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Health Exposure, Socio-Economic Vulnerability, and Infrastructure at Risk to Current and Projected Coastal Flooding in New York City

Lesley Patrick

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Health Exposure, Socio-Economic Vulnerability, and Infrastructure at Risk to Current and Projected Coastal Flooding in New York City

by

Lesley N. Patrick

A dissertation submitted to the Graduate Faculty in Earth and Environmental Sciences in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York

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The City University of New York
Abstract

Health Exposure, Socio-Economic Vulnerability, and Infrastructure at Risk to Current and Projected Coastal Flooding in New York City

by

Lesley N. Patrick

Advisor: Professor Juliana Maantay

This work uses a GIS-based methodology to develop and map a composite physical exposure, social vulnerability, and critical facilities index for New York City populations exposed to the current and predicted 100- and 500-year coastal floods. The objective is to illustrate how sea-level rise may affect future 100- and 500-year coastal floods in New York City, how these changes in future flood scenarios will affect the number and distribution of people at risk and their associated physical and socioeconomic impacts, and how these impacts will vary among neighborhoods.

Sea-level rise throughout the 21st century will result in increased flood exposure as current flood levels are achieved more frequently and new flood levels result in more widespread inundation. To increase the resiliency of coastal communities and allow populations to respond and recover to these hazards, it is important to develop a place-based understanding of how storm surge exposure, impacts, and community vulnerability will change over time. Both the physical and socioeconomic impacts of flooding events are often unevenly distributed, with socially vulnerable groups most likely to experience a disproportionate share of the detrimental effects. When both physical and socioeconomic vulnerability are present in combination, the risk to populations is exacerbated. Physical exposure, social vulnerability, and critical infrastructure are
combined to form an overall storm surge flood risk index that characterizes site-specific neighborhood levels of risk to flood hazard. Results show that future sea-level rise will increase the population at risk to the 100- and 500-year coastal floods, particularly under scenarios of potential population growth and distribution in the coastal and near-coastal zones. New York City must consider sea-level rise in their long term planning efforts to make coastal communities more resilient to future flood hazards.
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Chapter 1: Introduction

Coastal regions around the world are experiencing the effects of sea-level rise on local and regional flood events and these effects are expected to increase into the future (IPCC 2014a, 2014b, 2013, 2012; FitzGerald et al. 2008; Williams et al. 2009). Flood events pose great threat to the safety of coastal residents, their infrastructure, networks, and economy, and sea-level rise may exacerbate these threats by increasing the volume and extent of floodwaters. Sea-level rise alters the coastline physically, changing coastal landscapes through erosion and permanent land loss; barrier island breaching, segmentation and migration; and wetland ecosystem drowning. These physical changes to the coast can affect the movement of storm surge on land and result in increased impacts to infrastructure and coastal communities (FitzGerald et al. 2008; Gesch 2009; Williams et al. 2009). It is important to understand the distribution and extent of sea-level rise enhanced flood events in order to develop plans and policies that mitigate potential hazards and make the coastal region more resilient to storm surge.

While global sea levels are rising, global population is increasing and will continue to do so into the future. The world’s population is currently estimated to be 7.1 billion and is predicted to reach 9.38 billion by the year 2050 (US Census Bureau n.d.). One of the effects of this population increase is an overall migration from inland to high-risk coastal areas, increasing the density of people and infrastructure in places already vulnerable to flood hazards. McGranahan et al. (2007) assert that 10% of the global population is living less than 10m above sea level and that the urbanization rate in these low elevation coastal zones is 60%, compared to the global urbanization rate of less than 50%. In fact eight of the 10 largest cities in the world are coastal,
and in the United States 14 of the 20 largest cities are situated within 100km of the coast and less than 10m above sea level (Williams et al. 2009). Nicholls and Small (2002) estimate that by 1990, 1.2 billion people or approximately 23% of the world’s population was living within 100m of sea level and 100km from a coast. According to the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) this number could increase to 1.8 or 5.2 billion by the 2080s, depending on assumptions about coastward migration (Angel et al. 2011).

Continued growth of the low-lying coasts increases the vulnerability of these areas and exposes larger populations to coastal hazards such as inundation and storm surge (FitzGerald et al. 2008). With sea-level rise coastal regions will become more vulnerable as storm surge, founded upon higher sea levels, increases in elevation and inundation extent. Coastal flood events of a given magnitude – i.e., the 100-year flood - will have greater recurrence intervals in the future while new elevation benchmarks for those events are established. This means that new communities will become at-risk to flooding and communities currently at-risk will experience more frequent and intense flooding. An important component in the assessment of the vulnerability of a region to current and future flood impacts is the recognition that flood impacts will be disproportionate, influenced not only by differences in physical exposure to floodwaters but also by spatial variations in social and economic vulnerabilities (Wisner et al. 2003).

Over the past two decades emergency managers, prompted by an increase in the losses experienced through flood-related natural disasters (Pielke and Downton 2000; National Oceanic and Atmospheric Administration 2014), have shifted their attention from disaster response to
pre-event planning and preparedness. This shift is reflected in policies that emphasize preparation, mitigation, and adaptation strategies in addition to recovery measures. Assessments of who and what are exposed to flood hazards, how populations are differently vulnerable, and the impacts of exposure are necessary to develop structural and non-structural mitigation plans that are effective in increasing a system’s or society’s resilience. In New York and many other coastal cities, sea-level rise will increase the frequency and intensity of flood events, compressing the time scale over which floods will evolve (Horton et al. 2015). Coastal cities need to consider the intersection of flood inundation, the exacerbating effects of future sea-level rise, and residential development in coastal areas to identify existing and emerging areas of hazard and conduct vulnerability assessments to inform hazard mitigation plans as well as long-term risk reduction plans (Cutter and Finch 2008).

1.1. Objective and Hypothesis

The objective of this research is to determine how sea-level rise projections may alter the potential socioeconomic impacts of contemporary 100- and 500-year coastal flood events and of future flood events enhanced by sea-level rise scenarios, how changing flood exposure may affect the number and distribution of people at risk, and how flood impacts will vary among neighborhoods. This paper is founded on the (Cutter 1996; Cutter, Boruff, and Shirley 2003) hazards-of-place model of vulnerability that incorporates both biophysical and social indicators to evaluate overall vulnerability at the local level. Hazard exposure and community vulnerability are combined to spatially characterize risk for both present and future flood events.
Two key questions form the foundation of this work:

1. How will sea-level rise in the 2020s and 2050s:
   - Affect the area and population exposed to the 100- and 500-year coastal floods in all neighborhoods of New York City?
   - Create new areas of physical vulnerability and increase existing physical vulnerability in neighborhoods currently at-risk?
   - Interact with existing areas of social vulnerability and contribute to the landscape of overall storm surge flood risk?

2. Which elements of vulnerability exert the most influence on overall storm surge flood risk and how this does this influence vary with location?

The impacts of flood events are not evenly distributed among coastal communities. Both social and physical geographies interact to expose vulnerable populations to an elevated risk. In this work, a combined evaluation of floodwater exposure, social vulnerability, at-risk critical facilities, and potential floodwater contaminants provides a metric to rank neighborhood risk to flood hazards through an overall storm surge risk index that characterizes site-specific levels of risk to flood hazard. Using recent publically available sociodemographic data will allow community planners to identify pockets of socially and physically vulnerable populations and develop targeted resiliency strategies. The overlap of socially vulnerable populations with physical hazard will highlight the needs of communities that may require special attention, planning efforts, and mobilization to respond to and recover from disasters and hazards.
Other studies have aimed to measure and quantify community exposure and vulnerability to current and future hurricane storm surge scenarios. Shepard et al. (2012) apply a GIS based approach to assess future risk to sea-level rise and storm surge along the southern shores of Long Island, New York. Using publically available data sets such as US Census and SLOSH (Sea, Lake and Overland Surges from Hurricanes) model output, they develop three indices that capture exposure, social vulnerability, and critical infrastructure and facilities at risk to category 3 hurricane inundation scenarios both with and without sea-level rise. The fourth and final index captures ‘overall risk’ and is a product of the three indices above. The overall risk index represents the combined vulnerability of the people, property, and resources within a community.

They conclude that with sea-level rise 1) existing risk will likely increase and new areas of risk will emerge; and 2) increases in inundation area can in some areas result in amplified impacts. Frazier et al. (2010) also use US Census and SLOSH datasets to assess variations in socioeconomic exposure (i.e., populations, economic activity, and critical facilities) to category 1 - 5 hurricane storm surge scenarios both with and without sea-level rise in Sarasota County, Florida. They determine that, due to sea-level rise, socioeconomic exposure in hazard zones will increase and smaller hurricanes will resemble the surge of larger ones. Furthermore, an analysis of Sarasota County’s 2050 comprehensive plans shows concentrated population growth in the current and future storm surge risk zones.

This work is similar to previous efforts in purpose and scope but also unique in its choice of flood events, study area, and methodologies. For example, instead of evaluating sea-level rise inundation or hurricane storm surge scenarios as is commonly done, this work focuses on the 100- and 500-year flood events because they are used as benchmarks for insurance requirements
and/or planning scenarios and refer to a flood volume instead of a specific storm event. In this regard, the 100- or 500-year flood is broadly applicable and could be a product of wintertime nor’easters or of hurricanes of varying category strengths and path directions. It is also an appropriate selection for New York City as an East Coast locale with a relatively low frequency of direct and indirect hurricane hits (Smith 1999). Also unique is the use of a disaggregation technique to generate a more refined estimate of the population situated within flood zones. By scaling U.S. Census population data to a smaller unit of analysis (i.e., the tax lot) the selection of flooded areas located adjacent to flood boundaries is made at a finer resolution. The result is a more accurate representation of the count and distribution of the flood exposed population. Other studies (Rygel, O’sullivan, and Yarnal 2006; Kleinosky, Yarnal, and Fisher 2006; Wu, Yarnal, and Fisher 2002) use coarser methods such as centroid containment or areal weighting to select flooded populations at larger spatial units of analysis, resulting in greater margins of error (see section 6.2.2 for a discussion of floodplain population estimation techniques).

The assessment of overall storm surge flood risk in New York City is a unique challenge due to its population diversity and density. NYC is one of the densest and most ethnically and culturally diverse cities in the United States with great variation in the national origin, race, religion, income, and education attainment of its residents. The most ethnically diverse county is Queens. Queens also realizes incredible linguistic diversity with nearly 800 languages spoken by residents, 47.8% of which are identified as foreign born. What makes this diversity unique in the cityscape of NYC is that it is realized at incredible population densities. The heterogeneity of population characteristics is reflected in a spatial context when the socioeconomic and demographic data are used to assess vulnerability at the tax lot scale.
This research moves beyond the classic hazards-of-place vulnerability approach of overlapping biophysical and social vulnerabilities and incorporates two additional place-based factors that may also contribute to vulnerability: the potential contamination of floodwaters by spills or leaks of hazardous wastes and the compromise of facilities that serve the population in critically important ways. Hazardous wastes may have immediate and long-term impacts when they come into contact with the environment and population and could leak, spill, or overflow into floodwaters during flood events. They are included as a separate floodwater contaminants index that attenuates or enhances the biophysical (exposure) vulnerability. The contaminants index uses residential proximity to potential contaminant sources as an indicator of the degree of risk. Also considered as a separate index are critical facilities such as correctional facilities, group homes, and psychiatric care centers, that provide temporary or long-term residence in a group setting to large populations that may be sick or disabled. These facilities house a “special needs” population and warrant particular attention because of their complex and resource intensive evacuation needs. If they are situated in a flood zone, these facilities would need additional time for evacuation as well as arrangements for the relocation of residents, therefore these facilities are particularly important to identify in the context of citywide emergency planning and response.

The purpose of combining physical and social vulnerabilities and critical facilities in a spatial context is to identify the factors that contribute to local differences in vulnerability and target mitigation efforts at the most vulnerable groups to increase community resilience to future hazards.
1.2. Research Overview

This work uses a GIS-based methodology to develop and map a composite exposure and infrastructure vulnerability index for New York City populations within existing and predicted flood zones to assess overall flood risk at the intersection of exposure and vulnerability. Four individual indices were constructed using sociodemographic, cadastral, flood extent, and infrastructure-based datasets, each capturing an aspect of the risk populations face during flood events. These indices were then combined to form an overall storm surge flood risk index at the tax lot level. The index was mapped to illustrate the distribution of flood risk throughout the flood zones of the city and to highlight the most vulnerable areas.

The four individual indices are listed from left to right in Figure 1.1, and combined to form the overall storm surge flood risk index at the top of the figure. The first index, the storm surge exposure index, is founded upon the premise that higher floodwater elevations and high velocity breaking waves pose a greater threat to communities than smaller floodwater heights without wave action. This index ranks the degree to which people may be exposed to floodwaters and is intended to convey the potential for harm at different locations. Areas that rank higher on this index will likely experience greater damage to buildings and infrastructure, and have populations that are at greater risk to injury or mortality than areas that rank lower on the index. The second index is the social vulnerability index, which uses socioeconomic indicators derived from the US Census and American Community Survey to identify groups that have greater difficulty coping, adapting, or responding to flood events. These indicators describe characteristics of the population that are present even when a flood hazard is not present, yet these characteristics can
render residents particularly vulnerable when these events do occur. The indicators used in this social vulnerability index are listed in Figure 1.1.

**Figure 1.1.** The four individual indices - storm surge exposure index, social vulnerability index, critical facilities index, and storm surge floodwater contaminants index - that comprise the overall storm surge flood risk index. The components of the individual indices are listed below them.

The third index, the critical facilities index, considers facilities that provide essential services to residents and may become vulnerable to damage or failure during a flood event. Facility types were grouped into two categories: Group 1 comprised of facilities serving or temporarily housing a population needing direct assistance for mobility (e.g., disabled persons and/or the elderly) and
Group 2 consisting of facilities with complex evacuation and/or recovery needs (e.g., correctional facilities, single and family shelters, schools and day care centers). The grouping of the facilities is intended to convey a potentially greater vulnerability for Group 1 facilities than house people with mobility issues. Emergency managers should target areas with high concentrations of critical facilities to allow for coordinated evacuation and other preparatory measures (Morrow 2008). Finally, the fourth index - floodwater contaminants - uses residential proximity to facilities that handle or store toxic wastes as the criteria by which to evaluate the potential for exposure to chemicals and other hazards that may be released in floodwaters during a flood event. The nine types of facilities included in this index are listed in Figure 1.1. Finally, the four individual indices are aggregated without weights to form the overall storm surge flood risk index. By creating an overall flood risk index multiple aspects of potential vulnerability to flood events can be represented with one value and compared citywide. Also the incorporation of both physical social vulnerabilities into the overall storm surge flood risk index offers a place-based understanding of the local landscape of risk.

1.3. Document Structure

This work is divided into eight chapters in the following order: an introduction chapter, four background chapters, a methodology chapter, results and discussion, and a conclusions chapter with references and appendices at the end. This introduction chapter describes the goals and hypotheses of the dissertation itself and offers context for the questions being examined at the study location. The second chapter reviews the concept of vulnerability in the context of natural hazards and disasters as well as the evolution of models of social vulnerability. Social vulnerability assessments and indices developed in previous research are reviewed. Chapter three
describes global and regional trends of sea-level rise, sea-level rise projections for the New York City region, and the impact of sea-level rise on future flood events. Chapter four discusses the potential for sites of industrial wastes and other toxics sited along the waterfront to release hazardous materials into floodwaters during coastal flood events. Chapter five describes critical facilities in New York City that are situated in areas that are at-risk to current and future flood events. The sixth chapter describes the GIS methodologies of spatial analysis that were used to develop each of the four component indices, the overall storm surge flood risk index, and the spatial autocorrelation analysis. Chapter seven presents the results of the analysis and discusses the implications. Chapter eight states the conclusions of this work and discusses the limitations and opportunities for future analysis.
Chapter 2: Hazard and Vulnerability Assessments

Assessments of hazards and vulnerability have been widely used by planners, decision makers, and emergency managers to identify the areas most in need of assistance before, during, and after a disaster event. The following section discusses the emergence of hazard vulnerability research, the role of social vulnerability assessments in hazard planning, mitigation, and disaster response and recovery, and the utility of maps as visualization tools for improved planning and response.

2.1. Key Terms and Definitions

Throughout the research literature relating to hazards and vulnerability, the definition of key terms such as ‘risk’ and ‘vulnerability’ have varied when derived from different epistemologies, conceptual models, and frameworks. Other terms are used interchangeably as exemplified by the use of ‘vulnerability assessment’, ‘hazard assessment’, and ‘risk assessment’ to broadly describe the assessment of physical exposure and/or social vulnerability to a hazard. Still other terms have different meanings depending on field of research in which they are used. For example, the term ‘resilience’ is an outcome (i.e., ability to cope) in the hazards community but a process (i.e., learning and improving their capacity to handle hazards) in the global environmental change literature (Cutter et al. 2008). This work uses key terms that have accrued multiple definitions in the literature. To avoid confusion, table 2.1 lists these terms and defines them within the context of this work.
<table>
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<th>Key Terms and Definitions</th>
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<tr>
<td><strong>Adaptation</strong></td>
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<td><strong>Adaptive Capacity</strong></td>
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<td><strong>Biophysical Vulnerability</strong></td>
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<td><strong>Coping Capacity</strong></td>
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<td><strong>Resilience</strong></td>
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<td><strong>Social Vulnerability</strong></td>
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Table 2.1. The key terms used in this work and their definitions.
2.2. Hazard Vulnerability Research

Historically hazards research has been a pragmatic endeavor, solving practical problems stemming from extreme natural events. The first risk/hazards paradigm developed in the 1940s was an exposure-based approach that focused on the identification and distribution of human-occupied hazard zones, the range of adjustments available to individuals and society for reducing impact, and social acceptance or tolerance of the risks inherent with living in hazard zones (Cutter, Mitchell, and Scott 2000; Cutter et al. 2009). This approach was prominent until the 1970s when critiques emerged citing this hazard-centric approach as narrow in theory and lacking perspective on the role of human agency. Researchers began to argue for a broader view that considered the social construction of natural hazards and the socioeconomic drivers that make populations vulnerable to physical hazards.

The theoretical foundations of hazard vulnerability research continued to evolve as new conceptual models were developed. The three most commonly cited of these include the pressure and release model of disaster (Blaikie et al. 1994; Wisner et al. 2003), the hazards-of-place model (Cutter 1996), and the vulnerability/sustainability framework (Turner et al. 2003). The pressure and release model views disasters as existing at the intersection of physical exposure to a hazard on one end and a series of ‘pressures’ that create progressively greater vulnerability on the other. This human-centric approach tracks the impacts of hazards on a population from root causes to dynamic pressures to the unsafe conditions that create vulnerability. However the pressure and release model fails to cite the interaction of human and natural environments in the production of disasters and neglects the role of proximity to hazards (Cutter et al. 2008, 2009).
The hazards-of-place model (Figure 2.1) uses elements of the original risk/hazards paradigm and the pressure and release model, framing vulnerability as both a biophysical risk and social response but within the context of a specific geographic or social spatial domain (Cutter 1996; Cutter, Mitchell, and Scott 2000; Wu, Yarnal, and Fisher 2002). It is a placed-based perspective that emphasizes the interaction of physical and social vulnerability in a spatial and temporal context. In Figure 2.1, risk and mitigation interact to produce the hazard potential (see Table 2.1 for definition of key terms). Risk is the likelihood of incurring harm or experiencing a negative outcome from a hazard and mitigation refers to action taken to reduce or avoid risk or damage from a hazard. The hazard potential is moderated by geographic filters such as the site and situation of the place and proximity to the hazard to produce the biophysical vulnerability. The social fabric of the place also moderates the hazard potential through the pre-existing socioeconomic and demographic characteristics that influence a community’s ability to respond to, cope with, recover from, and adapt to hazards. This interaction produces the social vulnerability of the place. Finally the biophysical and social vulnerabilities combine to form the overall place vulnerability (Cutter 1996). This model is well suited for geospatial applications and as such is useful for identifying areas of risk and vulnerable populations. However it does not consider the root causes of social vulnerability, such as limited access to power and resources, or its larger contexts.
Like the hazards-of-place model, the vulnerability/sustainability framework developed by Turner et al (2003) is also place-based, but this approach is focused on situating local vulnerabilities within the context of regional and global influences and processes. The context it provides is useful for qualitative analyses but it does not distinguish social and physical vulnerabilities nor does it provide parameters that define the beginning and end of vulnerability relative to hazards (Cutter et al. 2008, 2009).

The reconceptualization of natural hazards as both a physical event and a socially constructed situation has changed the way the researchers understand hazard vulnerability. The shift from understanding disaster as a function of physical events that act upon people and places, to a
broader definition that includes situations constructed through social, political, and economic processes is a more contextual approach that considers the combination of physical and geographic factors as essential to producing a disaster.

Assessments of hazard vulnerability are frequently used as tools to identify and describe the hazards in a given place or region that have the greatest potential for impact and to describe the consequences of that impact. They consist of three main components: an assessment of the source of the hazard and who and what is exposed to it, an assessment of impacts on the population (loss, injury, harm), and an assessment of damage to infrastructure, facilities, and the economy (Cutter et al. 2009). Vulnerability assessments can also have a human-environment focus with emphasis on the conditions that expose people and places to extreme natural events, the characteristics that create vulnerability as a social condition, and the intersection of exposure and social vulnerability at a particular place or region.

2.3. Social Vulnerability

The term ‘vulnerability’ has been conceived in two prominent ways: 1) vulnerability as the potential exposure to a physical hazard and 2) vulnerability as patterns of differential losses among people affected by exposure to hazard (Wu, Yarnal, and Fisher 2002; Rygel, O’sullivan, and Yarnal 2006). The first perspective describes biophysical vulnerability while the second perspective addresses the social construction of vulnerability. These two perspectives evolved sequentially. Early definitions of vulnerability include simply the potential for loss (Cutter 1996) and “…being prone to or susceptible to damage or injury” (Blaikie et al. 1994), perspectives that place the emphasis on the impact of the hazard. Wisner et al. (2003) reframed this view from a social perspective, defining vulnerability as “…the characteristics of a person or group in terms
of their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard”.

In the context of this work, vulnerability is the susceptibility of both biophysical and social systems to a hazard (the event or occurrence that has the potential to cause harm to people or property).

The impacts of hazardous events are often unevenly distributed among and within communities. Even though neighborhoods may experience the same level of flood inundation or storm surge, the hazard is experienced differently at the community level with vulnerable groups more likely to suffer a disproportionate share of the effects. This is because the degree to which populations are vulnerable to hazards is more than just a function of exposure to the threat; it also is contingent upon social characteristics such as income, gender and age, that affect a population’s ability to respond to hazards.

Social vulnerability is a pre-existing condition, irrespective of any natural hazard, that describes the socioeconomic and demographic factors that influence the ability of a community to prepare for, respond to, and recover from a natural hazard. It is a function of the degree of exposure to a hazard (who or what is at risk) and the susceptibility of people and places to harm, as well as an indicator of community resistance and resilience. The factors that have the most influence on social vulnerability include access to political power and representation; access to resources, information, knowledge; availability of social networks; physical mobility and health; financial resources; residential building stock; and beliefs and customs (Wisner et al. 2003; Cutter 2001). These factors can be represented by a variety of indicators derived from socioeconomic and demographic datasets.
Some of the most commonly cited indicators include age, disabilities, socioeconomic status, gender, and race. Age is a factor in the context of evacuation, with the very young and elderly facing physical difficulties in mobility. The elderly in particular are subject to health problems and are also less likely to have the economic resources to respond and recover from a disaster (Morrow 2008). People with disabilities, both physical and mental, may have limited mobility and need assistance in disaster preparation, evacuation, and response. Poverty status is an indicator of people’s ability to afford preparedness actions, emergency supplies, and recovery measures (Fothergill and Peek 2004). Though wealthy populations may experience greater impacts to property and possessions, they have a greater safety net for recovery including insurance and other financial resources. The poor are less likely to be able to absorb even small degrees of loss, have less access to critical resources including financial assistance, and are more likely to live in substandard housing (Cutter et al. 2009). Gender can be an indicator of a vulnerable population as well, with women more vulnerable to disasters then men. They are more likely to face poverty and to serve as primary care givers to children, often in single status. Racial and ethnic minorities are more vulnerable to hazards because they are more likely to live in poverty, experience discrimination in housing, and be relegated to hazard-prone areas. Alone these indicators present social challenges, but in combination they pose great social burden to people and families facing natural disasters.

Assessments of socially vulnerable populations in flood prone areas have appeared in the literature for nearly 20 years. Socioeconomic and demographic data is collected - often through the US Census - and combined to develop a relative ranking of social vulnerability at the chosen spatial unit of analysis for a given geographic area. Some of these studies used factor analysis or principal component analysis to reduce the number of census variables (indicators of
vulnerability) to a smaller subset that explains the greatest percent of the variance among the variables within the study area dataset (Clark et al. 1998; Cutter, Boruff, and Shirley 2003; Cutter and Finch 2008; Fekete 2009; Kleinosky, Yarnal, and Fisher 2006; Rygel, O’sullivan, and Yarnal 2006; Schmidtlein et al. 2008). Factor analysis applies a statistical technique to the selection of social vulnerability index values, relying less of the judgment of the practitioner to determine which indicators should be included. Other studies use best judgment to select a small number of census variables for inclusion and then use standardizing techniques or percentile ranking to create an index of social vulnerability values (Chakraborty, Tobin, and Montz 2005; Cutter, Mitchell, and Scott 2000; Flanagan et al. 2011; Maantay, Maroko, and Culp 2009).

This research selects social vulnerability indicators that are commonly understood to be prime factors in creating social vulnerability. It largely refers to the work of Maantay et al. (2009), who estimated vulnerable urban populations for flood hazard in New York City through the creation of a vulnerability index. Socioeconomic and demographic data were selected at the census block group and census tract levels. The scale of analysis is sufficient to compare values at the neighborhood level while also making generalizations about the most influential factors citywide.

2.4. Coastal Hazard Vulnerability Mapping

Many studies have produced maps of coastlines physically vulnerable to future sea-level rise scenarios. Their purpose is to illustrate the impacts of accelerated sea-level rise on coastal lands and to estimate the spatial extent of areas at risk to inundation. In these efforts, projections of sea-level rise are added to topographic contours, orthometric datum, or tidal datum to map land that could be inundated or eroded by rising seas, and to delineate potential future coastlines.
within the continental United States. However many of these studies are limited in that they only evaluate sea-level rise inundation and do not account for specific flood events, they do not connect their analyses with designated flood hazard metrics, or evaluate populations or infrastructure at-risk (Titus and Richman 2001; Mazria and Kershner 2007; Poulter and Halpin 2007; Gesch 2009; Li et al. 2009; Cooper, Beevers, and Oppenheimer 2005; Gornitz, Couch, and Hartig 2002). And though high-resolution LiDAR (light detection and ranging) elevation data is used exclusively or partially in a few studies (Larsen et al. 2004; Poulter and Halpin 2007; Titus and Wang 2008; Gesch 2009) the majority of elevation datasets used in these studies are of coarse resolution which provides limited accuracy.

Other studies do connect their analyses to flood events and evaluate the vulnerability of populations at risk. Projections of sea-level rise have been added to specific flood events such as the SLOSH (Sea, Lake and Overland Surges from Hurricanes) model, a model which estimates storm surge heights from hurricanes, to assess vulnerability within future sea-level rise enhanced storm surge zones (Wu, Yarnal, and Fisher 2002; Kleinosky, Yarnal, and Fisher 2006; Rygel, O’Sullivan, and Yarnal 2006). These studies are particularly useful in places like New York City where coastline topography dictates that sea-level rise inundation will not be experienced as a daily event but rather as the increased height and extent of storm surge events. In addition to mapping future sea-level rise scenarios, a few studies evaluate sea-level rise enhanced storm surge zones under future scenarios of population growth to assess potential emerging areas of community vulnerability (Wu, Yarnal, and Fisher 2002; Kleinosky, Yarnal, and Fisher 2006). Other studies that examine current and enhanced storm surge conditions broaden their evaluation of biophysical and social community vulnerability by incorporating economic elements such as
parcel value and land use, as well as critical infrastructure and facilities in their assessments (Frazier et al. 2010; Shepard et al. 2012).

Studies of coastal flooding and inundation are enhanced by the use of maps that illustrate the location of vulnerable lands, features, and populations. This visual imagery of storm surge is essential in conveying to decision makers, stakeholders, and the public the increased risk of flood exposure due to higher seas. Geographic information systems have become a popular tool for developing these maps and depicting social vulnerability. Maps offer a visual comparison of values within and between study areas and are used to identify the most sensitive populations. Choropleth maps in particular use degrees of shading at the spatial unit of analysis (e.g., census unit) to indicate the value of the vulnerability, with darker colors indicating greater vulnerability (Clark et al. 1998; Wu, Yarnal, and Fisher 2002; Rygel, O’sullivan, and Yarnal 2006; Chakraborty, Tobin, and Montz 2005; Cutter, Mitchell, and Scott 2000). Vulnerability maps illustrate the local or regional landscape of risks, hazards, and vulnerability (also referred to as ‘riskscapes’ or ‘hazardscapes’ (Cutter, Mitchell, and Scott 2000)) and allow for more targeted emergency planning and response.

