevation data.

Dataset consistency

Because base flood elevations incorporating wave heights and wave runup were not calculated for the 2013 Preliminary FIRM 500-year flood extent, 500-year SWEL data were used as a proxy.

Table 3.1. Inundation areas for current and projected 100- and 500-year flood scenarios. Sources: 100-year flood scenario from *A Stronger, More Resilient New York*; 500-year flood scenario calculated by NPCC2.

100-year flood scenario	**Area (mi^2)**
FEMA 2013 Preliminary FIRM	50
Projected 2020s, 10”	59
Projected 2050s, 30”	72
Projected 2080s, 58”	85
Projected 2100s, 75”	91
500-year flood scenario	**Area (mi^2)**
FEMA preliminary FIRM	66
Projected 2020s, 10”	76
Projected 2050s, 30”	84
Projected 2080s, 58”	94
Projected 2100s, 75”	99

into account in the static modeling approach, the NPCC2 future flood maps may overestimate flood extent in areas where shoreline features such as seawalls and bulkheads have a large effect on floodwater movement. See Chapter 4 for a comparison of the results using the static and the dynamic modeling approaches for future flood mapping.

The NPCC2 maps do, however, account for hydrologic connectivity in the flood area, such that only land areas with direct connection to the ocean or flooded waterways are considered flooded. Hydrologic connectivity is a useful refinement to a static coastal flood-modeling approach that effectively eliminates from inclusion low-elevation areas surrounded by areas of higher elevation. That said, it is possible to experience inland flooding in areas not connected to the ocean or other water bodies due to flooding in underground passageways (e.g., transportation tunnels, sewers, utility conduits) or to an increase in hydrostatic pressure that elevates groundwater levels at inland locations. Neither static nor dynamic modeling takes this into account. Without a method to account for such underground water movement, future flood maps may underestimate the extent of flooded inland areas.

Further, the NPCC2 future flood maps do not contain flood-elevation information and should not be used to evaluate site-specific flood hazards or be used in lieu of FEMA FIRMs to determine building elevation or insurance requirements. The presence of man-made structures, permeable soils, vegetation, and other impediments to water movement will affect the extent of flooding, and these effects are not captured in the maps.

3.5 Conclusions and recommendations

The NPCC2 100- and 500-year future flood maps are presented as two-dimensional delineations of potential flood extent. Their intent and value lie in illustrating three distinct citywide areas of interest that should be monitored as sea level rise projections are updated through the 21st century: (1) areas currently within the 100- and 500-year flood areas; (2) areas that are not currently within the 100- and 500-year flood areas but will potentially be in the future; and (3) areas that are not currently in the 100- and 500-year flood areas and are unlikely to be in flood areas during the time slices used in this report. In Chapter 4 (NPCC, 2015) the NPCC2 sea level rise projections are incorporated into a dynamic storm surge model to more fully explore future flooding potential and to compare methodologies.

Future work should focus on quantifying the sources of uncertainty in both the data sets used to develop these maps and in the mapping process, and in displaying this uncertainty on the maps themselves. Known vertical uncertainties include those associated with the estimates of sea level rise and with the topographic LiDAR data (see Appendix IIC, NPCC, 2015).

Additional mapping work should consider alternative methods of assessing the extent of coastal flooding associated with different return periods and considering directly the effects of projected climate conditions using dynamic models with synthetic hurricanes (Emmanuel *et al.,* 2006; Lin *et al.,* 2012). Hurricane models such as these typically use large-scale atmospheric and oceanic data as input, which can be generated from global climate models (GCMs). Dynamic models with synthetic hurricanes could be used to prepare maps for both current and future climate conditions using the same methodology. This proposed future work will allow for the consideration of both 100- and 500-year average return periods as well as events with lower probabilities of occurrence that may produce large flooding extents similar to that which occurred during Hurricane Sandy.

Other future work of particular interest to stakeholders and planners are site-specific flood depth calculations. Estimates of uncertainty associated with the elevation, sea level rise, and FEMA flood heights should be used to determine to what degree of confidence flood depth calculations could be determined. Although the 90th-percentile sea level rise projections exceed the 95% error bounds of the elevation data, other sources of error such as those associated with FEMA's base flood elevations may not. The error associated with flood-depth calculations may exceed the value of those depths themselves.

Finally, future work should also consider the biophysical and social vulnerabilities to current and future flood events through the development of indices (Cutter *et al.,* 2000, 2003; Cutter and Finch, 2008; Flanagan *et al.,* 2011; Kleinosky *et al.,* 2006; Maantay *et al.,* 2009; Rygel *et al.,* 2006; Wu *et al.,* 2002). Storms are not "equal-impact events" because social and physical geographies interact to expose vulnerable populations to elevated risk (Cutter, 1996). Not all populations are exposed to the same degree of flooding: some will experience more wave action and greater flood heights than others, and not all populations have the same capacity to prepare for, respond to, and recover from a flood event. An overall flood vulnerability index that combines both social and biophysical vulnerability can characterize site-specific levels of risk to flood hazards and identify communities that may require special attention, planning efforts, and mobilization to respond to and recover from such disasters and hazards.