Maps of vulnerability to current and future flood zones in New York City allow for planners, decision makers, and emergency managers to identify the areas most in need of assistance. An index of social vulnerability combined with a spatial analysis of current and future flood events identifies both the geographic areas most likely to be impacted by flood hazards and areas most likely to suffer from hazard events. These areas do not always overlap but when they do these populations experience heightened vulnerability to floods. Mapping the distribution of the most
vulnerable populations allows planners and responders to evaluate the influence of social characteristics on overall vulnerability and to respond to that range of differential vulnerabilities across the city.
Chapter 3: Sea-Level Rise and Flooding in New York City

With its hyper-dense built environment of concrete and asphalt it can be easy to forget that New York City is a city of islands. Its five boroughs are situated in the New York harbor and estuary where the Atlantic Ocean, Hudson River, and East River meet. The boroughs of Manhattan and Staten Island are individual islands while Brooklyn and Queens are both situated on the western end of Long Island, an island formed from glacial debris left behind by the recession of the Laurentide ice sheet during the last glaciation. Multiple rivers, streams, and tidal straits thread throughout and between the boroughs creating nearly 600 miles of coastline (Figure 3.1). The borough of the Bronx is separated from the rest of the city by the Harlem and East Rivers. Through its northern border, it is the only borough directly connected to the mainland. The Hudson River separates Manhattan and the Bronx from New Jersey, and the East River divides Manhattan and the Bronx from Long Island. Staten Island is bounded by the Arthur Kill to the west, the Kill van Kull to the North, and the New York Bay and Atlantic Ocean to the east and south. These coastlines range in character from sandy beaches and marshlands to bulkheads and seawalls and they are affected to differing degrees by astronomical tides and weather events.
Figure 3.1. The five boroughs of New York City and the major waterways that surround them.

New York City is over 300 mi$^2$ in area (468 mi$^2$ including water) and home to a population of 8.4 million, making it the most populous city in the United States (US Census Bureau 2013). With 27,532 people per square mile, it is also one of the most densely populated metropolitan areas in the country with Manhattan ranking as the densest county. The city’s population is projected to grow throughout the 21$^{st}$ century with historical rates of population growth suggesting an additional one million residents by the year 2040. A major concern in the context of population growth is the development of additional housing units to accommodate new residents. As of
2011 the number of housing units in NYC was 3.3 million\(^1\). Currently NYC does not have the capacity to house one million additional residents because of limitations in the development of existing neighborhoods (Keenan and Chakrabarti 2013). Although ample additional residential zoned floor area is available throughout the city for (vertical) redevelopment, the majority of it is “landlocked” meaning that the available air rights cannot be or are not incentivized to be developed. Therefore the pressure to house incoming residents has forced development in expanding floodplains with high-density commercial and residential properties springing up along many waterfront areas, replacing abandoned factories and manufacturing sites (Jacob, Gornitz, and Rosenzweig 2007). The East River corridor offers many sites on or near the water that would accommodate the development of large residential housing complexes, particularly in western Brooklyn and Queens and southern areas of the Bronx. Keenan and Chakrabarti (2013) estimate that of the one million incoming residents approximately 70% could potentially be housed through infill of existing neighborhoods while the remaining 30% would have to be housed in large, new, mixed-income residential developments along the waterfront. Though new construction in the 100-year floodplain is regulated by building codes and standards, potential future changes in flood scenarios may not be accounted for.

3.1. Recent Coastal Flood Events

Many studies have cited the increased vulnerability of New York’s shorelines to climate induced sea-level rise due to its unique geography and climatology (Rosenzweig and Solecki 2000; Gornitz, Couch, and Hartig 2002; Colle et al. 2008). Though New York City is impacted by coastal, street and fluvial flooding, coastal flooding can have the most serious effects (Federal

Emergency Management Agency (FEMA) 2007). Coastal flooding occurs during weather events such as tropical storms, hurricanes, and nor’easters when the high winds and low barometric pressure of these intense storm systems act to push ocean water inland. The water that is pushed ashore, referred to as the storm surge, is often several meters above mean water level and can be amplified by astronomic tides. New York City is especially vulnerable to storm surge because of its extensive coastlines, dense population and its unique position at the right angle hinge of New York and New Jersey. This hinge, referred to as the New York Bight, acts to hold in place storm surge that is pushed into the Lower New York Bay by the cyclonic (counterclockwise) winds of hurricane and nor’easters. The northern edge of a storm can drive surge westward along the southern coastline of Long Island and into the coasts of Staten Island and Manhattan. With New Jersey at a right angle to the south, the surge has little outlet for retreat and could potentially build to heights in excess of 32 feet according to the highest theoretical storm surge produced by SLOSH (Sea, Lake and Overland Surges from Hurricanes) hurricane surge models.

Researchers know that New York State has been frequently impacted by storm surge from tropical and extratropical storms. Though the observational record of storm events spans only the last 150 years, contemporary newspapers, personal diaries, ship logs, and town histories have been used to extend this record back to the 1620s (Boose, Chamberlin, and Foster 2001). In addition, large prehistoric storms have left telltale signs of their passing in the geological proxy record and these signals have been used to extend the storm record over a few millennia (Liu and Fearn 2000b, 2000a; Donnelly, Bryant, et al. 2001; Donnelly, Roll, et al. 2001; Donnelly et al. 2004). Using this paleotempestological technique, Scileppi and Donnelly (2007) have concluded
that numerous strong hurricanes have impacted the NYC and Long Island region over the past ~3500 years.

Though the New York coastal area has been hit by 6 major (Category 3) hurricanes since 1851 (Ludlum 1963; Blake, Landsea, and Gibney 2011; Orton et al. 2015), nor’easters and winter storms are also responsible for major coastal flooding impacts due to their broad geographic extent and surge that persists through multiple cycles of high tide, often for several days. For example, the 1962 Ash Wednesday winter storm occurred during the spring equinox and lasted over 5 tidal cycles, resulting in 6.9-foot (2.1 meter) flood elevations at the Battery, New York. The December 1992 nor’easter, which arrived on a full moon and lasted three tidal cycles, flooded the Battery with 7.9 feet (2.4 meters) of water and led to the near complete shut down of the metropolitan New York transit system with the Port Authority Trans-Hudson (PATH) trains out of operation for 10 days (Gornitz, Couch, and Hartig 2002). In comparison to nor’easters, the impact of hurricane storm surge is typically of shorter duration. For example the Great Hurricane of 1938 was moving forward at speeds of 50 - 60 mph when it made landfall on Long Island. Though it blew the East River three blocks into Manhattan the surge didn’t last a full tidal cycle. The same was true when Hurricane Sandy struck the New York/New Jersey coastal region on the evening of October 29, 2012. Its period of maximum surge at the Battery was also brief, peaking once just after high tide around 9:30pm. The surge of hurricanes may be of shorter duration than that of nor’easters but the damage inflicted may be severe. Sandy’s peak surge of over 14 feet caused unprecedented damage to the city’s infrastructure including transportation, electric and natural gas utilities, wastewater treatment facilities, buildings, and services such as fuel, healthcare and food supplies.
There has been considerable discussion as to the potential for more frequent and intense hurricanes both globally and in the North Atlantic in the future. Both the 4\textsuperscript{th} and 5\textsuperscript{th} Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) state that there have been no clear global trends in hurricane activity over the past century, in part due to the absence of satellite technology data before 1970 (Bindoff et al. 2007; Hartmann et al. 2013). However it is likely\textsuperscript{2} that the global frequency of hurricanes will either decrease or remain the same under 21\textsuperscript{st} century greenhouse warming conditions. The frequency of intense storms (Saffir-Simpson category 3 or higher) will more likely than not\textsuperscript{3} increase substantially in many regions, including the North Atlantic (Christensen et al. 2013). In fact, Emanuel (2013) downscaled the CMIP5 global climate model\textsuperscript{4} to simulate 21\textsuperscript{st} century hurricane activity and found a 40% increase in storms ranked category 3 and higher in most regions throughout the world. Though the total number of tropical storms in the North Atlantic may decrease slightly, the number of intense hurricanes, extreme hurricane winds, and the amount of intense hurricane precipitation are all more likely than not\textsuperscript{3} projected to increase by the 2080s (Horton et al. 2014), in part due to expected warming of the upper ocean in the tropical cyclone genesis regions of the North Atlantic. The trend for nor’easter in the future is unknown.

Individual storm tracks are variable and poorly understood making it unclear how an increase in intense hurricanes in the North Atlantic may impact the New York City region. However, as sea-level rise will provide a higher baseline upon which storm surges and wave action are founded, an increase in storm intensity could pose great risks to coastal communities.

\textsuperscript{2} The IPCC defines likely as a greater than 66\% probability.  
\textsuperscript{3} The IPCC defines more likely than not as a greater than 50\% probability.  
\textsuperscript{4} CMIP5 refers to the Coupled Model Intercomparison Project Phase 5 (http://cmip-pcmdi.llnl.gov/cmip5/index.html)
3.2. **Long Term Trends in Global Sea Level Change**

Evidence of fluctuations in global sea levels have been observed in the geologic record and reconstructed for the past half billion years. Since the last glacial maximum approximately 20,000 years ago, we have been in an era of global sea-level rise with ocean levels first rapidly rising nearly 400 feet and then decelerating 9,000 years ago before finally leveling out to 0.04 to 0.08 inches per decade between 3,000 and 2,000 years ago (IPCC 2007; FitzGerald et al. 2008). Rates of sea-level rise accelerated during the late 19th century with estimates for the 20th century showing a global average sea-level rise of about 0.67 inches (+/-0.08) per decade (Church and White 2011). Satellite altimeter observations indicate that the rate of global sea-level rise increased to 0.13 inches (+/-0.02) per year between 1993 and 2009 (Church and White 2011). Though multiple processes contribute to sea-level rise, thermal expansion of the oceans and melting of land-based ice have been the dominant contributors to global average rise in the 20th century. Model-based sea-level rise projections in the fifth assessment of the Intergovernmental Panel on Climate Change (Church et al. 2013) predict that sea level will rise between 10.2 and 32.3 inches for the period 2081 - 2100 (relative to 1986 - 2005), a range that considers four Representative Concentration Pathway (RCP) scenarios of atmospheric greenhouse gas concentrations. RCP8.5, the pathway with the highest greenhouse gas emissions (Riahi et al. 2011), gives a rise of 20.5 to 38.6 inches by 2100. The improved semiempirical method presented by Vermeer and Rahmstorf (2009) suggests that global sea levels could reach one or even two meters by 2100.
3.3. Regional Sea Level Change as an Emerging Issue in New York City

Climate change adaptation and resilience has only become a major policy issue in New York City in the past decade. Before that time regional changes in sea level were not of significant concern to city stakeholders, agencies, and decision-makers. Two factors that influenced this shift in policy focus were 1) an increasing trend of global awareness, conversation, and decision-making about climate change science and impacts, and 2) an increase in climate events that had significant impact on New York City infrastructure and operations. As the impacts of climate change became more tangible, there emerged a growing need to develop a rigorous base of climate science information to inform future fiscal decisions and public policy. Projections of temperatures, precipitation, and sea-level rise throughout the 21st century were first developed for NYC in 2010 as a product of climate adaptation and resilience initiatives instituted by former Mayor Michael Bloomberg. These initiatives were the very forefront of climate change policy and action in New York City.

The first major report on global climate change science, impacts, and potential response strategies was published by the Intergovernmental Panel on Climate Change (IPCC) in 1990. By the second IPCC report in 1995 the content had expanded to include adaptations and mitigation, as well as economic and social dimensions of climate change. Through the IPCC, the international scientific community identified climate change as a critical science-policy issue and developed an assessment framework that has been replicated at multiple scales. Much of the climate change literature that has emerged in New York City from the 1990’s to present is derivative of the work of the IPCC.
In 1994 the conference *Metropolitan New York in the Greenhouse: Infrastructure Planning for an Uncertain Future* was convened in New York City to prepare the region’s infrastructure for climate change impacts and to encourage direct action toward mitigation or adaptation (Hill 1996). Though scenario planning was a significant topic in the conference, the first major scenario-based scientific assessment of climate impacts across the New York Metropolitan Region wasn’t developed until 2000 as part of the first comprehensive national climate assessment. The *Metropolitan East Coast (MEC) Assessment of Impacts of Potential Climate Variability and Change* report (Rosenzweig and Solecki 2000) recommended adaptations at both conceptual and operational levels, the creation of an Inter-Agency Climate Task Force, and the creation of a Climate Awareness Program to inform decision-makers and the general public about climate change and response. Overall, the report while widely cited was not immediately translated into significant policy changes or immediate management actions.

In 2006 the Mayor of New York City, Michael Bloomberg, formally announced the creation of a new Mayoral office - the Office of Long-Term Planning and Sustainability (OLTPS). The goal of this office was to “improve New York City’s quality of life, environmental sustainability, and resilience to climate change…” by developing cohesive sustainability plans. The detailed action plan developed by OLTPS titled *PlaNYC 2030: A Greener Greater New York*, called for the development of a strategic process to adapt to climate change impacts, the creation of a New York City Climate Change Advisory Board, updates to the 100-year floodplain maps, and the need to consider site-specific strategies for highly vulnerable communities in the city.
On August 8, 2007 a severe and largely unpredicted thunderstorm caused major and in some areas prolonged service disruptions of the Metropolitan Transportation Authority’s (MTA) transit system. This and other severe weather events emphasized the immediacy of climate change impacts and elevated the importance of adaptation measures that would fortify the city. The following August 2008, the Mayor announced the creation of the New York City Climate Change Adaptation Task Force, a group made up of City and State agencies, authorities and private companies that operate, maintain, or control critical infrastructure in New York City. The taskforce was charged with developing adaptation strategies to secure the city’s infrastructure from the effects of climate change. At the same time, the Mayor brought together the New York City Panel on Climate Change (NPCC). The Panel was composed of experts from the academic, legal, insurance, and engineering sectors and was convened to serve as technical advisor the Climate Change Adaptation Task Force. Central to the panel’s charge was the development of climate change projections for New York City, including future trends in temperature, precipitation, and sea-level rise. The NPCC developed a rigorous science base that included past, current, and expected future trends and scenarios developed from downscaled global climate models, as well as future flood maps illustrating the potential extent of the 100-year floodplain with projected sea-level rise. Their work was summarized in the 2010 report, *Climate Change Adaptation in New York City: Building a Risk Management Response* (Rosenzweig and Solecki 2010), which established the scientific foundation for climate change adaptation in NYC and guided the New York City Climate Change Adaptation Task Force members in their climate change adaptation planning process.
Then Hurricane Sandy struck at the end of October 2012 bringing record storm surge of 14 feet above MLLW\(^5\) to the Battery and exceeding the acting 100-year floodplain (as defined by FEMA’s 1983 Flood Insurance Rate Maps study) by 53% (NYC Office of the Mayor 2013). Storm impacts included 43 deaths, 2 million without power, tens of thousands of buildings impacted, and $19 billion in damage. Sandy highlighted the very real vulnerability of New York City’s infrastructure, natural environments, communities, and economies to the effects of storm surge and rising sea levels.

Two months later, Mayor Bloomberg created the Special Initiative for Rebuilding and Resiliency (SIRR) to address how to create a more resilient New York City in the wake of Hurricane Sandy. This initiative convened the Second New York City Panel on Climate Change (NPCC2), established them as a permanent body, and charged them with developing updated climate projections and future 100- and 500-year flood maps for New York City. The 400-page report of the SIRR, *PlaNYC: A Stronger, More Resilient New York*, was released on June 11, 2013 and focused on preparing for and protecting against the impacts of climate change (NYC Office of the Mayor 2013). Critical to informing this report of the relevant emerging climate science was the new release from the NPCC2 titled *Climate Risk Information 2013: Observations, Climate Change Projections, and Maps* (New York City Panel on Climate Change 2013a). This report contained updated future climate projections for New York City, including data on mean annual temperatures, total annual precipitation, sea-level rise, and extreme events. The NPCC2 has since updated and extended their 2013 climate projections for a 2015 publication in the Annals of the New York Academy of Sciences.

\(^5\) Mean Lower Low Water (MLLW) refers to the average height of the lowest tide recorded at a tide station each day during the recording period. See NOAA’s Tides and Currents website (http://tidesandcurrents.noaa.gov/datum_options.html) for more information on tidal datums.
3.3.1. Regional Rates of Sea Level Change: NPCC and NPCC2 Sea-Level Rise Projections

Currently, rates of relative sea-level rise in New York City as measured by tide gauges range between 0.86 and 1.5 inches per decade (2.9 and 3.8 cm) with the long term rate since 1900 averaging 1.2 inches per decade (3.1 cm). Approximately 40% of this rise is regional land subsidence, a process by which the land “sinks” in response to the retreat of the ice sheets after the last glacial maximum. Sea levels are rising twice as fast locally (1.2 inches per decade) as they are globally (0.67 inches per decade) (Horton et al. 2015).

In 2010, 2013, and 2015 the New York City Panel on Climate Change released 21st century projections for climate change and sea level rise in the New York City region. In their 2010 report, the NPCC presented two sets of sea level rise projections: one based on IPCC methods and a second “rapid ice melt” (RIM) scenario based on paleoclimate data. The IPCC-based methods approach considers multiple components such as global thermal expansion of water, local land subsidence, meltwater from glacier, ice caps, and ice sheets, and local water surface elevation, in the development of regional sea level rise scenarios. It uses seven global circulation models (GCMs) and the B1, A1B, and B2 emissions scenarios to develop sea-level rise projections for three time slices - 2020s, 2050s, and 2080s - each centered on a given decade (e.g., 2050 - 2059). These results indicate that sea level could rise 2 to 5 inches by the 2020s, 7 to 12 inches by the 2050s, and 12 to 23 inches by the 2080s relative to the baseline period of 2000-2004 (Table 3.1).

However, discussion in the scientific community suggested that the GCMs used in the IPCC Fourth Assessment Report (AR4) might have underestimated the range of possible sea level rise
(IPCC 2007). The probability of sea-level rise lower than the GCM projections of the IPCC-based methods is very low, but the probability of the sea-level rise exceeding the IPCC-based projections is higher. To address this possibility an alternative “rapid ice-melt” scenario was devised based on paleoclimate studies and extrapolated rates of ice melt from the West Antarctic and Greenland ice sheets. These polar ice sheets have the potential to contribute significantly to SLR if the current melt patterns continue to accelerate. Rapid Ice Melt projections suggest 5 to 10 inches by the 2020s, 19 to 29 inches by the 2050s, and 41 to 55 inches by the 2080s (Table 3.1).

New York City Panel on Climate Change, 2010

<table>
<thead>
<tr>
<th></th>
<th>Central range¹ sea-level rise projections</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Baseline 2000-2004</td>
</tr>
<tr>
<td>IPCC-based methods²</td>
<td>NA</td>
</tr>
<tr>
<td>Rapid ice-melt scenario³</td>
<td>NA</td>
</tr>
</tbody>
</table>

¹ Central range = middle 67% of values from model-based probabilities rounded to the nearest inch.
² The model-based sea-level rise projections.
³ “Rapid ice-melt” scenario is based on acceleration of recent rates of ice melt in the Greenland and West Antarctic ice sheets and paleoclimate studies.

Table 3.1. NPCC 2010 baseline sea-level rise and mean annual changes. Table modified from Rosenzweig and Solecki, 2010.

When reconvened in the wake of Hurricane Sandy in 2013, the Second New York City Panel on Climate Change (NPCC2) developed new climate change projections for the 2020s and 2050s. These projections were generally consistent with those produced in 2010 however the temperature and precipitation outcomes were founded upon a new and larger set of GCMs and updated emissions scenarios known as representative concentration pathways (RCPs). Sea-level rise projections were no longer founded on the GCM and rapid-ice melt methods, but instead
were developed using an expanded component-by-component approach. This component-based approach aggregates the following primary elements of sea-level change: meltwater from ice caps, glaciers, and ice sheets; the “fingerprint” of ice mass changes on land; vertical land movements (glacioisostatic adjustments); global thermal expansion of ocean water; and land water storage (New York City Panel on Climate Change 2013b). The 10th, 25th, 75th and 90th percentile values were estimated for each component, and all components at each percentile summed to give the aggregate sea level rise projection. For the 2020s these projections suggest a low-estimate (10th percentile) of 2 inches, a middle range (25th - 75th percentile) of 4 to 8 inches, and a high-estimate (90th percentile) of 11 inches, and for the 2050s a low-estimate of 7 inches, a middle range of 11 to 24 inches, and a high-estimate of 31 inches by the 2050s (Table 3.2). The 2013 NPCC2 sea-level rise projections for the 2020s and 2050s are the primary dataset used in this work to evaluate the population and infrastructure vulnerable to future flood events. Though the 2013 projections were superseded by the NPCC2 in 2015, these more recent projections were not available at the time of this analysis.

<table>
<thead>
<tr>
<th>Sea-level rise Baseline (2000-2004) 0 inches</th>
<th>Low Estimate (10th percentile)</th>
<th>Middle Range (25th - 75th percentile)</th>
<th>High Estimate (90th percentile)</th>
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<tr>
<td>2020s</td>
<td>2 inches</td>
<td>4 to 8 inches</td>
<td>11 inches</td>
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<tr>
<td>2050s</td>
<td>7 inches</td>
<td>11 to 24 inches</td>
<td>31 inches</td>
</tr>
</tbody>
</table>

Table 3.2. NPCC 2013 baseline sea-level rise and mean annual changes. Values are rounded to the nearest inch. Source: New York City Panel on Climate Change, 2013a.

In 2015 the NPCC2 released their most recent sea-level rise projections to date using the same expanded component-by-component based approach used in 2013. Estimates for the 2020s and 2050s were slightly refined and new projections for the 2080s and 2100 were included (Table
3.3). For the 2020s and 2050s, the high 90th percentile estimates were lowered by an inch relative to 2013 values bringing the projections to 10 and 30 inches respectively. Also the low 10th percentile estimate for the 2050s was raised from 7 to 8 inches. For the 2080s, projections indicate a low 10th percentile estimate of 13 inches, a middle range of 18 to 39 inches, and a high 90th percentile estimate of 58 inches, and for 2100 a low 10th percentile estimate of 15 inches, a middle range of 22 to 50 inches, and a high 90th percentile estimate of 75 inches.

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<tbody>
<tr>
<td>2020s</td>
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<td>2050s</td>
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<td>2080s</td>
<td>13 inches</td>
<td>18 to 39 inches</td>
<td>58 inches</td>
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<tr>
<td>2100</td>
<td>15 inches</td>
<td>22 to 50 inches</td>
<td>75 inches</td>
</tr>
</tbody>
</table>

Table 3.3. NPCC 2015 sea-level rise projections. Values are rounded to the nearest inch. Source: (Horton et al. 2015).

The NPCC2 also determined that as sea levels rise coastal flood heights will increase and floods of a given magnitude will occur with greater frequency.

3.4. Mapping Current and Sea-Level Rise Enhanced Flood Extents

When considering the impacts of sea-level rise on New York City’s coasts, the NPCC chose to focus on the 100-year floodplain instead of coastal inundation or hurricane surge scenarios. There were two prominent reasons for this decision: 1) the 100-year flood is used as the current critical benchmark for major land use, flood insurance, and policy decisions and therefore politically meaningful, and 2) as a theoretical value the 100-year flood can be used to
approximate potential flooding events, irrespective of the storm event with which they are associated. The 100-year flood, also referred to as the 1-in-100 year flood or the 1 percent annual chance flood, is defined as a statistical construct used to represent the probability that a flood of a certain discharge (and elevation) will occur with a 1% chance in any given year (Galloway et al. 2006).

However the record surge brought by Hurricane Sandy emphasized the need to look beyond the 100-year flood to assess future flood possibilities. Though flood insurance is not required for structures located in the 500-year floodplain, knowledge of the potential extent of this floodplain in the future can serve to guide long-term efforts for planning and resiliency and allow for protection our critical infrastructure and essential facilities. For this reason, in their second and third reports the NPCC2 chose to focus on both the 100- and 500-year floodplains.

To give visual dimension to the numeric projections of sea-level rise, the NPCC2 used future sea-level rise estimates to create maps illustrating the potential extent of future 100- and 500-year flood scenarios in New York City. These maps are founded upon the work of the Federal Emergency Management Agency (FEMA) that both modeled and mapped the current 100-and 500-year floods in NYC. FEMA is responsible for creating and maintaining Flood Insurance Rate Maps (FIRMs) that delineate the 100- and 500-year floodplains for all communities that participate in the National Flood Insurance Program (NFIP). These maps are used to determine if flood insurance is required when banks provide federally insured loans for new construction or building renovation. In New York State, compliance with the National Flood Insurance Program is mandatory for all jurisdictions and the existence of flood insurance plans at the community
level is a condition for any given property to obtain flood insurance. Construction within the 100-year floodplain is subject to special building codes, and insurance and environmental regulations. As a result, many of the flood-resistant construction codes of New York City are required to meet the state and federal requirements, which have been standardized through the International Building Code (IBC).

The 100- and 500-year flood zones of New York City were first delineated over 25 years ago by FEMA as part of their Flood Insurance Study (FIS) for New York City. An FIS is a document that contains information about flooding in a community and is produced in conjunction with the Flood Rate Insurance Map (FIRM). The 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 boundaries for the 100- and 500-year floods and base flood elevation (BFE) information for the 100-year flood. Base flood elevations refer to the elevations to which floodwaters are expected to rise during the 100-year flood event. They are measured relative to a given datum - either the National Geodetic Vertical Datum of 1929 (NGVD29) or the North American Vertical Datum of 1988 (NAVD88; FEMA's 2013 maps use NAVD88). FIRMs are essential to determining flood insurance premiums; setting the regulatory standard for structural elevations, building design standards, and flood proofing; and for the implementation of floodplain management and regulation practices. They are used by multiple parties including federal agencies, state and local governments, lending institutions, insurance agencies, surveyors, and the NFIP (Crowell et al. 2007).
FIRMs broadly distinguish between two types of flood hazard areas: areas exposed to the 100-year flood also known as Special Flood Hazard Areas (SFHA), and non-SHFA which includes areas in the 500-year floodplain as well as areas not exposed to flooding (Figure 3.2). Within the SHFA, areas subject to wave heights of three feet or greater are termed coastal high hazard areas and designated VE Zones where the V stands for “velocity wave action.” Areas within the SFHA not subject to velocity wave action are designated Coastal AE Zones. The Limit of Moderate Wave Action (LiMWA) is a line within the AE Zone that delineates the landward location of the 1.5-foot wave height. Base flood elevations are displayed as whole numbers rounded to the nearest foot in the VE and AE Zones. Beyond the SHFA, moderate flood hazard areas are subject to the 500-year flood and areas of minimal flood hazard are subject to less than the 500-year event. Though the flood zone designations discussed above are valuable for determining the areas of greatest flood hazard, they are difficult to estimate in future flood scenarios. For this reason the NPCC and NPCC2 flood maps do not include estimates of future base flood elevations, nor do they distinguish future zones of high velocity wave action.
**Figure 3.2.** A coastal profile showing the transition of FEMA designated flood zones from the ocean (left) moving onshore to the limit of the 100-year flood and beyond. The Special Flood Hazard Area contains Zones VE and AE. Zone X indicates areas beyond the 100-year flood zone that may be subject to the 500-year flood. Image source: https://www.fema.gov/coastal-flood-risk-study-process.

In addition to illustrating the potential extent of future 100- and 500-year flood scenarios, the NPCC also estimates the impact of sea-level rise on flood reoccurrence intervals. Sea-level rise increases the frequency with which floods of a given magnitude will be experienced so that future storm events and astronomical tides need be of much smaller magnitude to achieve the levels of flooding that we experience today from higher magnitude events. And future storm and tide events of large magnitude will achieve new flood heights and extents. For example, the current 100-year flood has a 1% chance of occurring in any given year, and associated flood heights reach 11.2 feet. By the 2080s, the current 100-year flood (1% chance annual flood) could occur with a 2% - 5.4% annual chance with flood elevations reaching 12.8 to 14.6 feet, 1.5 to 2.3 feet higher than currently experienced (Horton et al. 2014).
3.4.1. New York City Panel on Climate Change (NPCC) Flood Maps

The NPCC first published future flood maps in their 2010 report *Climate Change Adaptation in New York City: Building a Risk Management Approach*. This report features maps of the 100-year floodplain for the 2020s, 2050s, and 2080s, using the 90th percentile values of the 2010 IPCC-based and rapid ice-melt sea-level rise projection scenarios (Figure 3.3). The 90th percentile values equate to 5 inches for the 2020s, 13 inches for the 2050s, and 23 inches for the 2080s for the IPCC-based approach and 9 inches for the 2020s, 27 inches for the 2050s, and 53 inches for the 2080s for the rapid ice melt approach. FEMA’s 100-year floodplain, as defined by the 1983 FIS, is shown in purple with projections for the 2020s in red, the 2050s in orange, and the 2080s in yellow.

![Figure 3.3](image)

*Figure 3.3.* Maps of the potential future 100-year floodplains in New York City using the IPCC model-based approach (left) and the rapid ice melt approach (right) to sea-level rise projections. Source: Rosenzweig and Solecki, 2010.
The second round of NPCC2 future flood maps was featured in both the *Climate Risk Information 2013: Observations, Climate Change Projections, and Maps* and the *PlaNYC: A Stronger, More Resilient New York* reports using the 90th percentile values of the 2013 sea-level rise projections. Instead of using IPCC-based and rapid ice-melt scenarios, sea-level rise projections were developed using an expanded component-by-component approach (see section 3.1.1 for details on this approach). The 90th percentile values equate to 11 inches for the 2020s and 31 inches for the 2050s. The first of these maps illustrates the potential 100-year flood zone in the 2020s and 2050s and the second illustrates the potential 500-year flood zone for the 2020s and 2050s (Figures 3.4 and 3.5). The FEMA 100- and 500-year floodplains have been revised from the 1983 versions based on updates to the Flood Insurance Study for NYC. Revised floodplains are shown in purple with projections for the 2020s in yellow and the 2050s in red. The 2013 maps also differ from the maps created for the NPCC 2010 report in that they feature both the 100- and 500-year floodplains and lack projections for the 2080s.
Figure 3.4. Maps of the potential future 100-year floodplains in New York City using a component-by-component approach to sea-level rise projections. Source: New York City Panel on Climate Change, 2013.
Figure 3.5. Maps of the potential future 500-year floodplains in New York City using a component-by-component approach to sea-level rise projections. Source: New York City Panel on Climate Change, 2013.

Though the NPCC2 developed revised maps for their 2015 publication the future flood geographic information system (GIS) shapefiles were not available at the time of this analysis. Therefore the 500-year floodplain for the 2050s shown in Figure 2.5 was selected as the focus of this work because it was the best available data that also encompassed the greatest potential flood area and affected population.
3.4.2. NPCC Flood Maps - Methodology and Limitations

Despite their value in illustrating potential future flood scenarios the NPCC flood 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. This section reviews the flood mapping methodology and limitations, and describes the intended use of the maps.

Future flood scenarios were created using ESRI’s ArcGIS software as follows: FEMA’s base flood elevation values are used as baseline, projected sea-level rise values are added to the BFEs to give potential future BFE values, and then the future BFE values are extended landward until they reach an equivalent topographic elevation at which point the flood extent terminates. For the 2013 effort the NPCC began with FEMA’s best available flood maps for New York City, added high-estimate (90th percentile) projections of sea-level rise to the given BFEs, and then directed the GIS to select as ‘flooded’ the land between the coastal flood zone and nearest inland equivalent topographic elevation. Best available flood maps at the time of analysis were FEMA’s Advisory Base Flood Maps (released in February 2013) that provided the BFE values for the 500-year flood, and FEMA’s Preliminary Work Maps (released in June 2013) that provided the BFE values for the 100-year flood. The digital elevation model (DEM) used in the flood map process was also best available, developed from LiDAR (light detection and ranging) data collected in the spring of 2010. Vertical accuracy of the DEM was reported as a root mean square error (RMSE) of 9.5cm, which equates to a linear error at 95% confidence value of 7.3 inches (18.6cm). The 90<sup>th</sup> percentile sea-level rise projections of 11 inches (27.9cm) for the 2020s and 31 inches (78.7cm) for the 2050s both exceed the 95% error bounds of the elevation
data. Thus the vertical accuracy of the underlying elevation data is sufficient to support the mapped sea-level rise increments.

One unique aspect of the NPCC flood scenario maps relative to other storm surge and sea-level rise (inundation) mapping efforts is the integration of base flood elevation data into their future flood projections. Many sea-level rise and storm surge mapping methodologies use one constant elevation contour, such as mean sea level, as their baseline and simply add elevation to represent inundation. For example, Cooper et al. (2005) considered the 100-year flood in their analysis of the impacts of sea-level rise on New Jersey. They used FEMA’s 100-year flood elevation for Atlantic City (2.9m), added projections of sea-level rise elevation, and applied that new value to the entire New Jersey coastline by mapping the corresponding topographic contour. However, the configuration of the islands of New York City and their connecting water bodies allows storm surge to bottleneck in constricted areas, resulting in large changes in BFE values over small horizontal distances both parallel and perpendicular to the shoreline. This change 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 reflects the changing base flood elevation values nearer to shore. The NPCC 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. This unique approach to flood modeling is creative but also simplistic in that it makes broad assumptions about the movement of storm surge. In reality the movement of storm surge over land is a complex process generally understood via wave transformation modeling. Wave transformation modeling accounts for the effects of soils, vegetation, surface permeability, bathymetry, existing
structural and non-structural flood protections, friction, and other factors that affect the movement of floodwaters and result in local variations in flooding extent.

Without the use of hydrodynamic (including wave transformation) modeling to develop future flood projections, many assumptions had to be made in the GIS-based NPCC methodology about storm surge movement and wave action, and connectivity to the open ocean. In addition numerous sources of error or uncertainty are present in datasets that are foundational to the future flood maps. For example the NPCC sea-level rise projections, the modeled BFE and SWEL values developed by FEMA, and the underlying topographic dataset each have their own margin of error that is difficult to quantify and relay visually on the NPCC flood maps.

Due to the limitations and uncertainties discussed above, the flood areas delineated in the NPCC maps were not intended to represent precise flood boundaries or to be used to assess actual coastal hazards, insurance requirements, or to be used in lieu of the FEMA FIRMs. The maps were meant to illustrate three distinct areas of interest worthy of further study: (1) areas currently subject to the 100- and 500-year floods 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- and 500-year floods in the future; and (3) areas that do not currently flood and are unlikely to do so in the timeline of the climate projection scenarios (end of the current century). In this way the NPCC established a framework by which to evaluate future flood scenarios.

The future flood maps developed by the NPCC are the best available of such data and the boundaries of the 100- and 500-year floodplains are used in this work to define the extent of the
residential population considered to be at-risk to future flooding. A great advantage of these maps is that they are not specific to a given storm and instead present surge scenarios that could be achieved in tropical storm, hurricane, or nor’easter conditions, thereby broadening their applicability. Maps that approximate future flood zone extents are critical to decision and policy makers as well as the public to prepare for floods of increased elevation, extent, and duration. Also as a product of the NPCC, local and regional stakeholders and policy makers consider these maps in the development of their climate change adaptation plans and strategies. By using the best available data of the NPCC, this work can complement and add value to the ongoing citywide resiliency efforts.
Chapter 4: Potential Floodwater Contaminants

In the United States, working waterfronts shape the economy, development, and culture of local communities. They support a multitude of industries such as manufacturing; oil and gas; marine transportation, construction, ship and boat building; coastal tourism and recreation; and fishing and aquaculture, that rely on access to the waterfront for their success. Throughout history prominent waterfront activities have changed in response to technological innovations, the global economy, and environmental regulations with many coastal communities now being re-developed for residential, commercial, and recreational uses.

The New York City harbor was the economic engine for the city and the region throughout the 19th century. The waterfront was lined with piers and warehouses, rail lines connecting the coast to the interior, military facilities, and noxious industries, and was characterized as dangerous, foul-smelling, and polluted (Platt 2009). Though the industrial sector that once occupied much of the shoreline is now in decline, the working waterfront is still a vital part of New York City’s economy. The port of New York and New Jersey is the busiest on the East Coast and port activities are essential to the movement of goods and materials into the metropolitan region. Maritime, municipal, and industrial uses such as energy infrastructure, chemical and petroleum facilities, and wastewater treatment plants, as well as legacies of past industry such as abandoned highly contaminated sites continue to populate the New York City coastline. These sites often use, transport and/or store large volumes of toxic chemicals, hydrocarbons, heavy metals and hazardous wastes. Of particular concern in the context of storm surge events is the potential for on-site storage vessels to rupture or otherwise accidentally release hazardous materials into surrounding floodwaters. Two recent storm surge events, Hurricane Katrina in 2005 and
Hurricane Sandy in 2012, illustrate this potential. The following sections describe these events, their impact on coastal facilities and infrastructure, and the concern for environmental contamination in both the floodwaters and the residual sediments.

4.1. Hurricane Katrina

Hurricane Katrina made landfall in the state of Louisiana as a Category 3 storm on August 29, 2005 bringing heavy rains and extreme flooding to a large portion of the Gulf Coast. Storm surge elevations ranged from 10 to 19 feet in New Orleans, Louisiana, inducing breeches in the city’s levee system and inundating nearly 80% of the city with floodwaters 6 to over 16 feet deep. These floodwaters, supplemented by the storm surge and rain from Hurricane Rita just three weeks later, persisted for nearly six weeks and left behind sediments that were in some areas several feet thick (US EPA n.d.). Because New Orleans is situated within a dense infrastructure of oil terminals and wells, pipelines and refineries, there was widespread concern as to the potential for environmental contamination in both the floodwaters and the residual sediments. Facilities associated with chemical and petroleum production, storage, and distribution handle vast quantities of hazardous substances, the release of which could cause widespread contamination of near coastal waters.

Hurricane Katrina did in fact demonstrate the potential for storm surge to facilitate the release of large volumes of hazardous materials. Over 200 onshore releases of hazardous chemicals, petroleum, or natural gas were reported as a result of Katrina. Ten onshore storage tank releases of petroleum products were greater than 10,000 gallons each, amounting to more than 8 million gallons released in total. Damage to storage tanks, including valves and piping, was cited as the
cause of nine of these releases and most of the releases were in facilities where the storm surge was only two meters in elevation (Santella, Steinberg, and Sengul 2010). Tanks were lifted by the storm surge and their hulls or valves ruptured when they shifted or impacted other objects in the water. Of the non-petroleum onshore hazardous material release events, 26% were due to equipment damage (valves, pipes, etc.) and 22% were due to chemical storage tank damage. Approximately 10% of toxic release inventory (TRI) facilities and 28% of SIC 1311\(^6\) facilities located in surge areas experienced accidental releases (Santella, Steinberg, and Sengul 2010). By contrast in areas impacted only by hurricane strength winds (no surge), these numbers dropped to 1% and 10% respectively. Overall half of all releases of petroleum, chemicals and other industrial substances in the storm surge zone were greater than 1,000 gallons (liquid) each or greater than 1,000 pounds (solid compounds) each suggesting a considerable threat posed by hazardous material releases in areas of storm surge.

There was concern about other potential sources of floodwater pollutants as well, such as the toxic chemicals used by dry cleaners and service centers, the herbicides and pesticides stored in homes, the oil and gasoline in flooded vehicles, as well as bacterial contamination from uncontrolled biological wastes. To address these concerns samples from the floodwaters and residual sediment were collected and tested to assess the extent of chemical and biological contamination and determine the likelihood of human and wildlife health hazards. A comparison of studies conducted immediately after the storm, three weeks later, and then six weeks later show that elevated levels of metals and bacteria were present in the floodwaters, sediments, and soils and persisted after the waters had receded.

\(^6\) SIC 1311 facilities are facilities classified by the Standard Industrial Classification (SIC) as pertaining to crude petroleum and natural gas.
Pardue et al. (2005) sampled floodwaters between 5 and 9 days after the storm in areas where many first responders and residents were exposed. They found levels of lead, arsenic, and chromium that exceeded drinking water standards but were generally at levels ‘typical’ of stormwater. Fecal coliforms - bacteria that serve as an indicator of fecal contamination - were elevated compared to primary contact water standards but concentrations of volatile and semi-volatile organic pollutants were low.

A study of floodwaters and soils sampled three weeks after the storm found concentrations of the aldrin (a pesticide), arsenic, lead, and seven semi-volatile organic compounds in sediments/soil that exceeded the human health specific screening levels (HHSSL) established by the USEPA (Presley et al. 2006). Though floodwaters did not exceed the Safe Drinking Water Act Maximum Contaminant Levels (SDWA MCL), high concentrations of *Aeromonas spp*, a human pathogen associated with diarrhea and fresh wound infections, and other coliform bacteria were found in these samples. The authors concluded that environmental contaminants were present in New Orleans and encouraged further testing to evaluate the threat to human health.

Adams et al. (2007) collected samples from sediments and soils six weeks after the storm. Lead was found in 30% of samples at concentrations equal to or greater than drinking water action levels. In samples that underwent a batch leaching method, a process that simulated acid rain conditions to mobilize leachable metals, 50% of the leachate samples had arsenic concentrations equal to or greater than drinking water maximum contaminant level. Pesticides were detected in

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7 Volatile organic compounds (VOCs) include cleaning supplies, paint and paint remover, glues and adhesives, and pesticides, among many other substances. For a more exhaustive list see the EPA’s Introduction to Indoor Air Quality (IAQ) website: http://www.epa.gov/iaq/voc.html.
at least one location but most concentrations were non-detectable or at trace levels suggesting that localized contamination may have been present but general contamination had not occurred. Benzene or other gasoline constituents were not detected.

The studies cited above measure some pollutant concentrations with respect to drinking water standards. This comparison has been criticized as inappropriate for floodwater evaluation because exposure will occur by contact and not ingestion (Reible 2007). The US EPA offers nationally recommended recreational water quality criteria (RWQC) that are designed to protect human health in situations of primary contact recreation, such as swimming, surfing, and diving. The RWQC may offer a more realistic baseline against which to evaluate floodwater contamination by contact, however the drinking water standards do provide a conservative baseline.

4.2. Hurricane Sandy

When Hurricane Sandy made landfall in New Jersey on October 29, 2012 it became the largest storm in the recorded history of New York City eventually claiming 43 lives and causing over $19 billion in damage. From a meteorological perspective Sandy was also an enormous storm with a tropical-storm-force wind field that extended for nearly 1,000 miles at landfall. Prior to landfall as Sandy was tracking to the northeast along the east coast, multiple weather systems converged to shift its track abruptly west and cause it to reenergize and intensify. This shift brought the northeast quadrant of Sandy’s counterclockwise winds perpendicular to the city’s coastline, driving storm surge directly into the NYC Harbor. The storm arrived in NYC about
thirty minutes after high tide and on the evening of a spring tide bringing a record-breaking storm surge of greater than 14-feet$^8$ to the Battery in Lower Manhattan.

Hurricane Sandy’s impacts to the infrastructure and residents of NYC were extensive, affecting sectors such as transportation, telecommunications, public health, and energy, both within and outside of the flood zones (Table 4.1). Power outages had the greatest overall effect on the sectors rendering critical facilities inoperable and causing loss of or reduced service.

<table>
<thead>
<tr>
<th>Summary of Hurricane Sandy’s Impacts on New York City Sectors</th>
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<tr>
<td>Buildings</td>
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<td>Water</td>
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<td>Wastewater</td>
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Table 4.1. Summary of the impacts of Hurricane Sandy on several sectors of New York City. Source: New York City Office of the Mayor (2013).

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$^8$ Storm surge was measured relative to Mean Lower Low Water. See NOAA’s Tides and Currents website for more information on tidal datums: http://tidesandcurrents.noaa.gov/datum_options.html.
Prior to Hurricane Sandy’s arrival the presence of heavy chemicals and industrial wastes on the shores of New York City’s waterways had been noted with alarm by community-based organizations and environmental justice groups. In fact in the wake of Tropical Storm Irene in August 2011 and prior to Sandy’s landfall in October 2012, the New York City Environmental Justice Alliance (NYC-EJA) issued press releases calling for the New York City Mayor and State Governor to protect low-income waterfront neighborhoods from “…[potential] toxic exposures during hurricane storm surges” (New York City Environmental Justice Alliance 2012, 2011). NYC-EJA had previously documented the contamination hazards presented by Significant Maritime and Industrial Areas (SMIA) in six New York City neighborhoods. SMIA are a product of the NYC Waterfront Revitalization Program, which clusters the city’s heaviest industrial, and infrastructure uses into storm surge zones. These press releases voiced concern that storm surge could spread unsecured heavy chemicals throughout these predominantly low-income neighborhoods and result in immediate and cumulative risk exposures.

In addition to the presences of SMIA along the waterfront, two of New York City’s water bodies are on the National Priorities List as Federal Superfund Sites: the Gowanus Canal in Brooklyn and the Newtown Creek along the Brooklyn-Queens border. Both of these water bodies exceeded their banks during Hurricane Sandy bringing several feet of floodwaters to the surrounding neighborhoods. Many residents of these neighborhoods were concerned that the floodwaters that infiltrated their basements and seeped up the walls were laden with carcinogens and toxic wastes (Navarro 2012; Peeples, Shapiro, and Knafo 2012). The waters were described as murky and brown, with the pungent smells of dead fish and gasoline (Peeples, Shapiro, and Knafo 2012; Valhouli 2012).
Despite these observations the United States Environmental Protection Agency (US EPA) assessed these Superfund sites and reported that, in part due to actions that were taken in advance of the storm to secure the sites, they “…do not believe that any sites were impacted in ways that would pose a threat to nearby communities” (US EPA 2013). Regardless, on October 31st two days after Hurricane Sandy made landfall, the EPA took four floodwater samples from Gowanus Canal and then two samples from the Newtown Creek area on November 9th. The samples were analyzed for bacteria and 139 different chemicals\(^9\). Bacteria levels for both locations were high, suggesting that people should protect themselves when cleaning up floodwaters (EPA n.d.). Levels of volatile and semi-volatile organic compounds were low or not detected, and levels of petroleum related compounds were consistent with road runoff. Levels of heavy metals slightly exceeded drinking water standards in the Gowanus Canal but were at low levels or not detected at Newtown Creek (US EPA n.d., n.d.).

Perhaps the most conclusive evidence of post-Sandy floodwater contamination was the month long recreational waterbody advisory on the New York City waterways. On October 31, 2012 the New York City Department of Health & Mental Hygiene also issued an advisory stating that “…direct contact with the Hudson River, East River, New York Harbor, Jamaica Bay and the Kill Van Kull for recreational activities such as swimming, canoeing, kayaking, windsurfing or any other water activity that would entail possible direct contact with the water should be avoided until further notice” (NYC Department of Health & Mental Hygiene 2012). The city

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\(^9\) Though not specified in these reports, it is assumed all samples were evaluated with respect to the New York State Water Quality Standards (and guidance values) designed to protect waters for drinking and recreation uses. See the New York State Department of Environmental Conservation’s Water Quality Standards and Classifications website for details: http://www.dec.ny.gov/chemical/23853.html.
waterways were repeatedly tested for levels of coliform and dissolved oxygen until the waters were deemed acceptable for recreational use on November 30, 2012.

The NYS Department of Environmental Conservation fecal coliform standard for bathing and other recreation use is 200 colony forming units (CFU)/100mL. By contrast, the New Jersey Department of Environmental Protection and the US Environmental Protection Agency used the federal standard of 14 CFU/100mL - the standard for harvesting shellfish - as their baseline for recreational use. On November 29, 2012 samples were drawn from Newark Bay and the New York Harbor for analysis. None of the 10 samples sites tested was within acceptable limits. These results support the NJDEP’s advisory issued on October 29, 2012 to stay out of the water. The full reopening of all New Jersey state waters to full recreational use, including shellfish harvesting, wasn’t issued until April 11, 2013.

The water analyses cited above suggest that floodwater contamination, particularly in the form of elevated bacteria levels, was in fact a concern particularly in the first 30 days after Sandy. The EPA testing of the Gowanus and Newtown waterways provides a foundation for environmental contamination analysis, but would have been more robust had they analyzed a larger number of floodwater samples, included sediment samples, and resampled during a range of dates after the storm.

4.3. Hazard sources in NYC

Multiple sources of toxic chemicals and hazardous wastes are situated in various forms and facilities throughout New York City. This work creates an index of potential exposure to these
hazards in floodwaters by evaluating residential proximity to the following nine types of facilities: Chemical Bulk Storage, Petroleum Bulk Storage, and Major Oil Storage Facilities (MOSF), the Toxic Releases Inventory (TRI) facilities, the State Pollutant Discharge Elimination System (SPDES) facilities, State Superfund Sites, Brownfields, Water Pollution Control Plants and Combined Sewage Overflow (CSO) Outfalls. Each of these potential sources of hazard are detailed in the following sections.

4.3.1. Chemical Bulk Storage, Petroleum Bulk Storage, and Major Oil Storage Facilities

New York State’s Hazardous Substances Bulk Storage Program regulates the above ground and underground storage of petroleum and chemicals according to standards set by the Environmental Protection Agency (EPA) and the New York State Department of Environmental Conservation (DEC). These regulations were established to prevent leaks and spills of hazardous materials resulting from improper handling and maintenance of storage facilities. Improper storage and handling of hazardous substances can lead to spills that contaminate water supplies or pose a fire or hazardous fumes risk with potentially serious consequences to public health and the environment.

The most recent database of bulk storage in New York City lists 34,755 bulk storage facilities classified as Petroleum Bulk Storage, Chemical Bulk Storage, or Major Oil Storage Facility (Table 4.1). The dominant facility type are Petroleum Bulk Storage facilities, which account for both Underground Storage Tanks (USTs) and Aboveground Storage Tanks (ASTs) that have a singular or combined storage capacity greater than 1,100 and less than 400,000 gallons. Chemical Bulk Storage facilities store any volume of chemical substances that are subject to
Federal or State mandated regulation. Oil terminals and vessels that have a storage capacity of 400,000 gallons or more are termed Major Oil Storage Facilities.

These facilities are further classified according to their operating status: active, inactive, unregulated, unregistered, administratively closed, and no longer a MOSF. The exposure index developed in this work assigns greater weight to the active and unregulated faculties because they are actively storing or utilizing hazardous substances. The DEC defines ‘unregulated’ facilities as those that do not meet the thresholds for quantity or product type for regulation under one of the Bulk Storage Programs, but they do contain hazardous substances and can leak. Facilities that are administratively closed, inactive, or no longer a MOSF are considered to be devoid of hazardous substances and as such are not considered in this work. Unregistered tanks are unlawful to operate and delivery of any product to such tanks is prohibited, therefore they are also not considered in this work.

<table>
<thead>
<tr>
<th>DEC Program Type</th>
<th>Facility Status</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Bulk Storage</td>
<td>Active</td>
<td>109</td>
</tr>
<tr>
<td></td>
<td>Unregulated</td>
<td>352</td>
</tr>
<tr>
<td></td>
<td>Administratively Closed, Inactive, or Unregistered</td>
<td>37</td>
</tr>
<tr>
<td>Petroleum Bulk Storage</td>
<td>Active</td>
<td>25,871</td>
</tr>
<tr>
<td></td>
<td>Unregulated</td>
<td>6,491</td>
</tr>
<tr>
<td></td>
<td>Administratively Closed, Inactive, or Unregistered</td>
<td>1,523</td>
</tr>
<tr>
<td>Major Oil Storage Facility</td>
<td>Active</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>Unregulated</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Administratively Closed, Inactive, or No Longer a</td>
<td>198</td>
</tr>
<tr>
<td></td>
<td>Major Oil Storage Facility</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TOTAL</td>
<td>34,755</td>
</tr>
</tbody>
</table>

Table 4.2. The number (count) of New York City Bulk Storage Program Facilities and their facility status. Source: NYS DEC 2008.
4.3.2. *Toxics Release Inventory (TRI)*

The Toxics Release Inventory (TRI) is a mandatory self-reporting program administered by the United States Environmental Protection Agency (EPA) that was developed to track the management of toxic chemicals handled by facilities across the United States. Established as part of the 1986 Emergency Planning and Community Right-to-Know Act (EPCRA), the goal of TRI is to empower citizens and stakeholders with information about how toxic chemicals are managed. The list of over 650 chemicals covered by the TRI program covers those that cause “cancer or other chronic human health effects, significant adverse acute human health effects, or significant adverse environmental effects” (US EPA 2013). Facilities that meet certain industry, employee, and chemical thresholds are required to submit annual reports of these chemicals to the TRI program. These reports detail the quantities of chemicals they disposed of or released, recycled, purposed for energy recovery, or subjected to other forms of treatment.

Disposal and all other means of releases and treatments are performed either on-site or off-site. Releases include emissions to the air through fugitive (unconfined) or stack air releases, to local waterbodies as surface water discharges or transfers to wastewater treatment plants, and to the ground via (usually) off-site landfills and injection wells. Methods for recycling include solvent recovery and metals recovery, depending on the chemical being recycled, and the process of energy recovery involves combustion of toxic chemicals in furnaces or boilers that generate heat or energy for use.

Of the forty-one TRI facilities situated in New York City, twenty-five of them report on-site disposal or releases to air, land, water, and injected underground (Table 4.2). The other sixteen
facilities either treat their wastes off-site or use less than 500 pounds annually of each toxic chemical they handle. Regardless of the fate of these chemicals the potential hazard of TRI facilities lies in the onsite storage of hazardous chemicals prior to processing. In the case of Hurricane Katrina, the failure of storage tanks subject to storm surge was the most common mechanism of petroleum releases (Santella, Steinberg, and Sengul 2010).

The TRI database used in the exposure index was queried from the online TRI Explorer database. The Release Facility Report lists the TRI site locations, the chemicals being reported, and the pounds of releases, waste transfers, and overall waste quantity. However there are multiple other factors not captured in the database that are necessary to understand the potential impacts to public health. First, release estimates alone are not sufficient to determine to what degree, if any, the public could be exposed to these chemicals. The exact mechanism and pathway of release (air, land, water) is also an important to consideration to understand the means by which a population can be exposed. Second, the toxicity of TRI chemicals vary widely so the volume of a chemical present cannot alone be an indicator of health risk. Third, once released some chemicals will degrade over short time spans when exposed to sunlight, heat, and microorganisms, rendering them less harmful while other chemicals persist without degradation. And finally, chemicals can be incorporated into the food chain where they can accumulate and magnify in concentration. This bioaccumulation is best exemplified in the fish populations of the New York City Waterways that absorb and accumulate toxins such as polychlorinated biphenyls (PCBs) and mercury. Other factors involving the efficiency of waste management affect the amount of a toxic chemical that ultimately ends up in the environment.
<table>
<thead>
<tr>
<th>Borough</th>
<th>Count</th>
<th>On-Site Disposal/Releases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bronx</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Kings</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>Manhattan</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Queens</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>Richmond</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total: New York City</strong></td>
<td><strong>41</strong></td>
<td><strong>25</strong></td>
</tr>
</tbody>
</table>

**Table 4.3.** The number (count) of facilities that report to the Toxic Release Inventory in New York City. Source: EPA 2011.

4.3.3. *The State Pollutant Discharge Elimination System (SPDES)*

The State Pollutant Discharge Elimination System (SPDES) is a New York State permit program developed in accordance with the Clean Water Act that regulates point source discharges to surface and ground waters. The New York State Department of Environmental Conservation (DEC) administers the SPDES program through the issuance of general and individual wastewater discharge permits. General permits are issued for discharges that, when adhering to program guidelines, typically have a smaller and less significant impact on the environment. This includes private, commercial, or institutional sanitary discharges to groundwater only (not surface water) of 1,000 to 10,000 gallons per day; storm water discharges associated with industrial activity, construction, and municipal separate sewer systems; and concentrated animal feeding operations.

Individual permits are issued on a per facility basis and cover unique discharge characteristics. These permits cover industrial discharges of up to 10,000,000 or more gallons per day (gpd), municipal discharges of up to and over 40,000,000 gpd, private/commercial/institutional discharges of up to 100,000 gpd or more, power plant discharges of any size, and ballast
(marine) discharges of up to 1,000,000 gpd or more in any 24-hour period (New York State Department of Environmental Conservation 2003). All individual permits are classified into Major, Significant Major, Non-Significant Minor, and Petroleum remediation categories according to size, type, and Environmental Protection Agency (EPA) classification.

Of the over 8,000 active individual permits in New York State, 72% are sewage-type Non-Significant Minor private/commercial/institutional (Class 02) and 8% are Non-Significant Minor Industrial (Class 04). Though these two categories make up almost 80% of the wastewater discharges they are only responsible for 10% of the water pollution generated. However of the 90 SPDES permits in New York City, none are categorized as Class 02 or 04 (Table 4.3). The dominant permit type is Class 01, Significant Minor Industrial wastewater discharge. The category Significant Minor describes discharges to surface and ground waters that have the potential to contain toxics. Over one quarter of the permits are categorized as Major discharges by both the DEC and EPA. A Major permit is issued for wastewater that scores high on the following criteria: toxic pollutant potential, flow/stream flow volume, conventional pollutant content, public health impact, water quality factors, and proximity to near coastal waters (United States Environmental Protection Agency 1990). Facilities categorized as Major in New York City include fourteen water pollution control plants, multiple electricity generating stations, the ExxonMobile Greenpoint remediation project, and the Staten Island landfill.

Though NYC has only 25 Major SPDES permits compared to 55 Significant Minor permits, wastewater discharges qualifying as Major have the potential to affect significant environmental impact. Both Major and Minor permit facilities are included in this work.
### Table 4.4

<table>
<thead>
<tr>
<th>DEC Classification</th>
<th>SPDES Permit Category</th>
<th>EPA Classification</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 – Industrial</td>
<td>Significant Minor</td>
<td>Non-Major</td>
<td>55</td>
</tr>
<tr>
<td>02 - Private, Commercial, Institutional</td>
<td>Non-Significant Minor</td>
<td>Non-Major</td>
<td>0</td>
</tr>
<tr>
<td>03 – Industrial</td>
<td>Major</td>
<td>Major</td>
<td>11</td>
</tr>
<tr>
<td>04 - Industrial</td>
<td>Non-Significant Minor</td>
<td>Non-Major</td>
<td>0</td>
</tr>
<tr>
<td>05 - Municipal</td>
<td>Major</td>
<td>Major</td>
<td>14</td>
</tr>
<tr>
<td>07 - Municipal</td>
<td>Significant Minor</td>
<td>Non-Major</td>
<td>0</td>
</tr>
<tr>
<td>09 - Private, Commercial, Institutional</td>
<td>Significant Minor</td>
<td>Non-Major</td>
<td>10</td>
</tr>
<tr>
<td>10 - Industrial</td>
<td>Petroleum Remediation</td>
<td>Non-Major</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TOTAL</td>
</tr>
</tbody>
</table>

The number (count) of SPDES permits in New York City listed by DEC Classifications and their associated SPDES permit category. Source: NYS DEC 2011.

### 4.3.4. State Superfund Sites

The Registry of Inactive Hazardous Waste Disposal Sites is a program administered by the New York State Department of Environmental Conservation’s Division of Environmental Remediation (DER) that identifies, classifies, and remediates abandoned hazardous waste sites. This multi-stage process uses input from the Department of Health, local government agencies, and the public to prioritize hazardous sites, and develop remedial plans, and facilitate action to bring the sites into compliance.

The investigation and cleanup process begins with notification to the DER of potentially problematic sites. Once identified, these sites are subject to a Site Characterization (SC) investigation to determine if hazardous wastes are present and, if affirmed, whether they pose a significant threat to public health. An SC study evaluates the soils, surface waters, and groundwater, and records history of a site and concludes with a ranking of Class 1 indicating imminent danger to the public health or environment, Class 2 indicating a significant threat, or Class 3 showing no significant threat. All Class 1 and 2 sites undergo a Remedial
Investigation/Feasibility Study (RI/FS) that details the length, depth, and width of contamination, defines the pathways of migration, and develops remedial action choices that will permanently reduce or eliminate the contamination. The proposed remediation plan is open for public comment before the plan is finalized and remedial design and construction can begin. At sites where responsible parties cannot be found or held accountable for the contamination, the State pays for the site investigation and cleanup using the “State Superfund” that was created in the 1986 Environmental Quality Bond Act.