References

City of New York. 2013. New York City Special Initiative on Rebuilding and Resiliency, *A Stronger, More Resilient New York*. New York: 438pp.

Clarke, K.C. 1997. *Getting Started with Geographic Information Systems*. Upper Saddle River, NJ: Prentice Hall.

Crowell, M., E. Hirsch, and T.L. Hayes. 2007. Improving FEMA's coastal risk assessment through the National Flood Insurance Program: an historical overview. *Mar. Technol. Soc. J.* **41:** 18–27.

Cutter, S.L., 1996. Vulnerability to environmental hazards. *Prog. Human Geography* **20**(4): 529–539.

Cutter, S., B. Boruff, and W.L. Shirley. 2003. Social vulnerability to environmental hazards. *Soc. Sci. Q.* **84:** 242–261.

Cutter, S.L. and C. Finch. 2008. Temporal and spatial changes in social vulnerability to natural hazards. *Proc. Natl. Acad. Sci. USA*, **105:** 2301–2306.

Cutter, S.L., J.T. Mitchell, J.T., and M.S. Scott. 2000. Revealing the vulnerability of people and places: a case study of Georgetown County, South Carolina. *Ann. Assoc. Am. Geogr.* **90:** 713–737.

Emmanuel, K., S. Ravela, E. Vivant, and C. Risi. 2006. A statistical deterministic approach to hurricane risk assessment. *Bull. Am. Meteor. Soc.* **87:** 299–314.

Federal Emergency Management Agency (FEMA). 2013. *Flood Insurance Study: City of New York, New York, Bronx County, Richmond County, New York County, Queens County, Kings County*, 131. Washington, DC: FEMA.

Flanagan, B.E., E. Gregory, E. Hallisey, *et al.* 2011. A social vulnerability index for disaster management. *J. Homel. Secur. Emerg. Manag.* **8**(1): Article 3.

Georgas, N., P. Orton, A. Blumberg, *et al.* 2014. The impact of tidal phase on Hurricane Sandy's flooding around New York City and Long Island Sound. *J. of Extr. Even.* **01:** 1450006.

Gesch, D.B. 2009. Analysis of Lidar elevation data for improved identification and delineation of lands vulnerable to sea-level rise. *J. Coastal Res.* Special Issue **53:** 49–58.

Kleinosky, L., B. Yarnal, and A. Fisher. 2006. Vulnerability of Hampton Roads, Virginia to storm-surge flooding and sea-level rise. *Natural Hazards* **40:** 43–70, doi:10.1007/s11069-006-0004-z.

Li, X., R.J. Rowley, J.C. Kostelnick, *et al.* 2009. GIS analysis of global impacts from sea level rise. *Photogrammetric Eng. Remote Sens.* **75:** 807–818.

Lin, N., K. Emanuel, M. Oppenheimer, and E. Vanmarcke. 2012. Physically based assessment of hurricane surge threat under climate change. *Nat. Clim. Change* **2:** 462–467.

Maantay, J., A. Maroko, and G. Culp. 2009. Using geographic information science to estimate vulnerable urban populations for flood hazard and risk assessment in New York City. In *Geospatial Techniques in Urban Hazard and Disaster Analysis.* pp. 71–91. P.S. Showalter and Y. Lu, Eds. Dordrecht: Springer Netherlands.

Mileti, D. 1999. *Disasters by Design: A Reassessment of Natural Hazards in the United States.* New York: Joseph Henry Press.

NPCC. 2010. Climate Change Adaptation in New York City: Building a Risk Management Response, New York City Panel on Climate Change 2010 Report. C. Rosenzweig and W. Solecki, Eds. *Ann. N.Y. Acad. Sci.* **1196:** 1–354.

NPCC. 2013. *Climate Risk Information 2013: Observations, Climate Change Projections, and Maps.* New York: New York.

NPCC. 2015. Building the Knowledge Base for Climate Resiliency: New York City Panel on Climate Change 2015 Report. C. Rosenzweig and W. Solecki, Eds. *Ann. N.Y. Acad. Sci.* **1336**: 1–149.

NYCHMP. 2014. The City of New York Hazard Mitigation Plan. Accessed at http://www.nyc.gov/html/oem/html/planning_response/planning_hazard_mitigation_2014.shtml.

Poulter, B., and P.N. Halpin. 2008. Raster modelling of coastal flooding from sea-level rise. *Int. J. Geograph. Info. Sci.* **22:** 167–182.

Rygel, L., D. O'Sullivan, and B. Yarnal. 2006. A method for constructing a social vulnerability index: an application to hurricane storm surges in a developed country. *Mitig. Adapt. Strateg. Glob. Change* **11:** 741–764.

Titus, J.G. and C. Richman. 2001. Maps of lands vulnerable to sea level rise: modeled elevations along the U.S. Atlantic and Gulf coasts. *Climate Res.* **18:** 205–228.

Wu, S.-Y., B. Yarnal, and A. Fisher. 2002. Vulnerability of coastal communities to sea-level rise: a case study of Cape May County, New Jersey. *Climate Res.* **22:** 255–270.