Hazardous waste sites can also be classified as Class 4, Active or Completed. Class 4 sites have been properly closed but require continued management, Active sites are not on the Registry but are being remediated through another environmental remediation program, and Completed sites have been satisfactorily remediated. There are no Class 1 “imminent danger” State Superfund Sites in New York City, but there are sites classified as Class 2, 3, 4, as well as A (Active) and C (Completed). This exposure index focuses on Class 2 sites because of their level of threat to public health and the environment. There are currently forty-three Class 2 State Superfund Sites in New York City; the numbers by county are Bronx=1, Kings=16, New York=1, Queens=19, and Richmond=6. Two of these sites, Gowanus Canal in Kings, and Newtown Creek in Kings/Queens, are also listed as Federal Superfund Sites on the National Priorities List. The database used for this analysis describes the site class and location but does not offer information as to which specific hazardous materials are present.
4.3.5. Brownfields

The Brownfield Cleanup Program (BCP) is an environmental remediation program administered by the DEC’s Division of Environmental Remediation intended to provide incentive for persons to voluntarily remediate brownfield sites to a level that is protective of public health and the environment, rendering those sites available for reuse and redevelopment. Incentive for remediation is provided through tax credits available to taxpayers who enter into a Brownfield Site Cleanup Agreement (BCA) with the DEC. The brownfield redevelopment tax credit offers separate credits based on site cleanup, groundwater cleanup, and on site (re)development. Taxpayers may also be eligible to earn credit for real property taxes and for environmental remediation insurance (New York State Department of Taxation and Finance 2010).

Brownfields are defined by the DEC as “…real property, the redevelopment or reuse of which may be complicated by the presence or potential presence of a hazardous waste, petroleum, pollutant, or contaminant” (New York State Department of Environmental Conservation, Division of Environmental Remediation 2004). Eligible sites do not include State Superfund Class 1 or 2 sites or sites on the National Priorities List. There are 129 BCP sites in New York City, 85 of which are classified as ‘A (Active)’ and 44 of which are considered ‘C (Completed)’. Sites undergoing evaluation for potential contamination are not included in the DEC’s Environmental Remediation Dataset. The classification code ‘A’ refers to sites where work is underway and not yet complete while ‘C’ refers to sites where remediation has been satisfactorily completed. The BCP does not offer information about which hazardous wastes or toxics are present at Active sites. Only ‘A - Active’ sites are included in the index of floodwater
contaminants and they are distributed as follows: Bronx=15, Kings=27, New York=16, Queens=26, Richmond=1.

4.3.6. Water Pollution Control Plants and Combined Sewage Overflow Outfalls

The City of New York treats 1.3 gallons of wastewater every day and returns the disinfected water to the city’s waterways. To accomplish this feat, a combined sewer and sanitary sewer system transports wastewater from over 1 million buildings and thousands of sewer inlets to fourteen wastewater treatment plants located along the waterfront. These plants are sited at low elevations along the coast to allow for gravity assisted wastewater flow and efficient sludge removal by barge, however as such they are also particularly vulnerable to storm surge. During normal weather conditions the system can handle full treatment of wastewater, however the system capacity is exceeded when wastewater flow is two times greater than normal. In order to prevent sewage from backing up into the system during extreme weather events, combined stormwater and wastewater are discharged untreated into nearby waterways. These combined sewer overflows (CSOs) carry untreated human waste and pathogenic bacteria, ammonia, pesticides, petroleum products, litter, toxic metals and other hazardous substances to the waterways. CSOs can also carry large volumes of organic material and nutrients, which enter the waterways and consume much of the dissolved oxygen essential to sustaining marine life (New York City Department of Environmental Protection n.d.).

There are 427 CSO outfall locations along NYC’s shoreline managed by the New York City Department of Environmental Protection (Table 4.4). The outfalls are categorized into three Tiers: Tier 1 outfalls carry 50% of the total CSO volume, Tier 2 outfalls carry 20% of total CSO
volume and Tier 3 outfalls carry 10%. However the volume of discharge at a given CSO outfall can change through time, depending on the amount and location of rainfall, as well as the condition of the sewers and proximity of green (water retaining) infrastructure. The dataset used for this work does not distinguish tiers among the outfall locations therefore this exposure index must weight all CSO locations equally, instead of distinguishing them based on effluent volume and toxicity.

<table>
<thead>
<tr>
<th>Borough</th>
<th>Combined Sewage Overflow Outfalls (count)</th>
<th>Water Pollution Control Plants (count)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bronx</td>
<td>61</td>
<td>1</td>
</tr>
<tr>
<td>Brooklyn</td>
<td>82</td>
<td>5</td>
</tr>
<tr>
<td>Manhattan</td>
<td>159</td>
<td>2</td>
</tr>
<tr>
<td>Queens</td>
<td>86</td>
<td>4</td>
</tr>
<tr>
<td>Staten Island</td>
<td>39</td>
<td>5</td>
</tr>
<tr>
<td><strong>Total: New York City</strong></td>
<td><strong>427</strong></td>
<td><strong>14</strong></td>
</tr>
</tbody>
</table>

Table 4.5. The number (count) of Combined Sewage Overflow Outfalls and Water Pollution Control Plants in New York City. Source: NYC DEP 2013, NYC DCP 2012.

Hurricane Sandy provided a recent example of the impact of storm surge on NYC’s combined sewer system, including water treatment plants and pumping stations. The 14-foot storm surge caused damage to and/or power loss at 10 of the city’s treatment plants and 42 of the city’s 96 pumping stations, which are responsible for pumping sewage from low-lying areas to high elevations. Most of the damage involved electrical systems and equipment located on the lower levels that became inundated during the storm. Three of the wastewater treatment plants were completely non-operational for some period of time while the other plants were able to maintain partial treatment. These failures resulted in the discharge of 560 million gallons of untreated combined sewage, stormwater, and seawater, and another 800 million gallons of partially treated and disinfected wastewater into waterways (NYC Office of the Mayor 2013). Though DEP
testing showed little effect on post-storm harbor water quality the City issued a recreational water body advisory for the Hudson and East Rivers, New York Harbor, Jamaica Bay, and the Kill van Kull that remained in place for 30 days.
Chapter 5: At Risk Critical Facilities

Facilities and infrastructure are considered both critical and at-risk when they provide essential services to residents and are situated in flood areas. Examples include utility providers of electricity, natural gas, drinking water, wastewater treatment, and telecommunications; medical and health services; transportation infrastructure; and emergency response services. If these services are compromised or disabled during a flood event, potentially serious impacts can befall the surrounding community and health hazards can result. However the utility, transportation, and emergency response facilities listed above were not included in this analysis for two reasons: 1) lack of publically available data and 2) lack of spatial coincidence between facility locations and population impacts. The omitted facilities are addressed in more detail in section 5.2. This work instead focuses on facilities that provide services to or temporarily house a portion of the population and therefore may have special or resource intensive on-site evacuation needs.

Previous assessments of storm surge risk and vulnerability under present and future sea-level rise conditions have been incorporated critical facilities into their analysis. These studies define critical infrastructure as roads, bridges, utilities, airports, railways, and emergency services and other important lifelines upon which the population depends for information, services, and safety. For example, in an assessment of socioeconomic vulnerability and exposure to hurricane storm surge hazards in Sarasota County, Florida, Frazier et al. (2010) incorporate the amount and percentage of public safety facilities such as police, fire, and radio/television stations; medical services; facilities that service infrastructures such as electric, water and wastewater, and natural gas; facilities that serve basic community needs such as gas stations, grocery stores, and banks; and offices of government into their analysis. They compare the amount and percentage of these
facilities, as well as other socioeconomic variables, within current and future Category 1-5 hurricane storm surge zones and conclude that socioeconomic exposure in contemporary hazard zones is high and will increase with sea-level rise.

Shepard et al. (2012) consider critical facilities and infrastructure in their overall risk index of the southern shores of Long Island, New York. They combine hazard exposure and community vulnerability to quantify potential changes in risk under present and future sea-level rise conditions. Block groups were ranked to create an index based on the density of critical infrastructure and facilities located within, and this density was positively correlated with vulnerability. Transportation terminals, utility cables (using road length as proxy) and facilities, road density, critical facilities (police, fire, EMS), and community facilities were included. The most and least vulnerable communities were identified and the authors conclude that sea-level rise will increase existing risk and create new areas of risk.

The critical facilities index developed for this work is similar to the studies mentioned above but uses different criteria to select facilities for inclusion. The goal of this index is to identify the population potentially affected by critical facility failure due to floodwaters by assuming a spatial correlation between the facility location and residents at-risk. While this correlation may be proven for some variables it is not proven for other variables. For example, the service areas for utilities and emergency services are not always a matter of public record and cannot be approximated by administrative boundary or circular buffers, however the service area extents are critical to making accurate associations between compromised utility facilities and populations affected. Without this information utilities were not included in this critical facilities
index. Also transportation impacts are not always locally confined. For example, Hurricane Sandy’s impacts on the New York City transportation system illustrate that flooding effects were widespread throughout the city and not just relegated to the neighborhood surrounding flooded subway stations. Much of this system wide impact had to do with floodwaters that entered the system through point sources and then spread underground through the subway tunnels. This was the case in Lower Manhattan where flooding began at the South Ferry subway station and then extended uptown along the tracks. Subway service was completely suspended citywide for three days after Sandy, affecting far more than just the residents in the coastal zones. Therefore constraining transportation impacts to the neighborhoods surrounding damaged infrastructure would not reflect the true scope of the population affected by lost services.

5.1. **Resources at Risk**

The following datasets were collected from the Department of City Planning’s Selected Facilities and Program Sites in New York City database, Release 2012. This database was compiled from city, state and non-profit agency sources and is intended to assist in site and land use planning efforts. Facility types selected from the database were grouped into two categories: Group 1 is comprised of facilities with a population needing direct assistance for mobility (i.e., disabled persons and/or the elderly) and Group 2 consists of facilities with complex evacuation and/or recovery needs.

5.1.1. **Group 1 - Facilities with Residents Needing Physical Assistance**

Table 5.1 lists the Group 1 facility types that provide housing to disabled or minimally abled persons that would need physical assistance in the event of an evacuation.
GROUP 1:  
FACILITIES WITH RESIDENTS REQUIRING PHYSICAL ASSISTANCE  

<table>
<thead>
<tr>
<th>Hospitals and Residential Health Centers</th>
<th>- Nursing homes, Hospitals, Hospices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential Disability Centers</td>
<td>- Community and Supervised Individual Residences</td>
</tr>
<tr>
<td>High Rise Buildings</td>
<td>- Multi-family elevator buildings &gt; 7 stories high</td>
</tr>
</tbody>
</table>

Table 5.1. Critical facilities in Group 1 serve populations with physical disabilities who would require direct assistance for evacuation.

- **Residential Health Services**: This category includes hospitals, nursing homes, and hospices.
- **Residential Developmental Disability Services**: These facilities include hospital-based inpatient care, community and individual residences, intermediate care facilities, and developmental centers.
- **High Rise Residences**: Multi-family residential elevator buildings greater than seven floors in height.

Group 1 facilities provide temporary or long-term residence to a sick, disabled, and/or elderly population. These facilities warrant particular attention because evacuating hospitals, nursing homes, hospice centers, and disability centers in advance of or during a coastal storm requires a resource-intensive coordinated effort to mobilize the patients. For example in the case of Hurricane Sandy three hospitals closed in advance of the storm and three others - New York University’s Langone Medical Center, Bellevue Hospital, and Coney Island Hospital - shut down during or immediately after the storm due to the failure of mechanical or electrical systems.
(Manuel 2013; Redlener and Reilly 2012). The Office of Emergency management had to coordinate the evacuation of 2,000 patients. In addition twenty-six nursing home and adult care facilities were also closed and five partially closed, with 4,500 patients requiring evacuation (NYC Office of the Mayor 2013). These closings put tremendous strain on both the city’s emergency resources and healthcare system as a whole.

Residential high-rise buildings, defined as being greater than or equal to seven floors in height, were added to Group 1 also because of the lessons learned during Hurricane Sandy. Though high-rise buildings as a whole did not sustain much structural damage, they suffered significant non-structural damage to their systems and equipment that were housed in the basement or otherwise insufficiently elevated (NYC Office of the Mayor 2013). In addition to power loss borne by flooded equipment, power loss to substantial portions of the electrical service grid led to the disruption of water and elevator services in high-rise buildings. Residential high-rises are not required to have back-up power generators despite the need for electricity to run the elevators and pump water to the rooftop water tanks to restore water pressure. Elderly and disabled residents became shut-ins, trapped on the upper floors without functioning plumbing, lights, and heat. In some cases, residents went for days and weeks without essential medications (Manuel 2013). Many had to rely on family, neighbors, and volunteers to bring them the resources they needed (Green 2012). Other more physically able residents were forced to navigate dozens of stairs in darkened stairwells to bring needed supplies to their apartments.
5.1.2. **Group 2 - Complex or Coordinated Evacuation Requirements**

Group 2 facilities (Table 5.2) house moderate to large populations in group settings for short (daily) or, in the case of correctional facilities, group homes, chemical dependency treatment centers, psychiatric care centers, and homeless shelters, extended stays. These facilities are flagged for inclusion in the index because they would require additional planning and resources to mobilize and provide shelter for their population in the event of a flood. Unlike the Group 1 population, people in Group 2 are likely mobile but may not be able to make their own choices about evacuation and instead are under the authority of the facility.

<table>
<thead>
<tr>
<th>GROUP 2:</th>
</tr>
</thead>
<tbody>
<tr>
<td>FACILITIES WITH COMPLEX OR COORDINATED EVACUATION</td>
</tr>
<tr>
<td>Correctional Facilities</td>
</tr>
<tr>
<td>- Federal, State, and City Correctional Facilities</td>
</tr>
<tr>
<td>Residential Chemical Dependency Centers</td>
</tr>
<tr>
<td>- Detoxification and Withdrawal Centers</td>
</tr>
<tr>
<td>Group Homes</td>
</tr>
<tr>
<td>- Residential Group Homes for Children and Adults</td>
</tr>
<tr>
<td>Residential Mental Health Facilities</td>
</tr>
<tr>
<td>- Hospital and Psychiatric Center Care</td>
</tr>
<tr>
<td>Day Care Centers and Schools</td>
</tr>
<tr>
<td>- Head Start, Public, Private, Charter, Pre-K, K-12</td>
</tr>
<tr>
<td>Temporary/Transitional Housing Residents</td>
</tr>
<tr>
<td>- Shelter for Singles and Family Homeless Facilities</td>
</tr>
</tbody>
</table>

*Table 5.2.* Critical facilities in Group 2 may have complex evacuation needs.
• **Correctional Facilities:** These facilities include Federal, State, and City correctional facilities; State and City secure and non-secure juvenile justice facilities; and State Reception Centers (14-day stay).

• **Residential Chemical Dependency Services:** The facilities include inpatient detoxification and withdrawal services, inpatient rehabilitation and residential services, residential supportive living and rehab for youth, method one to abstinence residential services, and community residential service.

• **Residential Group Homes:** These facilities include services for children such as group foster homes and residences, foster institution, boarding homes, and supervised independent living. It also includes services for adults such as adult care facilities, and supportive single room occupancy housing.

• **Residential Mental Health Facilities:** These facilities include prison-based mental health units, State operated psychiatric centers, supported single room occupancies, youth community residences, and hospital-based inpatient care.

• **Day Care and Schools:** Day care includes public, private, and corporate group day care as well and public and private Head Start centers. Schools include public and charter schools as well as and private/parochial schools from pre-k though senior high school.

• **Temporary/Transitional Housing:** This includes shelters for singles as well as family homeless facilities contracted or operated by the Department of Homeless Services, non-contracted, and those with and unknown contract status.
5.2. **Resources Omitted**

Utilities such as the electric, steam, and natural gas systems supply essential services to residents yet were not included in the critical facilities index due to limited information such about the distribution of their services. The critical facilities index assumes that a flooded facility impacts the residents of the tax lot in which it is located, however for utilities the location of a facility does not always correspond to the location of services and it is the loss of service that is most relevant to the index. For example, during Hurricane Sandy floodwaters infiltrated the protective barriers at Con Edison’s East 13th Street substation in Manhattan rendering the station inoperable and knocking out power to most of Manhattan below 34th street. However, power remained in the Battery Park neighborhood of Manhattan that receives its electricity from Brooklyn. This example illustrates how electric networks can extend in any direction from their source, making it difficult to make connections between substation location and residents at-risk to lost services. An understanding of the location of utilities in the flood zones and the extent of their service network would have been necessary to make a meaningful contribution to the critical facilities index.

This work also omits public safety facilities such as police, fire, and emergency medical services (EMS) from the critical facilities index. These facilities were considered for inclusion based on the assumption that residents in areas whose emergency service facilities have been impacted by flooding are at greater risk to potential harm should they need to call on these services and find them unavailable. However the New York City police and fire departments have multiple levels of redundancy built into their response areas making it unlikely an area would be denied service due to a compromised police or fire station, so the assumption above isn’t supported.
For example, every fire station in the Fire Department of New York City (FDNY) covers primary, secondary, and tertiary response areas, each one bigger than the previous, such that if a primary station is unable to respond to a call a secondary and even tertiary station is available. Primary response areas do not overlap between fire stations but primary and secondary as well as secondary and tertiary areas do overlap among stations, and they do so in case the primary response area's engine or ladder truck is on another call at the time of an emergency. In this way every area of the city has at least three levels of back up and these back up stations are not necessarily further from a given response location than the primary station, in part due to the fact that response areas are not circular in shape but instead follow major thoroughfares and other neighborhood boundaries. In this regard the city is well covered by the FDNY even when an area’s primary station is unavailable. For reasons of security the response areas assigned to a given station are not made available to the public.

The issue of emergency response is really one of overall access during flood events, meaning that it is difficult for any and all emergency responders to move within flooded areas regardless of whether their actual facility has been compromised. This is best illustrated by the FDNY’s response to the fire that destroyed much of the Breezy Point neighborhood during Hurricane Sandy. Breezy Point, Queens is situated on the western end of the Rockaway Peninsula between the Atlantic Ocean to the south and Jamaica Bay to the north. When Sandy struck on October 29, 2012, storm surge came in contact with live electrical wires and sparked a house fire that spread to over 130 homes and burned unchecked for hours, growing to a six-alarm status. Two main issues impacted FDNY’s ability to respond effectively to the fire: 1) once they arrived in Breezy Point they were blocked from reaching the scene of the fire by floodwaters, and 2) when they
were able to get close enough to fight the fire they were unable to access the fire hydrants that were submerged underwater. The fact that the Rockaway firehouses were flooded was irrelevant because the department had moved their rolling stock out of the firehouses and across Jamaica Bay to the mainland prior to the arrival of the storm. This precautionary strategy was part of the emergency flood plan the Rockaway fire stations had developed in coordination with the Office of Emergency Management. It meant that although firefighters had to drive back over the Marine Parkway Bridge during the storm to reach Breezy Point, their engines and ladders were in service.

This scenario, in addition to the response area information above, illustrates that compromised emergency facilities are not the primary concern in flooding situations because 1) other non-compromised facilities can cover a given response area, and 2) the rolling stock equipment of stations in flood zones can be kept in operating condition by moving them out of flood zones. The primary concern is about emergency service access to areas experiencing flooding and then access to hydrants or other resources in these areas. In this case the best indicator of vulnerability in the context of access of emergency responders is the degree and height of floodwaters in a given neighborhood, not proximity to a compromised police/fire station, and degree of flooding/height of floodwaters is captured in the index of exposure to storm surge. Stations beyond the flood areas are positioned to move into flooded areas when the roads become passable, so the concern is really about mobility within flooded neighborhoods.
Chapter 6: Methodology

This research seeks to determine how sea-level rise projections may alter the potential socioeconomic impacts of contemporary 100- and 500-year flood events and of future flood events enhanced by sea-level rise scenarios, how changing flood exposure may affect the number and distribution of people at risk, and how flood impacts will vary among neighborhoods. In order to assess overall storm surge flood risk at the intersection of exposure and vulnerability, a GIS-based methodology was developed to map a composite exposure and infrastructure vulnerability index for New York City populations within existing and predicted flood zones. ESRI’s ArcGIS 10 and SPSS Statistics 20.0 software were used to quantify and characterize the population and infrastructure estimated to be at-risk. Four separate indices were constructed to capture exposure to floodwater heights and wave action, exposure to floodwater contaminants, social vulnerability, and critical facilities at-risk to flooding. The following sections detail the datasets used in the analyses and describe the processes for developing and aggregating the respective indices to form a composite overall flood risk index.

6.1. Datasets

Multiple spatially referenced datasets were obtained through publically available sources and through agency requests. The following datasets were used to evaluate present and potential future floodplain extent and to develop the index of exposure to flood water heights and wave action:

- FEMA’s Flood Insurance Rate Maps for New York City released in 1983

• The future 100- and 500-year flood zones for the 2020s and 2050s published in June 2013 were obtained with permission from the New York City Panel on Climate Change. These vector shapefiles contain polygons delineating the floodplain extent in four potential future flood scenarios.

The following datasets were used in the creation of the social vulnerability index:

• MapPLUTO (short for Property Land Use Tax lot Output) 2011 tax lot data files were retrieved from the NYC Department of City Planning’s Bytes of the Big Apple product. MapPLUTO merges tax lot data with tax lot features from the Department of Finance Digital Tax Map. Tax lot data was used as an ancillary dataset in population disaggregation. Access: http://www.nyc.gov/html/dcp/html/bytes/applbyte.shtml#pluto

• Block group cartographic boundary shapefiles were downloaded from the 2010 US Census Topologically Integrated Geographic Encoding and Referencing (TIGER) product. They were used to aggregate tax lot information to the block group level. Access: http://www.census.gov/geo/maps-data/data/cbf/cbf_blkgrp.html

• Sociodemographic data was collected from the 2010 U.S. Census survey and the American Community Survey 5-Year Summary Files, 2006 – 2010 and used in the creation of the social vulnerability index.

10 The Preliminary FIRMs for New York City were released on December 5, 2013 and supersede the Preliminary Work Maps. However the Preliminary FIRMs were not available at the time of this analysis.
The following datasets were used in the creation of the storm surge floodwater contaminants index:

- The October 2011 *State Pollutant Discharge Elimination System (SPEDES)* dataset created by the New York State Department of Environmental Conservation was retrieved through the NYSGIS Clearinghouse.
  

- Information about Brownfield and Superfund sites in New York City was gathered from the dataset *Environmental Remediation Sites – New York State (NYSDEC)* developed by the New York State Department of Environmental Conservation. Date of publication is April 2008 with the last metadata last update on November 2010.
  
  Access: [http://www.dec.ny.gov/geo/data/ptk](http://www.dec.ny.gov/geo/data/ptk)

- Information about chemical bulk storage, the petroleum bulk storage program, and major oil storage facilities was gathered from the *Bulk Storage Facilities Database Search – NYS (NYSDEC)* dataset created by the New York State Department of Environmental Conservation. Date of publication is April 2008, which is also listed as the currentness reference.
  

- The 2013 *Combined Sewer Overflow Outfalls* dataset created by the NYC Department of Environmental Protection was accessed by request.

- An inventory of New York City Water Pollution Control Plants was obtained from the 2012 *Selected Facilities and Program Sites* dataset (2012, rev.1) developed by the NYC Department of City Planning’s Bytes of the Big Apple product.
  
• The Toxic Release Inventory dataset for New York City was downloaded by querying Facility Release Reports for the 2011 reporting year using the Toxic Release Inventory Explorer Tool developed by the Environmental Protection Agency. Facilities reporting to TRI were required to submit RY 2011 data to EPA by July 1, 2012.

Access: http://iaspub.epa.gov/triexplorer/tri_release.facility

The following datasets were used in the creation of the critical facilities at-risk index:

• The 2012 Selected Facilities and Program Sites dataset (2012, rev.1) was retrieved from the NYC Department of City Planning’s Bytes of the Big Apple product. This dataset includes information about New York City schools, parks, libraries, public safety, day care, foster care, special needs housing, and health and mental health facilities and programs.


• An inventory of multi-family elevator buildings was selected from the MapPLUTO (short for Property Land Use Tax lot Output) 2011 tax lot data files retrieved from the NYC Department of City Planning’s Bytes of the Big Apple product.


6.2. Estimating the Population At-Risk to Flooding

To assess the individual and community impacts of current and potential future flooding it is important to understand the residential population at-risk. Maps of areal flood extent coupled with demographic data offer an opportunity to estimate the population at-risk by analyzing the aggregate residential population that intersects the flood zone. Various methods are used to achieve this estimation, each with limitations in accuracy and precision. This section describes
the method employed in this work to determine how many New York City residents are and will be at-risk to 100- and 500-year flood events.

6.2.1. Selecting the Flood Zones

This work considers the following six different flood scenarios for New York City: 1) present-day 100- and 2) 500-year floods; 11) 3) 100- and 4) 500-year floods for the 2020s timeslice; and 5) 100- and 6) 500-year floods for the 2050s timeslice. These flood scenarios were selected because they were developed by or are founded upon the FEMA flood insurance study for New York City, the products of which set the standard for flood insurance rates and land use planning decisions. FEMA FIRMs are created through hydrologic and hydraulic modeling and consider the effects of surge, wave action, and astronomical tides and are considered to be the best available data for the region. The future flood scenarios of the 2020s and 2050s are founded upon FEMA’s FIRMs and illustrate the potential impacts of sea-level rise on flood heights and extents.

6.2.2. Population Disaggregation

Disaggregation of data is the process of dividing a data set into its component parts to yield a finer unit of analysis. With respect to census derived population estimates, disaggregation is used to better represent populations within areas, such as floodplains, that do not coincide with census unit boundaries. By disaggregating and redistributing population from large census units into smaller units based on the location of residential housing, the residential population along the boundary of a floodplain can be more accurately approximated relative to other floodplain

11 Present day references FEMA’s Preliminary Work Maps for New York City released in June 2013.
population estimate techniques. This section describes the process of dasymetric disaggregation used in this work to determine population at-risk to current and future flood scenarios. First, the common techniques for estimating floodplain populations - centroid containment, areal weighting, and filtered areal weighting - are described below.

Centroid containment is a coarse method of estimation that selects for inclusion only the census units whose geometric centroid\(^\text{12}\) falls within the floodplain. As can be seen in Figure 6.1 (from Maantay and Maroko, 2009), centroid containment (left) has the potential to dramatically under or overestimate population when the polygon centroid and the floodplain do not coincide – i.e., a polygon can be widely flooded without including the centroid and vice versa. Areal weighting (center) is a technique that addresses the lack of spatial coincidence between census and floodplain boundaries and it has been used in multiple vulnerability studies (Clark et al. 1998; Wu, Yarnal, and Fisher 2002; Kleinosky, Yarnal, and Fisher 2006; Rygel, O’sullivan, and Yarnal 2006). This technique assumes a homogenous distribution of the population and a proportional relationship between the percentage of the census unit flooded and the percentage of at-risk population in the census unit. However a major source of error in the areal weighting technique is that populations are rarely homogeneously distributed throughout a geographic area due to the presence of non- or low-populated spaces such as manufacturing and industrial facilities, public and private parks and lots, water bodies, and extensive infrastructure. Even in residential areas population density can vary based on housing type and unit size, resulting in a heterogeneous population distribution. This is particularly the case for New York City.

\(^{12}\) A geometric centroid refers to the center of mass of a two dimensional object, or the arithmetic mean position of all the points in the shape. In this work the two-dimensional objects are the census unit polygons in ArcGIS.
The filtered areal weighting method was developed to address these unpopulated areas. Filtering is accomplished through the use of an ancillary dataset, often land-use or land-cover, that serves to exclude uninhabited areas from the analysis and redistribute the population in the remaining areas (Maantay, Maroko, and Herrmann 2007). Despite the improvement over the traditional areal weighting technique, filtered areal weighting still cannot account for variations in population density and can omit populations living in non-residentially zoned areas during the filtering process.

The Cadastral-based Expert Dasymetric System (CEDS) of population disaggregation has been used less extensively but offers greater precision than other methods such as centroid containment or areal weighting (Maantay, Maroko, and Herrmann 2007). In fact the areal weighting method, though useful as a simple first order approximation, has been shown to...
potentially underestimate the affected population by 37% compared to CEDS (Maantay and Maroko 2009). CEDS improves on areal weighting and other methods by using cadastral data as an ancillary dataset to filter out uninhabited areas and account for variations in population density. Cadastral data refers to the value, extent, and ownership of land for taxation purposes. It is more detailed and refined than land-use or land-cover data and, when applied using an ‘expert system’ that determines which variable in the cadastral dataset should be applied to each individual record, yields a customized disaggregation that best fits the data. It is a great advantage to be able to apply this method to the densely populated New York City area and achieve results at a high spatial resolution.

Maantay et al. (2007) evaluate census estimated vs. CEDS estimated populations in New York City using both ‘residential units’ and ‘residential area’ as cadastral datasets. They compared three methods of disaggregation derived population estimates to census derived population estimates: 1) CEDS with the expert system that selects the cadastral dataset (residential units or residential area) to be applied to each individual record, 2) dasymetrically derived population using ‘residential units’ alone (no expert system), and 3) dasymetrically derived population using ‘residential area’ alone (no expert system) and found that each of those methods differ from actual census population counts by 1) 6.37%, 2) 8.69% and 3) 9.44% respectively. The CEDS method outperforms the others, but offers only a small advantage over the dasymetrically derived approach. Rather than apply the full expert system as Maantay et al. (2007) have done, this work uses the second method - dasymetrically derived population using ‘residential units’ - to disaggregate population from the census block group level to the tax lot level, as this has shown to effectively estimate the hyper-heterogeneous population of New York City.
Dasymetric disaggregation was achieved as follows:

\[ \text{POP}_t = \text{POP}_c \times \frac{U_t}{U_c} \]  

(1)

where:

\[ \text{POP}_t = \text{dasymetrically derived tax lot-level population}; \]

\[ \text{POP}_c = \text{census population at the block group level}; \]

\[ U_t = \text{the number residential units at the tax lot level}; \text{ and} \]

\[ U_c = \text{the number of residential units at the block group level}. \]

After the population has been disaggregated to the tax lot level, the centroid containment method is ultimately used to select which tax lots are located within the floodplain. As described above, centroid containment has the potential to greatly over or underestimate the population in a floodplain when the unit of analysis is large, such as at the census block or block group level. However, the two advantages of dasymetric disaggregation are that the tax lot footprints are on average over 300 times smaller in area than those of block groups and they better reflect actual population distribution (Figure 6.2), so when the centroid containment method is applied to these small lots the result is more accurate.
Figure 6.2. Comparison of block group and tax lot sizes in the neighborhood of Bushwick Brooklyn. The block group outlined in red in the center of this aerial photo contains 172 tax lots highlighted in green. The area of the block group is 523,425 square feet, a value 253 times greater than the average tax lot area of 2,066 square feet. For this reason it is much more accurate to evaluate the boundary of a floodplain at the tax lot level, rather than the block group level.

Figure 6.3 describes the outcomes of floodplain population estimation using three techniques: centroid containment, areal weighting and dasymetric disaggregation. In this illustration a block group (red box) contains the four tax lots A, B, C, and D (black boxes) some of which are exposed to a hypothetical floodplain in blue. According to the U.S. Census the population of the block group is 500 and, according to MapPLUTO, it contains 180 residential units. The number of residential units per tax lot is also derived from MapPLUTO.
**Figure 6.3.** An example of floodplain population estimation using three techniques: centroid containment, areal weighting and dasymetric disaggregation. The red line indicates the block group extent and the tax lots within are drawn as black rectangles. The census-derived population for the block group is 500 and the Map PLUTO derived number of residential units for the block group is 180. A hypothetical floodplain is illustrated in blue enveloping the centroid of tax lot D but touching none of the other tax lot centroids. The floodplain population estimate is 0 by centroid containment, 170 by areal weighting, and 278 by dasymetric disaggregation.

Using centroid containment at the block group level to estimate the population in the floodplain would yield an estimate of zero because the block group centroid (red dot) does not fall within the floodplain. Therefore this entire block group would be omitted from a floodplain population count. Areal weighing at the block group level would calculate 35% of the total block group population as flooded, corresponding to the percentage of block group area flooded, and yield a population estimate of 170. In contrast, dasymetric disaggregation using the residential units ancillary data set yields a floodplain population estimate of 278. First, the block group population of 500 is disaggregated down to tax lot populations and the distribution of this
disaggregation is guided by the residential units dataset (see Figure 6.3, tax lot population calculations on the right). Then the tax lots whose centroids intersect the floodplain are selected for inclusion in the population count. In this case only the centroid of tax lot D intersects the floodwaters for a total floodplain population of 278. Though floodwaters move through a portion of tax lot C the centroid is not included in the flood area, and the tax lot is omitted from the population estimate.

6.3. Index I: Exposure to Storm Surge Index

An index of storm surge exposure was developed in ArcGIS to rank tax lots based on their potential to experience high storm surge elevations and high velocity wave action. Depending on their topography and proximity to the coastline, tax lots are exposed to different surge heights for a given flood which makes some tax lots more physically vulnerable than others. In addition to surge height, zones of high velocity wave action - defined by FEMA as zones of breaking waves greater than 3 feet - have the potential to inflict significant structural damage. As such, populations living in tax lots with greater exposure to storm surge and wave action are more physically vulnerable to flood events than populations in tax lots that experience low elevation flooding. This storm surge elevation index captures both the degree of exposure to floodwaters and the physical vulnerability of the residential population at the tax lot level.

The storm surge exposure index was created using FEMA’s Preliminary Work Maps for New York City (June 2013) and the New York City Panel on Climate Change future 100- and 500-

13 Damage assessments and wave tank research has shown that wave heights of 1.5 feet can cause significant structural damage. As such, beginning in 2009 FEMA coastal studies are also required to map the Limit of Moderate Wave Action (LiMWA), a line that delineates the landward location of the 1.5-foot wave height.
year flood zone maps for the 2020s and 2050s (June 2013). Tax lots are ranked 1 through 9 with higher numbers corresponding to greater exposure and subsequent vulnerability to harm (Figure 6.5). Tax lots subject to the current 100- and 500-year floods are ranked as more vulnerable than those subject to projected future flooding only, since current flood zones will continue to be flooded in the future at greater surge heights. FEMA designated zones of high-velocity wave action are ranked highest of all.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Description</th>
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<tbody>
<tr>
<td>Rank 1</td>
<td>Projected 500-Year Flood, 2050s</td>
</tr>
<tr>
<td>Rank 2</td>
<td>Projected 500-Year Flood, 2020s</td>
</tr>
<tr>
<td>Rank 3</td>
<td>Projected 100-Year Flood, 2050s</td>
</tr>
<tr>
<td>Rank 4</td>
<td>Projected 100-Year Flood, 2020s</td>
</tr>
<tr>
<td>Rank 5</td>
<td>FEMA Shaded X Zones</td>
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<tr>
<td>Rank 6</td>
<td>FEMA AE and AO Zones, BFE &lt; 10 ft</td>
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<tr>
<td>Rank 7</td>
<td>FEMA AE Zones, BFE 10 ft</td>
</tr>
<tr>
<td>Rank 8</td>
<td>FEMA AE Zones, BFE &gt; 10ft</td>
</tr>
<tr>
<td>Rank 9</td>
<td>FEMA VE Zones</td>
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</tbody>
</table>

**Figure 6.4.** Ranking of NYC tax lots based on their potential to experience high storm surge elevations and high velocity wave action. The higher the rank the greater the exposure to flood waters and the greater the physical vulnerability of the residential population. The 10ft BFE was chosen as the break value in the AE zones (zones subject to shallow flooding of 1 - 3 feet) based on the distribution of the base flood elevation data.

Figure 6.4 describes the ranks of exposure relative to population vulnerability. Rank 1 tax lots are situated well inland or at high elevation such that they are only projected to experience flooding during a 500-year flood event in the 2050s. They were selected in ArcGIS as tax lots in
the 500-year 2050s flood zone that are not also included in any other flood scenario. Rank 2 tax lots are only projected to experience flooding during a 500-year flood event in the 2050s or 2020s. They were selected in ArcGIS as tax lots within the 500-year 2020s and 2050s flood extents that are not also included in any other flood scenario. Rank 3 tax lots are projected to flood during a 500-year flood event in the 2050s or 2020s or a 100-year flood event in the 2050s. This succession is repeated such that the higher ranked tax lots are subject to a new degree of flooding in addition to the flooding experienced in lower ranks.

Tax lots ranked 1 through 4 are subject to future flooding in the 2020s or 2050s only. Lots also subject to the current 500-year flood are ranked 5, and lots ranked 6 through 9 are subject to the current FEMA designated 100-year flood event but vary in ranking based on base flood elevation and the presence or absence of high velocity wave action. The base flood elevations (BFEs) in rank 6 tax lots are less than 10 feet, the BFEs in rank 7 lots are equal to 10 feet, and the BFEs in rank 8 or 9 lots are greater than 10 feet. Lots that ranked 9 on the exposure to floodwaters index are also subject to high velocity wave action.

6.4. Index II: Exposure to Storm Surge Floodwater Contaminants Index

An index of exposure to potential storm surge floodwater contaminants was created from the facility types that utilize, store, and discharge toxic chemicals and hazardous wastes discussed in Chapter 4. The heterogeneous distribution of these facilities throughout New York City means that there is an uneven potential for residents to be exposed to floodwater contaminants from these sites, with many residential tax lots containing or proximal to multiple facilities. The tax lots determined to be at risk were selected using a buffer analysis, such that those lots with
centroids located within a designated facility buffer zone are considered at-risk to contamination during a flood event. The index of potential floodwater contaminants is largely an evaluation of the concentration of sites containing toxic chemicals and hazardous wastes at the tax lot level.

6.4.1. Buffer Technique: Description and Critique

Proximity analysis has been used in the environmental justice literature to examine the characteristics of the population near sites of environmental hazard (Chakraborty and Maantay 2011). It is based on the assumption that anyone living within a fixed distance of a given hazard is at risk to that hazard. In early environmental justice analysis, political and administrative boundaries were used to represent the size and shape of an at-risk area because population data was available for use at that spatial scale. However, it was recognized that the dispersion of hazardous emissions - whether through air or water - does not follow administrative boundaries and the use of a circular buffer around the emission site to approximate the affected area became a common practice (Glickman 1994; Glickman and Hersh 1995; Sheppard et al. 1999).

Aggregation of pre-defined census units within the buffer is then used to estimate the composition of the population affected. The challenge with aggregation is that the buffer and underlying geographic unit boundaries do not coincide such that the buffer includes both whole and partial census polygons. Three common options for measuring the demographics within a buffer are described below.
Figure 6.5. Three methods of measuring the demographics in buffer analysis: A) polygon containment, B) centroid containment, and C) buffer containment.

Figure 6.5 illustrates the polygon, centroid, and buffer containment methods for measuring the demographics in a buffer analysis (note that these and similar methods for estimating floodplain populations are discussed in section 6.2.2). The first method, polygon containment (Figure 6.5a) considers all the data in the polygons that are contained by or intersect the buffer. Centroid containment (Figure 6.5b) includes only those polygons whose centroids fall within the buffer zone. In both of these methods the shape of the buffer zone is determined by the outline of the included polygons and the data in these polygons is aggregated to form the buffer estimate. This is not the case for buffer containment (Figure 6.5c), a method that selects only the polygons and portions of polygons contained within the buffer. Because the circular shape of the buffer is maintained in this method, areal weighting must be applied to the data in the polygons only partially within the buffer.

Buffer analysis, particularly the use of circular buffers, has many limitations in use and may not effectively represent areas at-risk to hazard. However it can capture the intended dimensions of areas at-risk to hazards when the following three assumptions are met:

1. The hazard site is small enough to be treated as a point;
2. The impacts are confined in the specified circular area;
3. The impacts are equal and uniform in all directions (Liu 2001).

These assumptions are difficult to fulfill in the context of point source floodwater contamination analysis. With respect to the first assumption that the hazard site is small enough to be treated as a point, some sites of potential floodwater contaminants such as water pollution control plants occupy an entire tax lot and cannot be treated as a simple point. Though the centroid of the facility may be used as the buffer origin point, the buffered area surrounding the site may be smaller than intended if the site itself is large.

The second assumption that the impacts are confined in a specified circular area is untenable in the context of coastal storm surge flooding. Storm surge movement is very complex; floodwater moves both perpendicular and parallel to the coastline at multiple heights and is affected by land use/land cover, coastline structures, and other inland infrastructure. The movement of floodwater inundation and retreat can only be approximated by local or regional hydrodynamic models. The movement of contaminants within those floodwaters adds another layer of complexity. For these reasons it is impossible to assert that contaminants will affect the entire buffered area, only affect a portion of the buffered area, or that impacts will extend beyond the boundaries of the buffer.

The third assumption that impacts are equal and uniform in all directions implies that all people within the buffer zone are exposed to similar risks - i.e., that they are exposed to hazards of equal toxicity in the same dosage (Armstrong and Chakraborty 1997). However the dynamic nature of floodwater movement suggests that both exposure and dosage would vary within the buffer area. Also, because this work includes nine separate sources of hazards often within overlapping buffers, contaminants of different volumes and toxicity may be present in any given area. Or
multiple point sources of a single contaminant could be sited in a small area, potentially increasing the local volume of contaminant relative to point sources that are distributed evenly.

The use of circular buffers in the index of potential floodwater contaminants clearly does not meet assumptions discussed above; therefore buffers are not used to represent the spread, extent or direction of contaminant impacts. Instead buffers are used to evaluate of the concentration of toxic sites at the tax lot level, with the assumption that areas with dense concentrations of hazardous waste and chemical facilities are at-risk to greater toxic exposure and harm. Circular buffers are also used as a weighting tool to incorporate some measure of a site’s potential threat by assigning larger buffer distances to facilities that 1) store a greater volume of hazardous materials and 2) store, utilize, and discharge toxics that are easily mobilized (i.e., have a high potential to enter the floodwaters). In this regard, buffer distance (measured as radius from the site) is used as a proxy for pollutant volume and also a proxy for mobility (the potential to reach floodwaters). Using buffers as proxy for these factors gives greater weight to sites with a higher level of potential threat and these sites are counted in more tax lots in the floodwater contaminants index. Sites with a lower level of potential threat have smaller buffers and are less represented in the index.

For example, in this analysis SPDES permits categorized as Major were assigned a buffer distance of three-quarters of a mile while those categorized as Significant Minor were assigned a buffer distance of one-quarter mile. Major permits were given greater buffer distance because they score higher on the following criteria relative to Minor permits: toxic pollutant potential, flow/stream flow volume, conventional pollutant content, public health impact, water quality.
factors, and proximity to near coastal waters (see section 4.1.3). They have the potential to
discharge a greater volume of toxic pollutants as well as pollutants with greater toxicity. All
SPDES permitted facilities discharge pollutants directly into ground or surface waters making
their contaminants more mobile than those at sites where toxics are stored in closed containers
such as storage tanks.

The range of buffer distances used in this work - one-quarter, one-half, three-quarters, and one-
mile in radius - are similar to those used in previous studies of hazard sites (Zimmerman 1993;
Glickman 1994; Armstrong and Chakraborty 1997; Sheppard et al. 1999; Harner et al. 2002),
however it has been argued that the choice of buffer radius is often arbitrary and can affect study
results (Liu 2001). Armstrong and Chakraborty (1997) analysis of TRI facilities in Des Moines,
Iowa found that the proportion of minority and impoverished residents is higher in the half-mile
buffer distances relative to the one-mile buffer distances, suggesting that as the unit of analysis
becomes larger the population within becomes more similar to the city as a whole. This result is
in contrast to the analysis of Glickman and Hersh (1995) who studied industrial sites in
Allegheny County, Pennsylvania and found that a larger circular buffer distance of one-mile
contained a greater proportion of disadvantaged population than those within the one-half mile
buffer. In this work buffers are not used to evaluate social vulnerability or equity but only as
proxy for pollutant volume and mobility, so the sociodemographics within the buffered areas are
not considered and the concerns above do not apply.

Using buffers as a proxy for risk has been criticized as a simplistic approach that is often applied
with uncertainty (Bowen 1999). Harner et al. (2002) use one-half and one-mile buffer distances
to approximate different levels of perceived risk to different hazard sources. Superfund National Priority List (NPL) and Comprehensive Environmental Response Compensation and Liability Information System (CERCLIS) sites were buffered to one-mile and all other types of sites (e.g., TRI) to one-half mile on the premise that NPL and CERCLIS sites likely have a greater level of potential threat and therefore pose greater risk to the surrounding communities. However, because the exact volume and composition of pollutants at many hazardous sites is unknown or unreported and the exact level of toxins present can vary on a daily basis, it can be difficult to get a true measure of the level of potential threat.

The nine facility types selected for inclusion in the floodwater contaminant index include Chemical and Petroleum Bulk Storage facilities, and Major Oil Storage Facilities (MOSF), Toxic Releases Inventory (TRI) facilities, State Pollutant Discharge Elimination System (SPDES) Major and Minor facilities, State Superfund Sites, Brownfields, Water Pollution Control Plants and Combined Sewage Overflow (CSO) Outfalls. Buffers were created around each potential contaminant source using the buffer tool in ArcGIS. Distances were assigned based on the volume of contaminants at a given site and the potential for the toxic material to be spilled, discharged, or otherwise incorporated into floodwaters.

1-mile (5,280 ft) buffer

- Water Pollution Control Plants

Because of their potential to release large volumes of untreated sewage directly into or proximal to storm surge, NYC’s wastewater treatment plants were buffered to 1 mile.
¼ mile (3,960 ft) buffer

- Active or unregulated Major Oil Storage Facilities
Active or unregulated Major Oil Storage Facilities were assigned a buffer distance of ¾ mile due to their high storage capacity of 400,000 gallons or more.

- Facilities with State Pollutant Discharge Elimination System “Major” permits
Major permits are issued for discharges that score high in toxic pollutant potential, flow/stream flow volume, conventional pollutant content, public health impact, water quality factors, and proximity to near coastal waters. For these reasons they are buffered to ¾ mile.

½ mile (2,640 ft) buffer

- Class 2 State Superfund Sites
Though Class 2 Sites contain hazards that pose a significant threat to the public health or environment, the type of hazardous substance and potential pathway into floodwaters was not detailed in the superfund database. Therefore the buffer distance applied is ½ mile.

- Combined Sewage Overflow Outfalls
Combined Sewage Overflow Outfalls release untreated sewage directly into or proximal to storm surge. The volume of these releases cannot be ascertained from the given database so the buffer distance assigned is ½ mile, a smaller buffer than that of the water pollution control plants.

¼ mile (1,320 ft) buffer

- Toxics Release Inventory facilities with on-site disposal or releases
The TRI facilities used in this work self-report annual quantities of hazardous wastes released or disposed of on-site. However to understand the public health risk of these facilities situated in
flood zones, more information about the toxicity of each chemical and the mechanism of release (i.e., air vs. water or land release) or disposal is necessary. Since that information is not available in the TRI database the ¼ mile buffer is based on the threat of leaks or spills of stored chemicals into floodwaters, not based on the type of treatment the chemicals receive.

- **Active Brownfield Sites**

  Active brownfield sites are currently in the process of remediation but the type and volume of hazardous waste or contaminant present is not listed in the brownfields database. Without this information it is impossible to make assumptions about the magnitude of potential public health impacts. For this reason brownfields are assigned the smallest buffer distance of ¼ mile.

- **Facilities with State Pollutant Discharge Elimination System “Significant Minor” permits**

  Significant Minor permits are issued for discharges to surface and ground waters that have the potential to contain toxics, however they are not classified as having significant environmental impact. They are buffered to ¼ mile.

- **Active and Unregulated Chemical and Petroleum Bulk Storage facilities**

  Active and unregulated faculties are actively storing or utilizing hazardous substances but doing so in smaller volumes than Major Oil Storage Facilities, warranting a smaller buffer area of ¼ mile.

6.4.2. *Exposure to Storm Surge Floodwater Contaminants Index Methodology*

The exposure to floodwater contaminants index was created using ArcGIS and SPSS. The index considers all facilities within the extent of the 500-year flood boundary for the 2050s, the largest flood extent used in this work. Each of the nine selected facility types were added to ArcGIS as point shapefiles and then buffered with a circular buffer to their assigned distances. The NYC
MapPLUTO tax lot shapefile and 500-year 2050s flood shapefile were also added to ArcGIS, and the MapPLUTO shapefile was then clipped to the future flood extent. Using a one-to-many spatial join, tax lots from MapPLUTO that intersect the contaminant buffers were flagged and added to an output table. This one-to-many join was repeated for once for each of the nine potential contaminants, resulting in nine output tables for the 500-year 2050s flood extent. The output tables were opened in SPSS where repetitive instances of flagged lots (i.e., lots intersected by multiple instances of the same type of hazard) were aggregated to get the total number of tax lot intersects per hazard. The nine data tables were merged into one file, and each tax lot summed across the nine contaminants to get the total number of buffer intersections from all contaminants per tax lot. This final count of buffer intersections per tax lot is used to create the floodwater contaminants index. Values ranged from 0 for tax lots that were not intersected by any buffers to tax lots intersected by as many as 227 buffers.
Figure 6.6. Sources of potential storm surge floodwater contaminants in south Brooklyn, their buffer zones, and the tax lots at risk. Chemical and petroleum bulk storage facilities were omitted to maintain figure clarity. The 500-year floodplain for the 2050s is in blue.

Figure 6.6 illustrates how the tax lots in the southern Brooklyn 500-year 2050s floodplain can be intersected by zero, one, or multiple facility buffers. This affects their rank on the floodwater contaminants index because their index score is a count of how many buffer intersections each tax lot experiences. Buffer sizes range from $\frac{1}{4}$ to 1 mile in radius and the number of each facility type ranges from tens to thousands. For example, the sheer number of chemical and petroleum bulk storage facilities would have overwhelmed the other facility buffers so they were omitted from Figure 6.6 (though not omitted from the index). The water pollution control plant is buffered to a mile (red), the Superfund site is buffered to $\frac{1}{2}$ mile (orange), the toxic release inventory sites are buffered to $\frac{1}{4}$ mile (yellow), the major state pollutant discharge elimination system (SPDES) site are buffered to $\frac{3}{4}$ mile (green) and the SPDES minor sites are buffered to $\frac{1}{4}$
mile (blue), major oil storage facilities (MOSF) are buffered to ¾ mile (purple), and the brownfields are buffered to ¼ mile (pink).

6.5. Index III: Social Vulnerability Index

The social vulnerability of the population estimated to be affected by current and future 100- and 500-year flood events was measured by creating an index derived from a suite of selected socioeconomic indicators at the block group and census tract levels. The data collected and methods of aggregating the index are described in this section.

6.5.1. U.S. Census and American Community Survey Data

Social vulnerability assessment research to date has been conducted at multiple geographic units such as the county (Cutter, Boruff, and Shirley 2003; Cutter and Finch 2008; Fekete 2009), census tract (Flanagan et al. 2011; Maantay, Maroko, and Culp 2009), census block group (Kleinosky, Yarnal, and Fisher 2006; Peacock et al. 2011; Rygel, O’sullivan, and Yarnal 2006), and census block (Cutter, Mitchell, and Scott 2000; Wu, Yarnal, and Fisher 2002). The choice of the unit of analysis is influenced by the study area size (i.e., national, regional, or local analysis) and the availability of data (the smaller the geographic unit, the fewer detailed datasets that are available). Though results for a given study area can vary with different units of geographic analysis, Cutter et al. (1996) found that census tracts and block groups are the most appropriate for equity analysis because of intra-county and intra-zip code variations in indicators. This work used census block group data wherever available and census tract data otherwise, with these choices largely dictated by the availability of the socioeconomic indicators.
The population data used in the social vulnerability index was collected from the 2010 U.S. Census survey and the American Community Survey (ACS) 5-Year Summary Files, 2006 – 2010. The 2010 U.S. Census was the primary data source wherever possible, supplemented by the American Community Survey data when Census data was not available. Some Census data was not available was due to a change in the structure of the 2010 Census survey. Prior to the 2010 Census, the Census survey consisted of both long form and short form questionnaires. The short form gathered population count and basic demographic data while the long form also collected housing, demographic, and economic data. Data collected from both forms is typically necessary to construct a robust index of social vulnerability. However, in an effort to streamline decennial operations and provide more timely data the 2010 Census did not use the long form and instead sent out only the short form. The decennial long form was replaced by the ACS, which provides data not once every ten years but once every year of the decade. Therefore many of the common variables selected for inclusion in previous indices were not available through the 2010 U.S. Census and were sought from the ACS.

This work could have used the older 2000 Census long form data instead of using the ACS, however the value and relevance of the 2000 Census data is greatly diminished by the time that has passed since its collection. For this reason, the recent data collected by the American Community Survey over a 5-year range from 2006 - 2010 was used. The ACS is a survey of demographic, economic, and housing data collected every year and averaged over a given time period of 5, 3, or 1 years. ACS surveys only 3 million households per year and is less accurate with a higher margin of error than the U.S. Census, however because data is collected every year it is more current and in many ways more relevant. The 5-year survey is the most reliable of
ACS estimates, composed of the largest sample size and date range for areas of all population sizes, and it was the survey used for many indicators in this work.

The selection of variables was guided by the work of Cutter et al. (2003), Maantay et al. (2009), and Flanagan et al. (2011) grouped into domains as follows: socioeconomic status, household structure and disability, minority status and language, and group housing and transportation (Table 6.1).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Source</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Domain A: Socioeconomic Status</strong></td>
<td></td>
<td></td>
<td>Block Group</td>
</tr>
<tr>
<td>1. Percent persons below poverty</td>
<td>Individuals below poverty = &quot;Under 0.50&quot; + &quot;0.50 to 0.74&quot; + &quot;0.75 to 0.99&quot;; denominator is total population for whom poverty status is determined.</td>
<td>American Community Survey 5-Year Summary: 2006-2010. Table C17002 - Ratio of income to poverty level in the past 12 months.</td>
<td>Block Group</td>
</tr>
<tr>
<td>2. Percent civilian unemployed</td>
<td>Civilian persons unemployed divided by total civilian population. Civilian population = total population 16 years or older - persons in the armed forces.</td>
<td>American Community Survey 5-Year Summary: 2006-2010. Table B23001 - Sex by employment status for the pop 16 yrs and over.</td>
<td>Census Tract</td>
</tr>
<tr>
<td>3. Per Capita Income in 2011</td>
<td>The mean income computed for every person.</td>
<td>American Community Survey 5-Year Summary: 2006-2010. Table B19301 - Per capita income in the past 12 months (in 2010 inflation-adjusted dollars).</td>
<td>Census Tract</td>
</tr>
<tr>
<td>4. Percent adults with no high school diploma</td>
<td>Persons 25 yrs and older with less than a 12th grade education (including individuals with 12 grades but no diploma); denominator is the pop 25 yrs and over.</td>
<td>American Community Survey 5-Year Summary: 2006-2010. Table B15002 - Sex by educational attainment for the pop 25 yrs and over.</td>
<td>Block Group</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td>Source</td>
<td>Unit</td>
</tr>
<tr>
<td>----------</td>
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</tr>
<tr>
<td><strong>Domain B: Household structure and disability</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Percent persons 65 years of age or older</td>
<td>Persons 65 years of age or older; denominator is total population.</td>
<td>2010 Census Summary File 1, 100% Data. Table P12 - Sex by age.</td>
<td>Block Group</td>
</tr>
<tr>
<td>6. Percent persons 10 years of age or younger</td>
<td>Persons 10 years of age or younger; denominator is total population.</td>
<td>2010 Census Summary File 1, 100% Data. Table P12 - Sex by age.</td>
<td>Block Group</td>
</tr>
<tr>
<td>8. Percent male or female single householder with children under 18 years</td>
<td>Male/Female Householder, no spouse present, with own children under 18 years; denominator is total households.</td>
<td>American Community Survey 5-Year Summary: 2006-2010. Table DP02 - Selected social characteristics in the United States.</td>
<td>Census Tract</td>
</tr>
<tr>
<td><strong>Domain C: Minority Status and Language</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Percent Minority</td>
<td>Black or African American alone (not Hispanic or Latino) + All Hispanic or Latino; denominator is total pop.</td>
<td>2010 Census Summary File 1, 100% Data. Table QT-P4 - Race, combinations of two races, and not Hispanic or Latino.</td>
<td>Block Group</td>
</tr>
<tr>
<td>10. Percent persons 5 years of age or older who speak English less than well</td>
<td>For all age groups and all languages - the total of persons who speak English &quot;not well&quot; or &quot;not at all&quot;; denominator is total pop 5 yrs or older.</td>
<td>American Community Survey 5-Year Summary: 2006-2010. Table B16004 - Age by language spoken at home by ability to speak English for the pop 5 yrs and over.</td>
<td>Block Group</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td>Source</td>
<td>Unit</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td><strong>Domain D: Group Housing and Transportation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Percent multi-unit structure</td>
<td>Housing units with 10 or more units in structure; denominator is total occupied housing units.</td>
<td>American Community Survey 5-Year Summary: 2006-2010. Table B25024 - Units in structure.</td>
<td>Block Group</td>
</tr>
<tr>
<td>12. Percent Crowded Households</td>
<td>Total occupied housing units with more people than rooms (&gt; 1 person per room); denominator is total occupied housing units.</td>
<td>American Community Survey 5-Year Summary: 2006-2010. Table B25014 - Tenure by occupants per room.</td>
<td>Block Group</td>
</tr>
<tr>
<td>13. Percent households without a vehicle available</td>
<td>Households with no vehicle available; denominator is total occupied housing units.</td>
<td>American Community Survey 5-Year Summary: 2006-2010. Table B25044 - Tenure by vehicles available.</td>
<td>Block Group</td>
</tr>
<tr>
<td>14. Percent persons in group quarters</td>
<td>Total population in group quarters; denominator is total population.</td>
<td>2010 Census Summary File 1, 100% Data. Table P29 - Household type by relationship.</td>
<td>Block Group</td>
</tr>
</tbody>
</table>

Table 6.1. Variables used in the social vulnerability index, their geographic unit, and data source. Adapted from Flanagan et al. (2011), Maantay et al. (2009), and Cutter et al. (2003). Sources: 2010 U.S. Census, American Community Survey 5-Year Summary: 2006-2010.

6.5.2. Constructing the Social Vulnerability Index

Social vulnerability indices can be configured in a variety of ways to best measure the intended dimension of social vulnerability. Users can vary the structural design, indicator selection, and scale of analysis, and choose the best methods for data transformation, scaling, weighting and aggregation (Tate 2012). The index constructed in this work uses a deductive structure of fourteen indicators, each transformed from counts to percentages, normalized via rank order, and then aggregated without weights to form the final index value. Though Tate (2012) found the deductive design to be neither the most accurate nor the most precise, it was a practical option given the small number of indicators and the decision not to use a weighting scheme (Figure 6.7). Assigning weights to various indicators can have great influence on the index outcome and
must be assigned thoughtfully when used at all. In fact when creating the social vulnerability index for the United States, Cutter et al. (2003) report that in the absence of a defensible method for assigning weights they opted to treat each factor as having an equal contribution to the vulnerability index. This work also weights each indicator equally simply for lack of a rationale to do otherwise.

Figure 6.7. A model of deductive design for the construction of vulnerability indices. Each indicator (I.1. – I.6.) is transformed, normalized, and aggregated without weights to form the index. Reprinted from Tate (2012).

The social vulnerability index was created twice: once at the citywide level and once for the 500-year flood zone for the 2050s using ArcGIS and SPSS software. Indices were not constructed for each of the six flood extents considered in this work in order to conserve processing time and power. Instead the 500-year flood zone, which encompasses all other flood zones, was selected for social vulnerability analysis. The citywide and 500-year flood zone methodologies vary slightly in their respective datasets and processes so they are detailed separately below.

I. Social Vulnerability Index Methodology: Citywide

In this citywide methodology, a social vulnerability index value was calculated for every populated block group in NYC. Sociodemographic data from the 2010 U.S. Census and ACS
was gathered at the block group level wherever possible and the census tract level where block
group resolution was unavailable. The block group and census tract level datasets were opened in
SPSS and merged based on their GeoID variables. Cases where total population is equal to zero
were eliminated from the merged dataset. The sociodemographic variables were transformed
from count values to rate values (values per block group or census tract population) by dividing
the raw counts by the appropriate denominator (see Table 6.1 for descriptions of the variables
and their respective denominators). This brought the number of indicators in the social
vulnerability index to fourteen and eliminated their respective measurement scales. Each
indicator rate value was assigned a percentile rank to determine the top tenth percentile values in
the indicator dataset for each block group. The top tenth percentile values were recoded to the
number one and all other values were recoded to the number zero. The recoded percentile values
were summed across all fourteen indicator values for each block group, yielding a maximum
potential social vulnerability index value of fourteen and a minimum value of zero.

II. Social Vulnerability Index Methodology: 500-Year Flood Zone

In this methodology, a social vulnerability index value was calculated for every populated tax lot
in the 2050s 500-year flood zone. Prior to calculating the index values, population count was
disaggregated from the census block or census tract levels to the tax lot level using the
methodology described in section 6.2.2. Any tax lots without residential units were omitted from
the final tax lot population count.

The 2011 MapPLUTO tax lot dataset was added to ArcGIS along with the block group and
census tract cartographic boundary shapefiles. The three datasets were joined using a one-to-one
spatial join, and cases where total residential units are equal to zero were eliminated. The dataset was then exported as a dbf file and opened in SPSS. Sociodemographic datasets at the block group and census tract level were also opened in SPSS and the three datasets were merged based on their GeoID variables. This resulted in a citywide dataset with all cases at the tax lot level but also containing sociodemographic data at the block group and census tract levels.

The next step was to disaggregate the sociodemographic data to the tax lot level. To do this in SPSS, first the residential units variable was aggregated from the tax lot up to the block group and census tract levels. Then each sociodemographic variable was disaggregated from the block group or census tract level to the tax lot level using residential units as the auxiliary variable (see section 6.2.2 for a detailed description of dasymetric disaggregation). The sociodemographic variables were then transformed from count values to rate values (values per block group or census tract population), by dividing the raw counts by the appropriate denominator (see Table 6.1 for descriptions of the variables and their respective denominators). This brought the number of indicators in the social vulnerability index to fourteen and eliminated their respective measurement scales. The dataset was exported and opened in ArcGIS.

With the indicators dataset at the tax lot level open, the shapefile for the 500-year flood scenario for the 2050s was also added to ArcGIS. Using the select by location function, the tax lots from the indicator dataset whose centroids were located within the 500-year 2050s flood scenario were selected. These selections were then exported as a shapefile. The indicator rate values were then assigned a percentile rank to determine the top tenth percentile values at the tax lot level for each of the fourteen indictor datasets. The top tenth percentile values were recoded to the number one
and all other values were recoded to the number zero. The recoded percentile values were then summed across all fourteen indicator values for each tax lot, yielding a maximum potential value of fourteen and a minimum value of zero. The actual results never reached the maximum value of 14 but instead ranged from 0 to 10.

There is a notable difference in the citywide and 500-year 2050s flood zone methodologies that is reflected in their resulting index values. First, the citywide vulnerability index was evaluated at the census block group level while the 500-year 2050s flood scenario was evaluated at the tax lot level. This was done to more accurately delineate the population considered ‘flooded’ near the inland flood zone boundaries by using a smaller unit of analysis, the tax lot. Second, when determining the top tenth percentile values in each indicator dataset, values are evaluated against all other values in the dataset. As a result there is a shift toward higher social vulnerability index values in the 500-year 2050s flood zone relative to the citywide social vulnerability index dataset, due to the influence on the citywide dataset of census blocks with high index values located outside of flood zones. Despite this difference it was important to evaluate the 500-year 2050s flood zone unto itself to capture the range of vulnerability within affected tax lots. This difference would not be as pronounced had the citywide index values simply been applied to the tax lots in the flood zones.

6.6. Index IV: Critical Facilities Index

In addition to indices of flood exposure, floodwater hazard, and social vulnerability, an index of critical facilities was created from the facilities that provide services to or temporarily house a portion of the population discussed in Chapter 5. These facilities were grouped into two
categories: Group 1 consists of facilities with a population needing direct assistance for mobility (i.e., disabled persons and/or the elderly) and Group 2 considers facilities with complex evacuation and/or recovery needs. These facilities are considered to be ‘critical’ in the context of emergency preparedness and response because they may need additional support or resources to care for the population they serve in the event of a flood. The critical facilities index attempts to determine which residents will be most affected by the loss of essential services or temporary housing due to flooding by identifying critical facilities located in flood zones and aggregating them per tax lot.

6.6.1. Critical Facilities Index Methodology

The index of critical facilities was developed in ArcGIS and SPSS. The index considers all facilities within the extent of the 500-year flood boundary for the 2050s, the largest flood extent used in this work. In ArcGIS, the Group 1 and 2 facilities that intersect the 500-year flood zone for the 2050s were selected from the citywide critical facilities database and exported as a point shapefile (Table 6.2). Tax lots from MapPLUTO that intersect these point facilities were also selected and exported as a shapefile. The MapPLUTO polygon and facilities point data were joined into one file using a one-to-many spatial join that merged the tax lot and facilities attributes. Next, residential high-rise buildings (greater than or equal to seven floors in height) located in the 500-year flood zone for the 2050s were selected from the 2011 MapPLUTO dataset. The high-rise and merged tax lot and facilities datasets were imported into SPSS and merged on a common variable. Duplicate cases were identified and added together to give a total count for each tax lot of critical facilities situated within. This count ranged from 0 to 18.
Facilities in the 500-Year Zone in the 2050s: Listed by Type

<table>
<thead>
<tr>
<th>Type</th>
<th>Bronx</th>
<th>Brooklyn</th>
<th>Manhattan</th>
<th>Queens</th>
<th>Staten Island</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hospitals and Residential Health Centers</td>
<td>10</td>
<td>17</td>
<td>15</td>
<td>18</td>
<td>4</td>
<td>64</td>
</tr>
<tr>
<td>Residential Disability Centers</td>
<td>46</td>
<td>52</td>
<td>31</td>
<td>16</td>
<td>15</td>
<td>160</td>
</tr>
<tr>
<td>High Rise Buildings</td>
<td>31</td>
<td>157</td>
<td>319</td>
<td>67</td>
<td>3</td>
<td>577</td>
</tr>
<tr>
<td><strong>GROUP 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Correctional Facilities</td>
<td>12</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>Residential Chemical Dependency Centers</td>
<td>0</td>
<td>3</td>
<td>16</td>
<td>2</td>
<td>1</td>
<td>22</td>
</tr>
<tr>
<td>Group Homes</td>
<td>1</td>
<td>8</td>
<td>8</td>
<td>11</td>
<td>1</td>
<td>29</td>
</tr>
<tr>
<td>Residential Mental Health Facilities</td>
<td>7</td>
<td>2</td>
<td>25</td>
<td>2</td>
<td>7</td>
<td>43</td>
</tr>
<tr>
<td>Day Care Centers and Schools</td>
<td>54</td>
<td>301</td>
<td>261</td>
<td>108</td>
<td>28</td>
<td>752</td>
</tr>
<tr>
<td>Temporary/Transitional Housing</td>
<td>2</td>
<td>9</td>
<td>16</td>
<td>4</td>
<td>0</td>
<td>31</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>163</td>
<td>550</td>
<td>693</td>
<td>228</td>
<td>59</td>
<td>1,693</td>
</tr>
</tbody>
</table>

Table 6.2. The number of facilities listed by borough and citywide that were selected for use in the critical facilities index. This count includes only the facilities situated in the 500-year flood zone for the 2050s.

6.7. Index V: Overall Storm Surge Flood Risk Index

Every tax lot within the 2050s 500-year floodplain (116,019 tax lots) was selected for inclusion in the storm surge exposure, storm surge floodwater contaminants, and critical facilities indices. The social vulnerability index was calculated only for tax lots containing residential units with a population greater than zero for a total of 115,364 lots, a slightly smaller number than the previous indices. Figure 6.8 illustrates how the four indices were constructed and combined to form the overall flood risk index. The first column lists the index name and the indicators used in its construction. The second column describes the process by which the indicators were used to develop values that reflect the intended measurement of the index. The ‘Results’ column lists the range of output values for each index. Min-max linear scaling was then used to place all indices
into a common and dimensionless measurement scale of values between 0 - 25. The scaled values were added together to form the overall flood risk index. The rationale for scaling between 0 - 25 for each of the indices was to be able to evaluate the final composite index on a scale of 0 - 100. Though the overall flood risk index has a potential range of 0 - 100, the highest values reached just over 53 indicating that none of the tax lots scored maximum values for each of the four individual indices.
Figure 6.8: Construction of the four individual indices and the overall storm surge flood risk index. All indices were developed at the tax lot level using ArcGIS software. For a more detailed description of index datasets, design, and construction see sections 6.3 - 6.7.

<table>
<thead>
<tr>
<th>Group 1: Physical Assistance</th>
<th>Group 2: Coordinated Evacuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Storage</td>
<td>Perimeter Storage</td>
</tr>
<tr>
<td>Support/Aid</td>
<td>Toxic Release</td>
</tr>
<tr>
<td>Growers</td>
<td>Minor Oil Storage</td>
</tr>
<tr>
<td>Chemical Inventory</td>
<td>Petroleum Storage</td>
</tr>
</tbody>
</table>

Storm Surge Floodwater

Index and Indicators

<table>
<thead>
<tr>
<th>Social Vulnerability Index</th>
<th>Exposure Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>Floodwater Hazards</td>
</tr>
<tr>
<td>Language</td>
<td>Woody Action</td>
</tr>
<tr>
<td>Mobility Status</td>
<td>Education</td>
</tr>
<tr>
<td>Household Age &gt; 55</td>
<td>Education</td>
</tr>
<tr>
<td>Group Quarters</td>
<td>Income</td>
</tr>
<tr>
<td>Household Education</td>
<td>Employment</td>
</tr>
<tr>
<td>Female Head of Family</td>
<td>Poverty</td>
</tr>
</tbody>
</table>

Results

Storm Surge Floodwater

Composite Index

Storm Surge Floodwater

Index

Flood

Risk

False Results

Overall

Storm

Surge

Floodwater

Index

Values: the number of critical facilities per tax lot was calculated for the index. 1-2 The number of different buffers to their designated distances. 2. Hazardous facilities were buffered.

Values: index values. 4. Cadastrel values were summed across all 14 indicators for the index. Recade: 0.7. All other values.

Values: index values. 3. Top 10th percentile values were trimmed from each tax lot. 2. Values were transformed from distance-based metrics to tax lot level. 1. Social demographic indicators were derived from tax lot level values of between 1 and 9.

Values: index values. between 0 - 0.9. Tax lots were assigned an index value of between 1 and 9 based on the intensity or future flood zone.

Values: index values. between 0 - 25. Then were scaled from 0-1.8. Final index values.

Values: index values. between 0 - 25. Then were scaled from 0-1.8. Final index values.

Values: index values. between 0 - 25. Then were scaled from 0-1.8. Final index values.

Values: index values. between 0 - 25. Then were scaled from 0-1.8. Final index values.

Values: index values. between 0 - 25. Then were scaled from 0-1.8. Final index values.
6.7.1. Inverse Distance Weighting

Inverse distance weighting (IDW) was used to better visualize the tax lot data in the 2050s 500-year floodplain viewed at the citywide scale by developing a continuous surface of index values. IDW is a deterministic interpolation technique that creates surfaces from a known set of points. It is founded upon the assumption that points proximal to one another have more closely related values than points that are further apart. IDW predicts a value at a location using the measured values surrounding that location, with neighboring values having greater weight than those located further away (Figure 6.8). Weights are proportional to the inverse of the distance between the predicted and measured points, raised to a power value.

**Figure 6.9.** Example of inverse distance weighting interpolation where the red dot is the unknown point for which we are calculating a value \( Z(x) \) and the green dots are points with known values (in bold) at given distances (italics) from the red dot. The generalized IDW equation (top) is expressed using the red and green dot values and distances in the bottom equation. Because each value is divided by its distance squared, the closer points have greater influence on the calculated value \( Z(x) \) than the distant points.
The overall flood risk index was converted from polygon to points in ArcGIS. The inverse distance weighting tool was applied with the following parameters: fixed search radius of $\frac{1}{4}$ mile (1,320 feet), power value of 2, and output cell size of 250 ft. The result was clipped to the boundaries of the five boroughs. This process was applied to each of the four individual indices plus the overall storm surge flood risk index.

6.7.2. *Local Indices of Spatial Autocorrelation*

Local indicators of spatial autocorrelation (LISA) are used to assess the hypothesis of spatial randomness by identifying significant spatial clusters of high or low values or spatial outliers for a given location. The Anselin Local Moran’s I tool for ArcGIS generates a local Moran’s I value, a z-score (standard deviation), a p-values (probability), and a cluster/outlier code for each feature being evaluated. If the data is distributed normally the following two assumptions can be made: 1) the data that fall in the middle of the bell-curve reflect the expected outcome of the analysis, and 2) the data in the tails of the distribution where the z-scores are large and the p-values are small suggest something more interesting - that the observed spatial pattern is likely not random. The critical z-scores and p-values for corresponding confidence levels are shown in Table 6.3.

This work uses a confidence level of 95% to reject the null hypothesis of spatial randomness.

<table>
<thead>
<tr>
<th>Z-Score (Standard Deviations)</th>
<th>P-Value (Probability)</th>
<th>Confidence Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;-1.65$ or $&gt;1.65$</td>
<td>$&lt;0.10$</td>
<td>90%</td>
</tr>
<tr>
<td>$&lt;-1.96$ or $&gt;1.96$</td>
<td>$&lt;0.05$</td>
<td>95%</td>
</tr>
<tr>
<td>$&lt;-2.58$ or $&gt;2.58$</td>
<td>$&lt;0.01$</td>
<td>99%</td>
</tr>
</tbody>
</table>

*Table 6.3.* The critical z-scores and p-values for corresponding confidence levels. Source: ArcGIS Resources 10.1.
Five cluster/outlier codes are possible as output: not significant (p > 0.05; less than 95% confidence level), clusters of high values (high-high) and clusters of low values (low-low) that reflect positive local spatial autocorrelation, outliers in which a high value is surrounded by low values (high-low) and outliers in which a low value is surrounded by high values (low-high), both of which reflect negative local spatial autocorrelation. Local indicators of spatial autocorrelation were calculated for overall storm surge flood risk index values in the 500-year 2050s floodplain and mapped at both the citywide and neighborhood levels. Using the Anselin Local Moran’s I tool in ArcGIS, spatial relationships between data points were conceptualized as inverse distance squared meaning that neighboring values have greater influence on the value of analysis than features farther away. With the squared option selected, the neighborhood influence drops off sharply so only the closest values will have significant influence on the value being analyzed. Distances between values were calculated using a Euclidean (straight line) method. No standardization of spatial weights was applied.
Chapter 7: Results and Discussion

Following the methodologies described in chapter 6, this section describes the results of this research. It includes the following analyses: area and population estimates for current and future flood zones; indices of storm surge exposure, storm surge floodwater contaminants, social vulnerability, and at-risk critical facilities; a composite overall storm surge flood risk index; and spatial autocorrelation analysis.

Of the indices, three were calculated at the tax lot level but exclude lots without a residential population (i.e., no residential units according to the MapPLUTO database). The exception is the critical facilities index, which counts any tax lot where a facility is located, including tax lots without a residential population. The composite overall storm surge flood risk index contains both residential and non-residential tax lots. All results are mapped at the citywide and neighborhood scales with tax lots displayed to the boundaries of the 500-year flood in the 2050s, the largest floodplain extent used in this study. The surfaces of the citywide maps were interpolated via inverse distance weighting for better visualization. Choropleth maps are presented at a higher resolution for the following four areas:

- Southern Brooklyn and Jamaica Bay, Queens
- Lower Manhattan
- Eastern Staten Island
- Eastern Bronx including City Island

These four well-populated areas are projected to experience extensive flooding during a 500-year flood in the 2050s and as such were selected for closer study.
7.1. Citywide Flood Extent and Population At-Risk

When discussing the population at-risk to future flood events it is important to note that the population estimates used in this work are derived from the 2010 US Census only, and that estimates of future population are not applied. This is because future population projections do not account for the local distribution of population growth and change. The NYC Department of City Planning developed borough and citywide estimates of population changes through the 2040s (The New York City Department of City Planning 2013) and project a citywide population of 9 million for 2040, a 9.5% increase relative to the 2010 population of 8.2 million. The boroughs of the Bronx and Brooklyn are expected to experience the greatest percent growth, 14% and 11.3% respectively, with the smallest increase in growth projected for Manhattan at 6.7%.

However, despite these borough-wide projections, future changes in local-level populations are difficult to predict, as they are largely dependent upon changes in housing and zoning policy. Furthermore, future populations in coastal areas may vary even more dramatically than that of the city as a whole due to the following factors. First, there is the market demand for waterfront living combined with the pressure to house additional NYC residents both of which encourage residential floodplain development. Second, the NY Rising Buyout and Acquisition Programs by which the State purchases homes at high risk to repeated flooding, has engendered a retreat among coastal residents looking to move to a less flood-prone area instead of rebuilding in the floodplain. The highest risk areas - known as enhanced buyout areas - are to be maintained in perpetuity as coastal buffer zones, permanently reducing the local population. Purchases outside the enhanced buyout areas are eligible for redevelopment “…in a resilient manner” which
includes the possibility of residential construction (New York State Governors Office of Storm Recovery n.d.). For these reasons future population estimates of the NYC boroughs are highly uncertain and inapplicable for this tax lot level analysis, however current population estimates are a reasonable proxy to evaluate relative population changes in flood zones of different sizes.

Table 7.1 shows the flood area and residential population calculations for each of the seven past, current, and future flood scenarios as well as the percent difference in these values. Percent difference is calculated both relative to the previous flood zone and relative to the baseline of FEMA’s first 100-year flood map for New York City (1983). This scenario is included in the table for comparison with present day (2013) 100-year flood estimates.

<table>
<thead>
<tr>
<th>Flood Zone</th>
<th>Area (mi²)</th>
<th>% Change Area</th>
<th>Population</th>
<th>% Change Population</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Relative to previous flood zone</td>
<td>Relative to 1983 baseline</td>
<td>Relative to previous flood zone</td>
</tr>
<tr>
<td>FEMA 100-Year Flood, 1983</td>
<td>30.6</td>
<td>-</td>
<td>189,386</td>
<td>-</td>
</tr>
<tr>
<td>FEMA 100-Year Flood, 2013</td>
<td>44.9</td>
<td>47%</td>
<td>385,254</td>
<td>103%</td>
</tr>
<tr>
<td>NPCC2 100-Year Flood, 2020s</td>
<td>58.8</td>
<td>31%</td>
<td>587,265</td>
<td>52%</td>
</tr>
<tr>
<td>NPCC2 100-Year Flood, 2050s</td>
<td>71.2</td>
<td>21%</td>
<td>787,596</td>
<td>34%</td>
</tr>
<tr>
<td>FEMA 500-Year Flood, 2013</td>
<td>63.4</td>
<td>-</td>
<td>687,733</td>
<td>-</td>
</tr>
<tr>
<td>NPCC2 500-Year Flood, 2020s</td>
<td>82.1</td>
<td>29%</td>
<td>1,012,045</td>
<td>47%</td>
</tr>
<tr>
<td>NPCC2 500-Year Flood, 2050s</td>
<td>89.5</td>
<td>9%</td>
<td>1,196,422</td>
<td>18%</td>
</tr>
</tbody>
</table>

Table 7.1. The size of past, current, and projected future 100- and 500-year floodplains for New York City and the residential population in the flood zones as per the 2010 Census.

At 30.6 mi² in size, the 1983 original FEMA 100-year floodplain for New York City is 10% of the city’s 304.8 mi² area. It contains a modern-day population of 189,386, which is 2% of the city’s 8.2 million residents (as per the 2010 US Census). Population density increases moving
inland so it is expected that as the 100-year floodplain increases in size the number of affected population will increase sharply at first. This was indeed evident in the calculation of floodplains in FEMA’s Preliminary Work Maps (PWM) for New York City released in June 2013. The 100-year flood area increased 47% from the 1983 floodplain area to 44.9 mi² and the affected population increased over 100% to 385,254. According to New York City Panel on Climate Change (NPCC) projections the size of the PWM 100-year floodplain could increase 31% by the 2020s (in a scenario of 11 inches of sea-level rise) and another 21% to 71.2 mi² by the 2050s (with 31 inches of sea-level rise). The size of the current 500-year floodplain is 63.4 mi² and it is projected to increase to 82.1 mi² in the 2020s and to 89.5 mi² - almost 1/3 of the city’s land area - by the 2050s. Approximately 1.2 million residents could be at-risk to the 500-year flood in the 2050s, which is nearly 15% of the present-day population.

It might be expected that the 100- and 500-year flood areas would increase moderately in size with 11 inches of sea-level rise in the 2020s and then increase more noticeably with an additional 20 inches of sea-level rise in the 2050s (for a total of 31 inches of sea-level rise in the 2050s relative to the current flood area). However the opposite is true. For both the 100- and 500-year flood scenarios flood area increases by approximately 30% in the 2020s relative to current scenarios, and then 21% and 9% respectively in the 2050s relative to the 2020s despite the greater sea-level rise in this interval. This trend is also observed in the population at-risk for each flood scenario. The population at-risk increases approximately 50% in the 2020s relative to current scenarios, and then 34% and 18% respectively in the 2050s relative to the 2020s. The increased rate of flood inundation between the current and 2020s scenarios, relative to the rate of inundation between the 2020s to 2050s scenarios, is likely due to the changes in topography and
slope as floodwaters move from the coast inland. When the slope of the land is shallow small vertical changes in flood elevation translate to greater horizontal flooding than with steeper slopes. On average the topographic gradient becomes steeper from the coastline to the interior resulting in a broader floodplain closer to the coastline for a given increment of vertical flood elevation.

Though not covered in this work, it has been noted that areas with low slopes have higher uncertainty when mapping floodplains than areas with high slopes (NOAA 2010). Large vertical errors in flood elevation will have a limited horizontal expression on steeper slopes. In contrast, small vertical errors in flood elevation that can generate a large horizontal error on low slopes. Uncertainty in the current and future NPCC flood maps is an important limitation of this study that is discussed further in chapter 8.

7.2. Flood Extent and Population At-Risk by Borough

The movement of storm surge is a dynamic process influenced by local topography, bathymetry, land use and infrastructure and resulting in local differences in the rate and extent of flooding. Figure 7.1 depicts differences in 100- and 500-year flood area for each borough.
The borough of Queens experiences the greatest flood extent for all six flood scenarios followed closely by Brooklyn, then Staten Island, the Bronx and Manhattan. Queens experiences roughly three times the flood extent of the Bronx and five times that of Manhattan, a difference in some scenarios of nearly 25 square miles. The difference between the 100- and 500-year flood extents for a given timeslice is most pronounced within the boroughs of Brooklyn and Queens. The current 100- and 500-year flood areas are nearly equal in the Bronx but this changes significantly in the 2020s and 2050s with the 500-year exceeding the 100-year flood. This means that not only do the boroughs experience different floodplains for a given flood but the rate at which the floodplains increase in size varies by borough. Also, as was noted citywide, the 100- and 500-year flood areas and population impacts in each borough increase more sharply with 11 inches of sea-level rise in the 2020s and then more moderately with an additional 20 inches of sea-level rise in the 2050s.
Figure 7.2. Residential population at-risk to the current and future 100- and 500-year flood zones for the five boroughs of New York City. The purple bars represent 500-year flood scenarios and the blue bars represent 100-year flood scenarios. Source: 2010 U.S. Census.

Figure 7.2 shows the differences in population at-risk to the 100- and 500-year flood for each borough. All population estimates are based on the counts of the 2010 U.S. Census, and not on projections of future population. What is clear in the comparison of figures 7.1 and 7.2 is that the number of residents at-risk to flooding by borough does not necessarily correspond to that borough’s flood extent. Though surpassed by Queens in terms of flood size, Brooklyn has the largest population at-risk to flooding for all six flood scenarios with over 21% of the 2.5 million residents subject to flooding by a 500-year flood in the 2050s. Manhattan has the second largest population at-risk in all flood scenarios except for the current 100-year flood (topped by Queens). It is the most densely populated county in the United States, so despite having the smallest floodplain of the five boroughs for a 500-year flood in the 2050s (6.3 mi$^2$) almost 19% of Manhattan residents have the potential to be at-risk. Queens has the third largest population at-
risk overall followed by Staten Island and the Bronx, though the Bronx at-risk population exceeds that of Staten Island in the 500-year floodplain for the 2020s and 2050s.

The difference in population at-risk relative to the size of the flood extent is closely tied to land use in the coastal areas of the boroughs. Some sections of the coast are zoned for open space and recreation, commercial uses, or industry/manufacturing with limited to non-existent residential population. Therefore residential communities buffered from the open water by industrial or commercial neighborhoods may not be affected by the current 100-year flood but will increasingly become affected by floods in the 2020s and 2050s as floodwaters move further inland to the residentially zoned areas. For example, large portions of land subject to flooding in Queens are part of the Gateway National Recreation Area, including the uninhabited intertidal salt marshes of the Jamaica Bay Wildlife Refuge, and the parks of Fort Tilden, Breezy Point Tip, and Jacob Riis (see Appendix A for a neighborhood map of New York City). The John F. Kennedy (JFK) International Airport also occupies a large area of land on the eastern shores of Jamaica Bay and is subject to flooding in every flood scenario except the current 100-year flood. For this reason, though Queens experiences the largest area of flooding it does not have the largest at-risk population.

Other boroughs have sections of non-residential land use along the coast. For example, the southern Brooklyn coastline is home to the Jamaica Bay Wildlife Refuge, coastal landfill sites, several parks and open spaces, and the former airport Floyd Bennett Field. Also the northwest Brooklyn neighborhoods of Sunset Park, Red Hook and the Navy Yard are zoned almost exclusively for manufacturing at the water’s edge. In addition to the many parks at the water’s
edge of the Bronx, the world’s largest produce market is zoned for manufacturing in the waterfront neighborhood of Hunts Point and multiple sites of manufacturing are situated along the banks of the Harlem River. Each of these areas can sustain flooding without direct impact to residential populations.

The six flood scenarios result in different flood extents and populations at-risk for a given timeslice, as well as different rates of flooding (i.e., percent change over time) when evaluated borough-by-borough. The charts in figure 7.3 show area in square miles (left) and population at-risk (right) to the current and future 100- and 500-year flood zones for each of the five boroughs. The axes for each chart are scaled to reflect the values for that borough. The left Y-axis of the population chart is a raw count and the right Y-axis shows percent of total borough population.
Figure 7.3. Area in square miles (left) and population at-risk (right) to the current and future 100- and 500-year flood zones for each of the five New York City boroughs. The bar graphs are stacked with the darker green on the bottom representing the 100-year flood and the lighter green above representing the 500-year flood. The left Y-axis of the flood areas chart (left) is in square miles. The left Y-axis of the population chart (right) is a raw count and the right Y-axis shows percent of total borough population.

Though Brooklyn ranks second to Queens in terms of flood extent, it experiences the largest amount of floodplain growth from the current 100-year flood scenario to a 500-year flood in the
2050s and the largest increase of at-risk population. Manhattan has the smallest amount of floodplain growth from the current 100-year flood scenario to a 500-year flood in the 2050s, despite more than doubling in size from 3 to 6.3 mi², but is has the second largest increase of at-risk population. Staten Island has the smallest increase in at-risk population growth, though still more than doubling from 28,958 to 63,343 residents, and the second smallest amount of floodplain growth. These examples illustrate that trends in future flood extent and affected population will vary at the borough level. An understanding of the variations in flood impacts and risk at the borough and, where possible, community level is important not only for emergency management and response, but also for planners and policy makers who are managing population growth and development in coastal zones that are increasingly at-risk.

The variations and trends in flood extent and population exposure to current and future 100-and 500-year flood events the can be summarized as follows:

- Sea-level rise will increase the extent of the 100- and 500-year floodplains in the future. Citywide, the additional 31 inches of sea-level rise by the 2050s results in 59% greater flood area than present for the 100-year flood and 41% greater flood area than present for the 500-year flood.

- The number and percentage of residents in sea-level rise enhanced flood zones also shows an increasing trend. By the 2050s, the citywide population in the 100-year flood zone more than doubles and the population in the 500-year flood zone increases 74% relative to the present. This trend is not due to an increase in population in these areas, but rather to the increase in the extent of flooding which affects a larger portion of the population.
• The distribution of flood extent and affected population varies by borough with Queens experiencing the greatest flood extent and Brooklyn having the largest population at-risk.
• The current 100-year flood will nearly equal the current 500-year flood by the 2020s and will exceed the current 500-year flood by the 2050s.

7.3. Indices at the Citywide Scale

The indices of storm surge exposure, storm surge floodwater contaminants, social vulnerability, and at-risk critical facilities and the composite overall flood risk index were mapped at the citywide scale to the extent of the 500-year flood boundary for the 2050s, the largest flood extent used in this work. Each index was scaled to values between 0 and 25 with light purple indicating low values and dark purple representing high values. Results were calculated at the tax lot level and the map surfaces were interpolated using inverse distance weighting. This was done to more easily visualize the high-resolution dataset at the citywide scale.

In the storm surge exposure index shown in Figure 7.4 areas of low floodwater elevation rank low relative to areas of high base flood elevations and/or wave action which rank high on the index scale. The eastern shores of Staten Island, the southern shore of Brooklyn and Queens including the Rockaway Peninsula, and the easternmost portion of the Bronx and northern Queens show the highest exposure to storm surge. These areas are subject to greater flood heights and wave action relative to other areas of coastline for two primary reasons: 1) their proximity and orientation to the Atlantic Ocean makes Brooklyn, southern Queens and Staten Island vulnerable to surge moving in from the open ocean and 2) the bottleneck effects of waters being pushed westward by winds and waves to the intersection of the East River and the Long
Island Sound expose the Bronx and Queens to high floodwater elevations. It should be noted however that the distribution and severity of storm surge is greatly affected by the timing of the storm event relative to the daily high and low tides, particularly since tidal peaks are not coincident around the city (Georgas et al. 2014).

**Figure 7.4.** The index of exposure to floodwaters within the 500-year flood zone for the 2050s in New York City. Data for the index was generated at the tax lot level and the map surface was interpolated via inverse distance weighting. Tax lots without a residential population were not included.
The storm surge exposure index was not developed using historical flood data but rather from scenarios of current and future floods modeled by FEMA and the NPCC. However a field-verified Hurricane Sandy floodplain developed by FEMA\textsuperscript{14} using high-water marks and tide gauge data shows many of the same flooding “hotspots” seen in Figure 7.4, thereby supporting the modeled flood scenarios. It should be noted that this index captures the potential for storm surge exposure along the NYC coastline, but the actual values during a storm event will depend on the timing of landfall or peak storm intensity relative to astronomical tides.

The storm surge floodwater contaminants index (Figure 7.5) considers the following potential contaminant sources: Chemical Bulk Storage, Petroleum Bulk Storage, and Major Oil Storage Facilities (MOSF), Toxics Release Inventory (TRI) facilities, State Pollutant Discharge Elimination System (SPDES) facilities, Level II State Superfund Sites, Brownfields, Water Pollution Control Plants, and Combined Sewage Overflow (CSO) Outfalls. The index was constructed such that facilities with the greatest volume of hazardous materials affect a greater number of tax lots than facilities using, storing, or handling small amounts of hazardous materials. However, high-volume facilities have the same influence on an individual tax lot as low-volume facilities (i.e., they are counted only once in the index) so in this regard no distinctions were made based on volume. The index is also unable to distinguish among the toxicity of materials, partially because the exact and complete listing of handled materials was unavailable. Therefore the impact of each facility in the index is in the number of tax lots subject to potential contamination, a number determined by the facility buffer radius. In this way high

\textsuperscript{14} See the FEMA Modeling Task Force (MOTF)-Hurricane Sandy Impact Analysis at http://fema.maps.arcgis.com/home/item.html?id=307dd522499d4a44a33d7296a5da5ea0
scores on the index map reflect a dense cluster of facilities and low scores reflect a low density of facilities.

Figure 7.5. The storm surge floodwater contaminants index within the 500-year flood zone for the 2050s in New York City. Data for the index was generated at the tax lot level and the map surface was interpolated via inverse distance weighting. Tax lots without a residential population were not included.
Distinctly high values are shown in Manhattan, with some moderate values in the westernmost part of Queens and a hot spot in the Bronx, southern Brooklyn and JFK airport in Queens. The type of potential hazard exerting the most influence in this index are the petroleum bulk storage facilities, which number over 25,000 in NYC. Despite being buffered to only ¼ mile the petroleum bulk storage buffer zones are so numerous that some tax lots were intersected by over 200 separate buffers. The density of petroleum bulk storage facilities in Manhattan is the primary cause of high values in that area. The hot spot on the Coney Island Peninsula of southern Brooklyn is also a cluster of bulk petroleum and chemical storage facilities. Finally, JFK airport in Queens ranks high on the floodwater contaminants index because it is a very large tax lot that contains or is proximal to major oil storage facilities, SPDES major and minor facilities, TRI facilities, petroleum and chemical storage facilities, and the Jamaica Bay water pollution control plant.

Social vulnerability index values (Figure 7.6) are notably high in the Bronx, the East Harlem and Lower East Side (LES) neighborhoods of Manhattan, in select neighborhoods around the perimeter of Brooklyn, and in the Far Rockaway neighborhood of Queens on the Rockaway Peninsula. Tax lots that score high on the social vulnerability index do so by having values in the top 10th percentile for several of fourteen vulnerability indicators. The vulnerability indicators with the greatest influence on the index score vary between neighborhoods, and are described in greater detail in the case studies that follow. The east coast of Staten Island, Coney Island peninsula, the Edgewater Park neighborhood of the eastern Bronx, and the College Point neighborhood of northern Queens each contained some of the lowest values on the social vulnerability index.
The index of social vulnerability within the 500-year flood zone for the 2050s in New York City. Data for each index was generated at the tax lot level and the map surfaces were interpolated via inverse distance weighting. Tax lots without a residential population were not included.

One additional observation of note is in reference to the citywide social vulnerability index shown in Figure 7.7. The values shown in Figure 7.7 differ from those shown in the index of social vulnerability for the 500-year flood zone in Figure 7.6 because the citywide values in Figure 7.7 are determined from an analysis of all census blocks in the city, even those beyond the

Figure 7.6. The index of social vulnerability within the 500-year flood zone for the 2050s in New York City. Data for each index was generated at the tax lot level and the map surfaces were interpolated via inverse distance weighting. Tax lots without a residential population were not included.
flood zones. The reason for including an assessment of social vulnerability citywide is to check for spatial coincidence between social vulnerability values and the 500-year 2050s flood zone. In Figure 7.7, the flood zone is overlain on the social vulnerability data to view the values both within and outside of the flood zone. There does not appear to be spatial coincidence between areas with the highest social vulnerability values and areas of high physical vulnerability (i.e. the flood zones). Most areas experiencing high social vulnerability are located outside of the flood zones and social vulnerability values within flood zones are of medium to low levels.

**Figure 7.7.** The citywide index of social vulnerability for the New York City population shown at the census block level. The 500-year flood scenario for the 2050s is overlain in a hatch pattern. Sources: US Census 2010; American Community Survey 5-Year, 2006 - 2010, the New York City Panel on Climate Change.
In contrast to the previous induces, the index of critical at-risk facilities (Figure 7.8) has few moderate values with most scores ranking as either high or low. Hot spots include the Coney Island Peninsula, eastern portions of the Rockaway Peninsula, neighborhoods along the eastern shores of Manhattan, the Kingsbridge neighborhood of the Bronx, and JFK airport, among others. The facilities included in this index are not weighted by the type of critical service they provide, but are strictly a count of the number of critical facilities per tax lot. Buffers were not used to approximate impacts on neighboring tax lots, therefore the areas scoring highest on the index reflect multiple facilities per tax lot and low scores reflect few to no facilities per tax lot.
Figure 7.8. The index of critical facilities within the 500-year flood zone for the 2050s in New York City. Data for each index was generated at the tax lot level and the map surfaces were interpolated via inverse distance weighting. Unlike the other indices, tax lots without a residential population were included.

Figures 7.4 through 7.8 use color to illustrate areas of high and low risk or vulnerability but do not specify index values nor the frequency with which these values occur. Instead frequency distribution histograms of the scaled values of each of the indices were created in SPSS software.
to better understand the distribution of each index data set (Figure 7.9). For each histogram the frequency count is on the y-axis, index values are on the x-axis, and the minimum, maximum, standard deviation and mean values are listed on the chart area. The dataset size (N = 116,031) is the same for each index and represents the total number of tax lots evaluated in the 500-year flood zone for the 2050s.

Peak frequencies for the storm surge exposure index reveal a multimodal distribution shown in Figure 7.9A. The most frequent values represent areas located between the current 100- and 500-year flood zones (scaled value of 13.89) followed by the current 100-year flood zone with base flood elevations of 10 feet (scaled value of 19.44). The least frequent values represent the projected 500-year flood zone for the 2050s (scaled value of 2.78) and the current 100-year flood with breaking wave action (scaled value of 25). In contrast the storm surge floodwater contaminants index (Figure 7.9B) is right-skewed with only one distinct peak frequency value at 0.11 corresponding to a raw value of 1. Though the raw values range from 0 - 227 buffer intersections per tax lot, low values make up the vast majority of the cases with values above 3 representing a cumulative 10% of all cases.
Figure 7.9. Frequency distribution histograms for the scaled values of each of the four individual indices: A) storm surge exposure, B) storm surge floodwater contaminants, C) social vulnerability, and D) critical facilities. The frequency count is on the y-axis and the index values are on the x-axis.

The social vulnerability index values (Figure 7.9C) show a right-skewed distribution with 66% tax lots ranking 0 or 1 in raw values. Frequencies then decline exponentially as they move toward higher values. The tall spike near the origin of the histogram of critical facilities index
values (Figure 7.9D) reveals that nearly 99% of tax lots ranked 0, meaning that just over 1% of tax lots contained critical facilities as defined in this work. The design of the critical facilities index biases results to a high frequency of 0 values by restricting the starting data set in terms of facility type and impact area. If more facilities were included in the index and their areas of influence expanded to surrounding tax lots, high index values would be more frequent.
Figure 7.10. The overall storm surge flood risk index within the 500-year flood zone for the 2050s in New York City is calculated from the combination of the following four indices: the index of storm surge exposure, the index of exposure to storm surge floodwater contaminants, the social vulnerability index, and the index of at-risk critical facilities. The index surface was interpolated using inverse distance weighting. Tax lots without a residential population were not included.

The four individual indices, with index scores from 0 - 25, were added together to form the combined overall storm surge flood risk index shown in Figure 7.10. Though the combined overall storm surge flood risk index has a potential range of 0 - 100, the highest values reached
just over 53 indicating that none of the tax lots scored maximum values for each of the four individual indices. The histogram in Figure 7.11 shows the distribution and frequency of the values in the overall storm surge flood risk index. Though the mean value is nearly 18 the most frequent values are in the low 20s, with frequencies climbing from 0 toward peak values and then falling off shortly thereafter. Values are infrequent near the min and max of the distribution.

**Figure 7.11.** Frequency distribution histogram for the overall storm surge flood risk index. The frequency count is on the y-axis and the index values are on the x-axis.
In Figure 7.12 the contribution of each of the four individual index values to the overall storm surge flood risk index can be traced by comparing areas in the overall index to the same areas in the composite indices. This visualization is incredibly useful for determining which of the individual indices most influences the overall flood risk index score. For example, the eastern shore of Staten Island, an area that experienced high storm surge elevations and suffered extensive structural damage during Hurricane Sandy, shows high values on the index of exposure to floodwaters. However, the area ranks only moderately high on the overall flood risk index because of its low rankings in the other three indices: social vulnerability, exposure to storm surge floodwater contaminants, and critical at-risk facilities. In this case, floodwater heights and wave action (exposure) are clearly the dominant influence on the overall storm surge flood risk index. The Coney Island Peninsula was also heavily affected by floodwater elevations and wave action (exposure) and scored high on both the storm surge exposure and overall storm surge flood risk indices, and relatively low on the other three indices.
Figure 7.12. The storm surge exposure index (A), the storm surge floodwater contaminants index (B), the social vulnerability index (C), the index of at-risk critical facilities (D), and the overall storm surge flood risk index within the 500-year flood zone for the 2050s.

By contrast, nearly all of the areas in Manhattan subject to the 500-year flood in the 2050s ranked high on the overall storm surge flood risk index despite experiencing lower storm surge elevations than other boroughs. Manhattan ranked consistently high on the storm surge floodwater contaminants index, moderately high on the social vulnerability index, and showed many hot spots of critical at-risk facilities. In combination these rankings result in a high score on the overall storm surge flood risk index. Spots along the Rockaway Peninsula ranked high to moderately high on the overall risk index because of their high ranking on the storm surge
exposure index, and the few areas of high values on the social vulnerability and critical at-risk facilities indices. A few smaller high-ranking areas, such as those in the Bronx and northern Brooklyn, can be better evaluated at the neighborhood scale.

In summary, several important observations about the citywide overall storm surge flood risk index are noted:

- Flood areas further from the coastline ranked the lower on the overall storm surge flood risk index than coastal areas, and this transition from high coastal to low interior values can best be observed along the eastern coast of Staten Island, in southern Brooklyn, and in Southern Queens.
- With the exception of the index of critical at-risk facilities, index scores tend to be clustered into areas of high, moderate, and low values, suggesting the data is spatially correlated. And the transition in values from one area to the next is gradual, not abrupt. There are very few, if any, areas of high values surrounded by low values or vice versa. This observation is further realized using tests of spatial autocorrelation in section 7.5.
- Of all the boroughs, Manhattan’s 500-year 2050s flood zone had the greatest percentage of high index values and was most influenced by high scores on the index of at-risk critical facilities.
- The influence of the four individual indices on the overall storm surge flood risk index values varies with location. This emphasizes the geographic component of vulnerability analysis and the intersection of physical and social vulnerabilities as a place-based interaction.
7.4. Indices at the Neighborhood Scale

Index values were also displayed at neighborhood scales to more closely view the local distribution of values. The population density and diversity of New York City creates a landscape of physical and social vulnerabilities that differ at very local scales. Understanding the influence of these local variations on the overall flood risk index is important for a comprehensive assessment of vulnerability. Local level maps of the overall flood index were created from the citywide maps, but displayed as choropleth maps at the tax lot level instead of interpolating to form a continuous surface. The following four areas projected to experience extensive flooding during a 500-year flood in the 2050s were selected from the NYC coastline: southern Brooklyn and Jamaica Bay, Queens; Lower Manhattan; eastern Staten Island; and eastern Bronx. Mean values of overall flood risk are highest in Lower Manhattan followed by eastern Staten Island, southern Brooklyn and Jamaica Bay, Queens, and eastern Bronx, with average scores of 30, 19, 17, and 14 respectively. The following sections describe these neighborhoods, note areas of high and low index values, and discuss the impact of these values on the overall flood risk index. Tax lots without a residential population are not considered for the social vulnerability index.

7.4.1. South Brooklyn and Jamaica Bay, Queens

The southern Brooklyn neighborhoods on the Coney Island peninsula and those surrounding Jamaica Bay, Queens, including the Rockaway Peninsula, experience the most extensive flooding in all of the five boroughs and as such were selected for closer study (Figure 7.13). The broad extent of flooding in this area is due to the low land elevation and the orientation and proximity of the coastline to the Atlantic Ocean. The coastline consists of sensitive environments
such as sandy beaches, salt marsh and grasslands that, unlike the coastlines of the New York Harbor, are exposed to direct storm surge and wave action from the Atlantic Ocean.

**Figure 7.13.** Neighborhoods of southern Brooklyn and Queens in the 500-year flood zone for the 2050s (flood zone in light blue). Census tracts are outlined in grey. Federal National Parks Service lands and parks owned by the City of New York are in green. The JFK Airport is indicated in grey.

**Jamaica Bay**

Situated along the coastline of southern Brooklyn and Queens are federal and New York City owned parks and open spaces created for recreation and preservation (Figure 7.13). The majority of the parkland is part of the Gateway National Recreation Area, consisting of the Jamaica Bay Wildlife Refuge; Fort Tilden, Jacob Riis Park, and Breezy Point Tip on the Rockaway Peninsula; and the decommissioned airfield Floyd Bennett Field. Jamaica Bay is the approximately 40 square mile estuary at the center of these parklands and open spaces. It is a semi-enclosed body
of water consisting of a network of channels and marshy areas with one residential neighborhood, Broad Channel, in the middle. Its only connection to the ocean is through the Rockaway Inlet on its western end. With the exception of storm events, the Bay is largely sheltered from the Atlantic Ocean by the Rockaway Peninsula. The Jamaica Bay area is mostly open water but also consists of salt marsh, sand dunes, grasslands, and woodlands. It serves as a major stop on the Atlantic Flyway bird migration route, provides recreational and outdoor opportunities for millions of urban residents, and contributes to the overall environmental health of the region through the provision of ecological services.

Multiple non-profits and community organizations such as The Nature Conservancy, Jamaica Bay Ecowatchers, and the Rockaway Waterfront Alliance; city agencies such as the NYC Department of Parks, the NYC Department of Environmental Protection, the US Army Corps of Engineers, and the NYC Office of Recovery and Resilience; and educational institutions and programs such as New York Eco-Schools, are currently engaged in the stewardship, study, and/or management of the Bay and surrounding environs. The Science and Resilience Institute at Jamaica Bay (SRIJB), a recently formed high-level research center dedicated to the study of coastal resilience issues, has developed a mission to increase our understanding of how disturbances impact natural and human systems in the Bay and in other urban watersheds. A current pressing issue in NYC is the development of plans to fortify the Bay and protect its residents from sea-level rise enhanced storm events. This work could support the research goals of SRIJB and other organizations and agencies and contribute to the discussion of creating resiliency by providing insight into the physical and social vulnerability of Jamaica Bay residents to current and potential future flood events.
Rockaway Peninsula

The Rockaway Peninsula section of Queens is part of the outer beaches of Long Island formed by the littoral drift of sand during the last glacial retreat. It is exposed to the Atlantic Ocean along its southern shores and separated from Brooklyn and the rest of Queens by Jamaica Bay to its northwest. With the exception of the western neighborhood of Breezy Point, the Rockaway Peninsula consists of non-residential parkland on its western end, becomes increasingly populated toward its center, and then most heavily populated in the easternmost neighborhood of Far Rockaway. Though one or two-family homes make up 86% of the residential buildings, 55% of all housing units are located in multi-family buildings. Seventy-eight percent of residential buildings were constructed before modern construction standards were adopted (NYC Office of the Mayor 2013). This is relevant in the context of post-Hurricane Sandy building damage assessments conducted by the NYC Department of Buildings. The percentage of buildings marked as damaged or destroyed was higher on the Rockaway Peninsula relative to the citywide percentage, indicating both the physical vulnerability of the peninsula and of the building stock.

Bridge and subway infrastructure serve as a critical links connecting the peninsula to the rest of the city. Residents are served by three bridges to the mainland: two connecting through the Broad Channel neighborhood in Jamaica Bay, and the third connecting Jacob Riis Park to Floyd Bennett Field across the Rockaway Inlet. The Metropolitan Transportation Authority (MTA) 8th Avenue Express (A) line runs parallel to the Broad Channel bridges operating from Howard Beach, Queens, south across the Bay and then east to the Far Rockaway neighborhood. The shuttle (S) line runs from Broad Channel south across the Bay and then west to the Rockaway Park neighborhood. MTA bus service is also available across the three bridges.
Hurricane Sandy’s Impacts

Southern Brooklyn and Jamaica Bay, Queens have great physically vulnerability to both floodwater heights and wave action during storm surge events. When Hurricane Sandy struck in October 2012, tide gauges and high water marks around Jamaica Bay recorded storm surge elevations between 10 and 13 feet (United States Geological Survey 2014). The storm surge breached the East Pond of the Jamaica Bay Wildlife Refuge in at least two places and scoured a 50-foot channel into the West Pond creating a tidal lagoon (Riepe n.d.). In addition to physical changes to the coastline, Sandy’s floodwaters affected sectors such as transportation, telecommunications, public health, and energy, both within and outside of the flood zones. For example, the A train viaduct connecting Howard Beach, Broad Channel, and the Rockaways was washed away in two locations and not restored until May 2013, seven months after the storm. Electrical system failure caused four of NYCs wastewater pollution control plants (WPCP) in the Jamaica Bay area to shutdown completely during the storm and affected operations at other facilities throughout the City. The Coney Island WPCP and Rockaway WPCP were knocked offline for two hours and three days respectively, discharging their effluent directly into the waters of Jamaica Bay. Ultimately 560 gallons of untreated and 800 gallons of partially treated and disinfected wastewater were released into NYC waterways. Despite this massive release, impacts to the Jamaica Bay ecosystem were minimal and the marshes and wildlife survived with very little loss.

Flood Indices

Figure 7.14 shows the four indices that compose the overall storm surge flood risk index in southern Brooklyn and Queens with values displayed at the tax lot level. Figure 7.14A shows the
tax lots as they rank in terms of storm surge exposure. For the current 100-year storm, the tax lots ranked ‘high’ are projected to experience floodwater elevations in excess of 10 feet (Zone AE) and tax lots ranked ‘medium’ will have floodwater elevations of 10 feet (see Figure 3.2 for an overview of FEMA designated flood zones). The ‘low-med’ tax lots are subject to floodwaters less than 10 feet in elevation. Though zones of high velocity breaking waves greater than 3 feet in height (Zone VE) are ranked highest on this index, they do not occur in areas of residential tax lots. VE zones occur over areas of open water, and then typically transition to AE Zones (wave action smaller than 3 feet) as they move ashore and reach infrastructure or other land cover. Along the southern shore of the Rockaway Peninsula the transition from VE to AE zones occurs abruptly at face of beachfront property. Regardless of this downgrade in classification the boardwalk and other beachfront infrastructure and properties experienced significant damage from Hurricane Sandy’s storm surge. Also note that areas further inland that experience of high floodwater elevations and smaller breaking waves (AE) are also vulnerable to moderate to significant storm surge damage.

The tax lots ranking highest on the storm surge exposure index include the Breezy Point and southern Rockaway Park neighborhoods on the Rockaway Peninsula, along with Gerritsen Beach and the majority of the Coney Island Peninsula. Moderately high values are found along the Rockaway Peninsula though the elevation of the Far Rockaway neighborhood results in lower flood elevations to the east. Storm surge exposure index values are highest closest to the shoreline and become progressively smaller as floodwaters move inland.
Figure 7.14B shows the tax lots as they rank in terms of potential storm surge floodwater contaminants through a count of sites that handle or store hazardous wastes. Overall the southern Brooklyn and Queens area does not score high on this index with only one tax lot, JFK airport, ranking ‘medium-high’. As mentioned in section 7.3, JFK is proximal to major oil storage facilities, SPDES major and minor facilities, TRI facilities, petroleum and chemical storage facilities, and the Jamaica Bay water pollution control plant (WPCP). The vast majority of neighborhoods rank ‘low’ with Brighton Beach ranking ‘medium’ due an average of 50 to 60 counts of bulk petroleum and chemical storage facilities per tax lot. To the north of Brighton Beach, Marine Park averages between 40 and 50 bulk storage counts per tax lot. The Rockaway Beach neighborhood scores ‘low-medium’ with an average of 10 bulk petroleum or chemical storage facilities per tax lot but the area is also influenced by the Jamaica WPCP, a SPDES Major site, six combined sewage overflow outfall sites, and a Superfund site.
Figure 7.14. The storm surge exposure index (A), storm surge floodwater contaminants index (B), social vulnerability index (C), and critical facilities index (D) for south Brooklyn and Jamaica Bay (Queens, including the Rockaway Peninsula). Tax lots are ranked from low values in light purple to high values in dark purple.
The highest social vulnerability index values (Figure 7.14C) in the southern Brooklyn and Queens 500-year 2050s flood zone were calculated for tax lots that ranked in the top tenth percentile values for 7 or 8 of the 14 indicators of social vulnerability. High ranking tax lots (in dark purple) were located on the eastern end of Rockaway Peninsula, the New Lots and East New York areas of Brooklyn, and the Coney Island and Brighton Beach neighborhoods of the Coney Island Peninsula (see Figure 7.13 for neighborhood map). The indicators most frequently included (i.e., top tenth percentile values) in the tax lots ranked ‘high’ are listed as follows in descending order: speak English less than ‘well’, live in a multi-unit structure, crowded housing (greater than 1 person per room), single householder with children, 65 years of age or older, no vehicle, 10 years of age or younger, and no high school diploma. The prominence of non-native English speakers is in part due to a strong concentration of Russian speaking immigrants in the Brighton Beach and Coney Island neighborhoods. Living below the poverty line, low household income, and minority status infrequently ranked in the top tenth percentile of these tax lots. Unemployment and group quarters status (group homes) did not contribute to the highest-ranking tax lots. ‘Medium’ to ‘medium-high’ social vulnerability values are found in the Breezy Point, Coney Island, Brighton Beach, and Arverne neighborhoods, with the lowest values in the neighborhoods to the north and west of Floyd Bennett Field.

With the exception of a few tax lots, the vast majority of areas scored ‘low’ on the critical facilities index (Figure 7.14D). The tax lots with the highest values had five or more critical facilities situated within them. Lots ranked ‘medium’ have two critical facilities within, and those ranking ‘low’ had no critical facilities. Notably JFK airport scored a ‘medium’ value on this index due to the presence of infant and preschool programs on the tax lot.
The overall storm surge flood risk index for southern Brooklyn and Jamaica Bay, Queens shows ‘high’ and ‘medium-high’ values in the Far Rockaway, Coney Island, and Brighton Beach neighborhoods (Figure 7.15). These tax lots scored ‘high’ on the storm surge exposure and social vulnerability indices, and Brighton Beach also scored ‘medium’ on the floodwater contaminants index. JFK airport is one of the few tax lots that ranked ‘medium’ on the overall storm surge floodwater index due to its scores on the floodwater contaminants, storm surge exposure, and critical facilities indices. It does not have a residential population and therefore was not included in the social vulnerability index. Other tax lots that ranked ‘medium’ do have a residential population and were included in the social vulnerability index.
Figure 7.15. The overall storm surge flood risk index for south Brooklyn and Jamaica Bay, Queens, including the Rockaway peninsula. Tax lots are ranked from low values in light purple to high values in dark purple, and the 500-year flood zone for the 2050s is shown in transparent blue (right).
7.4.2. *Lower Manhattan*

The neighborhoods of Lower Manhattan, shown in Figure 7.16, are some of the densest in the city, with Stuyvesant Town, the Lower East Side, and Chinatown housing a combined average of 92,160 people per square mile (NYC Office of the Mayor 2013). This average is more than three times greater than the citywide population density of 27,742 people per square mile (U.S. Census 2013) and more than 33% greater than the population density of Manhattan (69,468 people per square mile as per the U.S. Census 2010), the most densely populated county in the country. The area is bounded to the east by the East River, the south by the New York Bay, and to the west by the Hudson River. Bulkheads reinforce most of the coastline, which is then buffered from residential buildings by parklands, open space, and major roadways.
Figure 7.16. Neighborhoods of Lower Manhattan in the 500-year flood zone for the 2050s (flood zone in light blue). Census tracts are outlined in grey.

In addition to being some of the densest neighborhoods in the city, Stuyvesant Town, the Lower East Side, and Chinatown experience poverty rates of 12%, 31%, and 43% respectively. Several of the public housing developments operated by the New York City Housing Authority (NYCHA) are situated here. These neighborhoods are characterized as strongly residential with street level retail stores, and the vast majority of the population residing in multi-story attached buildings or high-rise developments in park-like surroundings. The neighborhoods along the Hudson River to the west are also residential but contain significantly more commercial and retail space. Also, in contrast to the east side, the demographics of the west side neighborhoods
describe median household incomes well above the city average, high property values for owner occupied residential units, and a strong proportion of homeowners. In fact with median household incomes in Battery Park City, Tribeca, and the West Village two to three times the city median, they are by far the most affluent neighborhoods in southern Manhattan, and a strong contrast to the neighborhoods of the east side.

Flood Indices

It might be expected that the discrepancy in income between the east and west side neighborhoods would be reflected in the index of social vulnerability and potentially in the siting of facilities containing potential floodwater hazards. And in fact the greatest area of tax lots ranking ‘high’ on the overall storm surge flood risk index in Lower Manhattan are in the Chinatown, Lower East Side, and Stuyvesant Town neighborhoods. This section examines the contributing factors to flood vulnerability on a per neighborhood basis.
The storm surge exposure index (A), storm surge floodwater contaminants index (B), social vulnerability index (C), critical facilities index (D), and the overall storm surge flood risk index (right) for lower Manhattan. Tax lots are ranked from low to high values and the 500-year flood zone for the 2050s is shown in transparent blue (right).
Figure 7.17 shows the four indices that compose the overall flood risk index in Lower Manhattan with values displayed at the tax lot level. Figure 7.17A shows tax lots ranked in terms of exposure to current and future scenarios of storm surge. Unlike other flooded areas in the city, tax lots along the entire east and west coastlines are projected to experience 100-year floodwater elevations in excess of 10 feet (Zone AE, ranked ‘high’ and shaded dark purple). Zone AE flooding affects a greater portion of the population along the East River shores than the Hudson River shores, in part due to the population density of the east side neighborhoods. According to FEMA’s current 100-year flood maps for NYC there are very few tax lots projected to experience floodwater elevations of exactly 10 feet (ranked ‘medium-high’). This is in contrast to the Brooklyn-Queens study area that showed a large number of tax lots impacted by 10 feet of surge. Instead flood zones in lower Manhattan transition from elevations of 11 feet or greater (Zone AE) directly into areas in the 500-year flood zone (Zone X). Tax lots in Zone X areas are ranked ‘medium’. As was noted in southern Brooklyn and Queens, flood exposure index values are highest closest to the shoreline and become smaller as floodwaters move inland. The tax lots shaded light purple are projected to experience flooding only in a 500-year future flood scenario.

The tax lots of the 500-year 2050s flood zone of Chinatown were ranked ‘high’ on the social vulnerability index (Figure 7.17C), followed by a cluster of ‘medium-high’ values in the Lower East Side and a few small clusters of ‘medium-high’ tax lots in the neighborhoods along the west side. These tax lots were ranked in the top tenth percentile values for 7 or 8 of the 14 indicators of social vulnerability. The indicators consistently included (i.e., top tenth percentile values) in the highest ranked tax lots are listed as follows: speak English less than ‘well’, live in a multi-unit structure, crowded housing (greater than 1 person per room), single householder with
children, 65 years of age or older, live in a group quarters arrangement, and no high school diploma. Minority status was also included in the majority of highest-ranking tax lots. Having children 10 years of age or younger ranked only once in the top tenth percentile of these tax lots. Unemployment, poverty, and density did not contribute to the highest-ranking tax lots. ‘Medium’ to ‘medium-high’ values of social vulnerability are found in the East Village, Lower East Side, and Stuyvesant Town neighborhoods, with ‘medium’ values dominating the west side of Manhattan. The handful of ‘low’ social vulnerability values are scattered throughout the area, comprising the few residential tax lots on the Financial District and several health services facilities to the north in Gramercy.

The vast majority of the area scored ‘low’ on the critical facilities index (Figure 7.17D), with a few tax lots ranked ‘medium’ and a very small number ranking ‘medium-high’. The lots with the highest values had four to five or more critical facilities situated within. For example, the Bellevue Hospital in Gramercy ranked ‘medium-high’ because of its many services including inpatient care, day care programs, and detoxification center. Beth Israel Medical Center in Stuyvesant Town also offers detoxification, rehabilitation, and psychiatric services. These facilities rank ‘medium-high’ on the critical facilities index for the multitude of functions they perform. Lots ranked ‘medium’ have two to three critical facilities within, and on the east side of Lower Manhattan these are mostly day care centers, after school programs, and schools. Lots ranking ‘low’ had no critical facilities.

The overall storm surge flood risk index for Lower Manhattan shows most of the ‘high’ values in neighborhoods along the East River with very few high values along the west side. This is
because east side tax lots scored ‘high’ on the storm surge exposure and storm surge floodwater contaminants indices, and ‘medium-high’ on the social vulnerability index. ‘Medium-high’ vulnerability tax lots are distributed fairly equally throughout the area and their values are a product of ‘medium’ to ‘high’ scores in at least two other indices. Overall flood risk values scoring ‘medium’ are more abundant on the west side, ‘low-medium’ ranked tax lots are disbursed widely but are relatively few, and only three of over 3,300 tax lots were classified as ‘low’. Lower Manhattan has the highest average overall flood risk index value of any of the case study areas.

7.4.3. Eastern Shore of Staten Island

The neighborhoods along the eastern shores of Staten Island, stretching approximately three miles from the Oakwood Beach neighborhood to South Beach (Figure 7.18), have generally ‘low’ to ‘medium’ overall flood risk values. This area is characterized as a series of low-density residential communities with small business corridors serving mixed income families. The median household income of $68,000 is above the citywide average as are rates of home ownership at 68% (NYC Office of the Mayor 2013). Population density is well below city average. The majority (84%) of housing units consist of detached 1- and 2- family bungalow style wood-frame construction homes spaced closely together with a few areas of semi-attached or attached homes. Over half of these homes were constructed prior to the implementation of FEMA’s flood resistant construction standards in 1983. Multi-family walk-up and elevator buildings comprise a combined 15% of the housing units in the area.
According to a post-Hurricane Sandy damage assessment conducted by the New York City Department of Buildings, Staten Island suffered major structural damages from Sandy. The number of buildings tagged as damaged or destroyed was higher in the South Beach, Midland Beach, New Dorp Beach, and Oakwood Beach neighborhoods than the citywide average (NYC Office of the Mayor 2013). This is in part due to damaging wave action that extended inland from the coast and also due to the type of building stock that dominates the area. The NYC Department of Buildings determined that the 1- and 2- family low-rise wood-frame buildings constructed prior to 1983 to be some of the most vulnerable to storm surge and these structures comprise 90% of all buildings in the eastern shore area. In some instances bungalows were wiped clean from their foundations.

The eastern shores are also particularly susceptible to high floodwater depths due to the intersection of topography and the built environment. From South Beach to Midland Beach, the four-lane Father Cappodano Boulevard divides the residential areas to the west from the parkland, boardwalk, and promenade that line the beachfront. It also marks a change in topography with the boulevard built at higher elevation than the residential land to the west, resulting in a depression that fills and retains the floodwaters that breach the roadway. Floodwater depths in the depressed land can exceed those of waters closer to shore. Depths above ground of greater than 10 feet were experienced to the west of the boulevard in the New Dorp Beach, Midland Beach, and South Beach neighborhoods during Hurricane Sandy.
Figure 7.18. The storm surge exposure index (A), storm surge floodwater contaminants index (B), social vulnerability index (C), critical facilities index (D), and the overall storm surge flood risk index (right) for the eastern shore of Staten Island. Tax lots are ranked from low to high values and the 500-year flood zone for the 2050s is colored light blue.

Figure 7.18 shows the four indices that compose the overall storm surge flood risk index along the eastern shores of Staten Island with values displayed at the tax lot level. This area is situated in the New York Bight (see section 2.1) making it particularly vulnerable to storm surge. Figure 7.18A captures this physical vulnerability, showing tax lots ranked in terms of exposure to current and storm surge flood scenarios. The majority of lots adjacent to the coast rank ‘high’ (Zone AE, shaded dark purple) on the storm surge exposure index with 100-year floodwater
elevations in excess of 10 feet. Hospital and mental health facilities in the neighborhood of South Beach provide the exception with a rank of ‘medium’ indicating flooding only during the 500-year flood event. No tax lots experienced 100-year floodwaters of exactly 10 feet in elevation (Zone AE). Instead, as is the case in lower Manhattan, flood zones transition from elevations of 11 feet or greater (Zone AE) directly into areas in the 500-year flood zone (Zone X). Tax lots in Zone X areas are ranked ‘medium’. The small number of tax lots ranked ‘low-med’ and ‘low’ are projected to experience flooding only in a 100- and 500-year future flood scenario. Once again flood exposure index values are highest closest to the shoreline and become smaller as floodwaters move inland.

The potential for storm surge floodwater contaminants (Figure 7.18B) is not a major concern along the eastern shores of Staten Island. All tax lots ranked in the ‘low’ category of the floodwater contaminants index with no values exceeding scores of nine. Of the nine potential hazard sources, only three types are present in the area: petroleum or chemical bulk storage facilities, the Oakwood Beach water pollution control plant, and State Pollutant Discharge Elimination System (SPDES) permit facilities. However these facilities were not abundant enough to warrant even a ‘low-medium’ score on the index.

The social vulnerability index (Figure 7.18C) values do not show great range with all tax lots ranked either ‘low’ or ‘low-medium’. The ‘low-medium’ tax lots were ranked in the top tenth percentile values for 1 to 3 of the 14 indicators of social vulnerability. The indicators included most frequently (i.e., top tenth percentile values) in the ‘low-medium’ ranked tax lots are listed in descending order: no access to a vehicle, live in a group quarters arrangement, live in a multi-
unit structure, speak English less than ‘well’, and having children 10 years of age or younger. Minority status, crowded housing (greater than 1 person per room), single householder status with children, and being 65 years of age or older were included in the top ranked lots infrequently. Unemployment, poverty, density, and no high school diploma did not contribute to the highest-ranking tax lots.

With the exception of a very small number of tax lots, the entire Staten Island case study area ranked ‘low’ on the critical facilities index (Figure 7.18D) with no facilities to account for. A few lots, including New Dorp High School, scored greater than zero on the index and ranked ‘low-medium’. The most obvious anomalies in this index are the large lots ranking ‘high’ and ‘medium’ in the neighborhood of South Beach. These lots were categorized as containing 13 and 3 critical facilities respectively, however this number is a reflection of the diversity of services these facilities provide rather than an accounting of separate facilities per tax lot. For example, the South Beach Psychiatric Center ranks ‘high’ and is categorized as providing day care, inpatient detoxification and rehabilitation, residential disability services, and psychiatric services including mental health transitional residences. The Staten Island University Hospital ranks ‘medium’ for providing different types of specialized inpatient care. Each of these services are listed separately in the facilities database for NYC and count toward the critical facilities total per tax lot.

The overall storm surge flood risk index for eastern Staten Island is dominated by ‘medium’ values along the coast and stretching inland before transitioning to ‘low-medium’ and then ‘low’ values at the landward edge of the floodplain. The South Beach Psychiatric Center and Staten
Island University Hospital tax lots are the exception to this pattern ranking ‘medium-high’. The distribution of overall storm surge flood risk values resembles the storm surge exposure index, suggesting physical vulnerability as the dominant influence. The other indices - storm surge floodwater contaminants, social vulnerability, and critical facilities - all score very low and have much less influence on the overall storm surge flood risk index values. Of the four case study areas eastern Staten Island has the second highest average overall flood risk index value.

7.4.4. *Eastern Bronx, City Island*

The eastern shores of the Bronx, including the neighborhoods of County Club, Edgewater Park, Throgs Neck, and City Island, show ‘low’ to ‘medium’ overall flood risk values (Fig 7.19). In fact, relative to the other case study areas, the eastern Bronx and City Island have the lowest average overall storm surge flood risk values. This area was selected for closer study due to its high storm surge exposure rankings, but its physical vulnerability is moderated by low social vulnerability, low exposure to floodwater contaminants, and few at-risk critical facilities. The four neighborhoods and their index scores are described in the following paragraphs.
Figure 7.19. The overall storm surge flood risk index for the Eastern Bronx, including City Island. Tax lots are ranked from low to high values, and the 500-year flood zone for the 2050s is shown in transparent blue.

City Island is part of the Pelham Islands group off the eastern shores of the Bronx. The island is small, approximately 0.4 square miles in area, and bounded by Long Island Sound to the east, Eastchester Bay to the west, and connected to the mainland by the City Island Bridge at the north.
end. It is home to 4,456 residents, according to the 2010 US Census, making population density well below the citywide average. Demographic data describes residents as 80% white, 10% Hispanic, and 10% Black, Asian, or other, with median household incomes of $73,100 relative to citywide average $55,246 (2010 US Census). City Island shows ‘medium’ overall storm surge flood risk values at the northern tip and western shores of the island. These values mirror well the ‘high’ values shown in Figure 7.20 on the storm surge exposure index (Figure 7.20A), indicating areas of floodwater elevations greater than 10 feet. ‘Low-medium’ and ‘low’ values of overall storm surge flood risk are observed on the Island throughout the rest of the 500-year flood zone for the 2050s. No ‘high’ or ‘medium-high’ values are observed. With few exceptions the Island ranks ‘low-medium’ on the social vulnerability index (Figure 7.20C), and ‘low’ on both the storm surge floodwater contaminants (Figure 7.20B) and critical facilities indices (Figure 7.20D).
Figure 7.20. The storm surge floodwater exposure index (A), storm surge floodwater contaminants index (B), social vulnerability index (C), critical facilities index (D) for eastern shores of the Bronx, including City Island. Tax lots are ranked from low to high values.
County Club is a predominantly upper middle class neighborhood of the Bronx with a large Italian-American population. It is bounded by Pelham Bay Park to the north and Eastchester Bay to the east and the New England Throughway (I-95) to the west. Though low relative to the citywide average, the population density of County Club is the highest relative to the other neighborhoods in this area. The population of 3,419 residents is composed by race as follows: 85% white, 12% Hispanic, and 3% Asian or other. The median household income is $64,410, higher than the citywide average (US Census 2010). Country Club has tax lots ranking mostly ‘low’ and ‘low-medium’ on the overall storm surge flood risk index, with lots closer to the coast ranking ‘medium’ and one lot ranking ‘medium-high’. These ‘medium-high’ and ‘medium’ value lots are strongly influenced by the ‘high’ values shown on the storm surge exposure index (Figure 7.20A), indicating areas of floodwater elevations greater than 10 feet. Social vulnerability index values (Figure 7.20C) are slightly elevated in the southern part of the neighborhood, perhaps contributing to ‘low-medium’ overall flood risk index values. The area ranks almost entirely ‘low’ on both the floodwater contaminants and critical facilities indices.

Edgewater Park is a small community of bungalows converted to year-round homes that is situated between Eastchester Bay to the east and north and the Throgs Neck Expressway to the west and south. Its low-density population of 999 is the smallest of the area neighborhoods and demographic data describes residents as 63% white, 26% Hispanic, and 11% black, Asian, and other. Like the other local neighborhoods, the median household income of $71,965 is above the citywide average (US Census 2010). Edgewater Park ranks mostly ‘low’ and ‘low-medium’ on the overall storm surge flood risk index, with a few ‘medium’ values in the northern and southern ends of the neighborhood. These ‘medium’ values rank ‘high’ on the storm surge
exposure index in Figure 7.20A. The neighborhood ranks ‘low-medium’ on the social vulnerability index (Figure 7.20C), and ‘low’ on the floodwater contaminants and critical facilities indices (Figures 7.20C, 7.20D).

Throgs Neck refers to the southernmost neighborhood in this area that ends in narrow spit of land extending south into the East River. For the purposes of this analysis the Throgs Neck neighborhood captures all tax lots to the southwest of Edgewater Park as divided by the Throgs Neck Expressway. Though its population of 19,594 is higher than other neighborhoods in the area, population density is still below the citywide average. Demographic data describes Throgs Neck residents as 48% white, 33% Hispanic, 13% black, and 6% Asian or other. The median household income is $65,731, a value higher than the citywide average (US Census 2010). Throgs Neck ranks ‘low’ to ‘medium’ on the overall flood risk index with clusters of ‘medium’ values on the western and eastern sides of the neighborhood. As was the case in other neighborhoods, the overall storm surge flood risk values mirror those of the storm surge exposure index (Figure 7.20A), suggesting that physical vulnerability is the dominant influence in overall flood vulnerability. The southern coastline is protected in sections by bluffs that extend up to 50 feet above the water and either protect the neighborhood from floodwaters, or decrease their physical vulnerability to flood heights and wave action. The cluster of low storm surge exposure values seen on the southern shores of Throgs Neck is a function of the elevation of the bluffs, as is the absence of floodwaters along the western edge of the spit. The neighborhood ranks ‘low’ and ‘low-medium’ on the social vulnerability index (Figure 7.20C), and ‘low’ on the floodwater contaminants and critical facilities indices (Figure 7.20B and 7.20D).
Each of the four locations discussed above were selected for study at the tax lot scale due to the projected extent of floodwater exposure to the 500-year flood extent in the 2050s projected in these areas.

The purpose of examining vulnerability and risk at local scales is to better illustrate how pre-existing characteristics of neighborhoods contribute to a landscape of high and low overall storm surge flood risk values. For some areas the greatest threat is the potential for floodwater contamination from nearby TRI or wastewater treatment facilities. In other neighborhoods, social vulnerability is high and poses great threat to the community even when physical vulnerability is low. In still other areas, residents of group quarters facilities such as hospitals and group homes may find themselves unable to respond to a storm surge threat, even if physical and social vulnerability are low. It’s important to realize that different vulnerabilities tend to overlap many areas creating local spots of increased vulnerability.

7.5. Local Indices of Spatial Autocorrelation

Local indicators of spatial autocorrelation (LISA) statistics were calculated in the citywide 500-year floodplain for the 2050s to test the null hypothesis of spatial randomness for the overall flood risk index values. The results shown in Figure 7.21 are classified as follows: not significant (p > 0.05; less than 95% confidence level), clusters of high index values (high-high) and clusters of low values (low-low) both of which reflect positive local spatial autocorrelation, outliers in which a high value is surrounded by low values (high-low) and outliers in which a low value is surrounded by high values (low-high), both of which reflect negative local spatial autocorrelation. Both positive and negative spatial autocorrelation are found throughout the 500-
year 2050s floodplain with areas of positive autocorrelation far outnumbering areas of negative autocorrelation. This suggests that, more often than not, the values of the overall storm surge flood risk index are not random in their distribution but instead are similar to neighboring values and likely reflect the spatial component of the datasets from which the overall flood risk index was constructed. For example, tax lot level values of floodwater heights, social vulnerability, and exposure to floodwater contaminants are more similar to neighboring values than distant values. It should be noted that part of the reason that neighboring values are similar is that, for the social vulnerability index, the sociodemographic data was disaggregated from block group and census tract levels down to the tax lot levels. This means the variables are not independent at the tax lot level but rather reflect the values of the larger geography from which they were derived. As such more clustering is expected. However this methodology was not applied to the other three indices so disaggregation related clustering is not expected in those results.

An analysis of autocorrelation among the datasets emphasizes the relevance of spatial context when evaluating physical and social vulnerabilities. The data set values used in the overall flood risk index are not randomly distributed but instead show local influence. Community needs in the context of emergency preparedness and response likely reflect the patterns of distribution and clustering viewed in Figure 7.21. The results are better viewed at the neighborhood scale in the maps that follow.
Local Spatial Autocorrelation (Morans I)

Key
- Not Significant
- High High
- High Low
- Low High
- Low Low

Figure 7.21. Local indicators of spatial autocorrelation (LISA) were calculated using the Anselin Local Moran’s I tool in ArcGIS. Positive autocorrelation is indicated by clusters of high values (purple) and clusters of low values (pink). Negative autocorrelation is indicated by high values surrounded by low values (yellow) and low values surrounded by high values (green).
A closer look at the southern Brooklyn and Jamaica Bay, Queens neighborhood shows that high-high value clusters (purple) are mainly situated close to the coastline in areas such as the Coney Island peninsula and the Rockaway Peninsula, with smaller clusters in the Howard Beach neighborhood of Queens and the Gravesend neighborhood of Brooklyn (Figure 7.22). Low-low value clusters (pink) are found all along the landward most edge of the flood zone furthest from the coastline in neighborhoods such as Georgetown, and Canarsie in Brooklyn, and Brookville and Rosedale in Queens (see Figure 7.11 for a neighborhood map). In between the high-high and low-low value clusters is large area of tax lots whose values were not significant (p > 0.05). There are a few tax areas of high-low negative spatial autocorrelation (yellow), the most obvious being JFK airport but also a few lots in the New Lots, East New York, and Paerdegat Basin neighborhoods. This is likely because JFK is quite anomalous relative to surrounding residential tax lots in that it is a very large, low population tax lot that earned the highest score on the storm surge floodwater contaminants index, a moderate score on the floodwater exposure and critical facilities indices (the moderate score on the critical facilities index was still one of the highest scores in the flood zone), and a low score on the social vulnerability index. These characteristics are in contrast to nearly every one of the neighboring tax lots, hence the high-low negative autocorrelation. Low value tax lots surrounded by high value lots (green) are very few with the most prominent in the Lindenwood neighborhood of Queens.
Southern Brooklyn and Jamaica Bay, Queens

Figure 7.22. Local indicators of spatial autocorrelation (LISA) values at the tax lot level for southern Brooklyn and Jamaica Bay, Queens.

High-high values clusters (purple) are the most prominent feature in Figure 7.23, a map of Local Moran’s I values for Lower Manhattan, indicating strong positive spatial correlation throughout the area. Lots of low-high values (green) and values of non-significance (grey) are equally present in very low numbers. There were no tax lots showing positive spatial autocorrelation as low-low values (pink) or lots of negative correlation as high-low values (yellow).
The majority of tax lots on the eastern shores of Staten Island (Figure 7.24) are classified as not significant (grey) by the local Moran’s I test. Areas of low-low value positive spatial autocorrelation (pink) rim the landward most edge of the flood zone as was observed in southern Brooklyn and Jamaica Bay, Queens. The large area of high-high autocorrelation (purple) in the
South Beach neighborhood is the Staten Island University Hospital and South Beach Psychiatric Center. Other high-high values are found along the Midland Beach coastline as well near the terminus of the flood zone inland from Midland Beach. Only two tax lots show negative spatial autocorrelation, one with high-low values (yellow) and the other with low-high values (green).

**Figure 7.24.** Local indicators of spatial autocorrelation (LISA) values at the tax lot level for eastern Staten Island.
Eastern Bronx, City Island

![Map of Eastern Bronx, City Island showing local indicators of spatial autocorrelation (LISA) values at the tax lot level for eastern Bronx, City Island.](image)

**Figure 7.25.** Local indicators of spatial autocorrelation (LISA) values at the tax lot level for eastern Bronx, City Island.

The eastern shores of the Bronx (Figure 7.25) are dominated by positive spatial autocorrelation in the form of low-low values (pink). A few tax lots classified as showing high-high correlation (purple) are situated that the northern tip of City Island and to the south of the Edgewater Park neighborhood in Throgs Neck. The rest of Throgs Neck has mostly not significant (grey) values. Negative autocorrelation in the form of high-low values (yellow) are found in low numbers on
City Island and in the County Club neighborhood. Only one instance of low-high values (green), located in the Throgs Neck neighborhood, is observed.

7.6. **Theoretical Contributions**

This work builds upon the hazards-of-place model of place vulnerability developed by Cutter (1996) by promoting the use of multiple indices in the creation of an overall place-based flood risk index. The use of additional physical and social vulnerability indices to augment traditional indices is an innovative way to capture elements of local level vulnerability specific to New York City. As discussed in section 2.2, the hazards-of-place model begins with the interaction of risk and mitigation producing the hazard potential. In the context of this work, risk refers to the likelihood of occurrence of the 100- and 500-year flood events in NYC and the consequence of such events. Mitigation can serve to reduce risk through effective policies or it can amplify risk through poor or absent mitigation efforts. The hazard potential is then either moderated or enhanced through a geographic filter and the social fabric of the place to form the biophysical and social vulnerabilities. In combination, these two form the overall vulnerability of place.

The index of overall risk to storm surge flooding is based on the components and interactions of the hazards-of-place model, but it differs in in three fundamental ways. First mitigation is treated as a possible outcome of the use of the indices but not as an index input. Though continued mitigation efforts in NYC may reduce flood risk and ultimately reduce the hazard potential, mitigation is difficult to quantify and without a measured value cannot be incorporated into the overall flood risk index. However, by illustrating the landscape of flood risk values the overall
flood risk index could be used in the development of targeted mitigation strategies both citywide and at the community level.

Second, the four individual indices and overall flood risk index were developed without reference to a specific measure of hazard potential. Though hazard potential in the hazards-of-place model is foundational to the production of biophysical and social vulnerabilities, this concept is also challenging to quantify and include in the overall index. However the primary physical vulnerability datasets - FEMA’s 100- and 500-year modeled flood extents - that were used to delineate the coastal flood study area and develop the index of storm surge exposure are based on flood probability and as such inherently include measures of risk. They also account for measures that can mitigate flood extent such as land use/land type and physical barriers. So these important datasets do bring elements of risk and mitigation into the overall flood risk index though perhaps not in the order intended in the hazards-of-place model.

Finally, this work goes beyond the use of previously developed indices to develop new indices that measure elements physical and social vulnerability specific to the hyper-heterogeneous and hyper-dense population of New York City. In the hazard-of-place model, the hazard potential is filtered using socioeconomic indicators to produce the social vulnerability. Though an index of social vulnerability was developed in this research, an index of critical at-risk facilities was also created to measure how populations may become increasingly vulnerable when critical social services are compromised during a storm event. This is particularly relevant in NYC where critical facilities are abundant, serve large portions of the population, and an integral part of daily life. In combination the two indices offer a broader measure of social vulnerability that looks beyond socioeconomic and sociodemographic indicators.
The hazard potential is also filtered through its geographic context to produce the biophysical vulnerability. The storm surge exposure index provides site-specific measures of physical vulnerability based on flood heights and wave action. In addition, the storm surge floodwater contaminants index accounts for the multitude of hazardous wastes sites that could potentially release toxic materials into floodwaters during a flood event. If released, these hazardous materials could infiltrate homes and businesses and pose health risks to residents and individuals involved in clean up efforts. In combination the two indices offer a measure of physical vulnerability that is more comprehensive than what is commonly used in flood vulnerability studies: simple exposure to floodwaters.

7.7. Index Validation and Sensitivity Analysis

Validation of indices of social and natural hazards vulnerability is used to assess the robustness and reliability of the index values, and is particularly important if indices are intended to be used as a decision-making tool. A common method of validation for physical models is to compare modeled results to a set of measured external reference data. However social vulnerability and other multidimensional models that incorporate social processes are not directly observable and rely instead on proxy data such as economic losses due to natural hazard, mortality, or infrastructure damage to approximate empirical measurement. Proxy data can be difficult to find and is only effective when the assumed correlation with the dimension being measured is accurate and consistent over the study area, and this is not always the case (Cutter and Finch 2008). Another method uses recovery outcomes from a natural hazard event to validate indices developed based on pre-event data. This approach has been used infrequently to date but was
recently applied to metrics of community resilience in the wake of Hurricane Katrina (Burton 2015).

When proxy or post-event data is not available or plausible, sensitivity analysis can be used to provide internal index validation through an evaluation of the methods and data used for index construction (Tate 2012). Sensitivity analysis examines how choices of input data and methodology affect the output by changing one input parameter at a time while the other parameters are held constant and measuring the resulting changes in index output. Through sensitivity analysis, modelers can assess the influence of different index parameters and make informed decisions about how to improve model robustness. Though this method has been applied to the construction of the social vulnerability index, results have been contradictory as to the influence of indicator selection in the index output (Schmidtlein et al. 2008; Chakraborty, Tobin, and Montz 2005).

This work does not yet include internal or external validation of the individual and composite flood risk indices. With few templates to draw from, the storm surge floodwater contaminants, critical facilities, and overall flood risk indices were instead developed using expert judgment of the subject matter, conservative index construction, and careful data selection with detailed justification provided for choices of data and design. By contrast the social vulnerability index was constructed based on the methods employed in a multitude of previous studies, and was most influenced by previous vulnerability indices created for New York City. The storm surge exposure index was also constructed using expert judgment, but this process was fairly
straightforward as the dataset is self-sorted into exposure categories that are easily ranked. Index validation and sensitivity analysis as future work are discussed in Chapter 8.
Chapter 8: Conclusions

This section draws conclusions from two sets of results: first, the analysis of current and future flood extents and populations at-risk to flooding, both citywide and by borough; and second the construction and application of the overall storm surge flood risk index for New York City. It also includes a discussion of study limitations brought about by lack of data and data omissions, uncertainties in foundational datasets, and broad assumptions in methodology. Future work is discussed throughout and the chapter concludes with a brief discussion of policy implications for New York City.

As sea levels rise, the land area subjected to flood events increases in size and more people are potentially affected by flooding. However this work shows that increases in sea levels, flood areas, and affected population do not always correlate in proportion to each other in New York City. Each of the five boroughs experiences different floodplains extents for a given flood volume (i.e., the 100- or 500-year flood) and for given increments of sea-level rise indicating that the physical expression of flood events in New York City is very much dependent on local geographies. This research also demonstrates that increases in sea-level rise and increases in flood extents are not proportional. For example, the area and population affected citywide by the 100- and 500-year floods increases more sharply with a smaller increment of sea-level rise from current levels to the 2020s (11 inches) than it does with a greater increment of sea-level rise (20 inches) from the 2020s to the 2050s. This result is contrary to what might be expected, however it is a function of the influence exerted by the near shore topography and the built environment, both of which can attenuate (or enhance) both sea-level rise and floodplain extents. In addition,
this analysis indicates that the number of additional residents at-risk to flooding through the 2020s and 2050s does not correspond proportionally to increases in flood extent (i.e., a 5% increase in flood area does not correlate to a 5% increase in population at-risk). This is because flooding in areas zoned for commercial, manufacturing, and open space increases the land area flooded without increasing the affected population.

The contribution of different sources of physical and social vulnerability to overall storm surge flood risk at the neighborhood level is also examined. One of the intentions of this work is to discern which elements of vulnerability exert the most influence on overall storm surge flood risk, and how this influence varies with location. In three of the four case study areas, physical vulnerability is the greatest influence on the overall storm surge flood risk index with floodwater contaminants dominating the fourth index. This result emphasizes the local component of overall storm surge flood risk and indicates that the dominant vulnerabilities will vary at the neighborhood scale.

Examining vulnerability and risk at local scales can better illustrate how pre-existing characteristics of neighborhoods contribute to a landscape of high and low overall flood risk values. This information is valuable in the context of long-term hazard mitigation and coastal resilience planning, and also in the shorter timeframe of emergency management and response. Different neighborhoods require different types and levels of mitigation measures, hazard preparedness, and response and recovery assistance to flood hazards. For some locations the greatest threat is the potential for floodwater contaminants while in other areas social vulnerability compromises the ability of the community to recover from even low exposure flood
events. In many locations several elements of vulnerability overlap to create a heightened overall risk to flood events. These areas may require more intensive or specialized planning to protect people and infrastructure from flood impacts.

Finally, overall storm surge flood risk index values were tested at the tax lot level for spatial randomness. The results indicate that the majority of index values show statistically significant spatial autocorrelation with neighboring index values. This correlation means that most of the physical and social characteristics measured by the four individual indices have strong spatial components.

8.1. Limitations

This section reviews several of the study limitations and considers their effect on the overall results.

Weighting Strategies

When constructing the social vulnerability, exposure to floodwater contaminants, critical facilities, and overall flood indices no weighting strategy was applied. Weighting is used to add emphasis to certain variables of an index using empirical evidence or expert judgment. Though it is clear that some variables have greater influence over the outcome of an index than other variables, without a defensible method to distinguish and quantify this difference it is best omitted. The only weighted index was that of exposure to floodwaters, which assigned higher scores to areas of high flood elevations and destructive zones of wave action than to areas of lower elevation flooding. This was possible because these areas were already defined and
delineated by FEMA and the NPCC. The absence of weighting strategy is an appropriate choice for the indices mentioned above and ultimately serves to eliminate any biases introduced through using judgment alone. However without comparative studies or external reference data it is difficult to evaluate whether the omission of weighting schemes produces results that are more accurate than weighted results.

For example, in the index of potential floodwater hazards the sheer volume of petroleum and chemical bulk storage facilities in some areas overwhelmed the influence of other larger and more toxic hazardous waste sites. By using a raw count of facilities per tax lot, a heating oil storage tank was effectively equal in impact to a wastewater treatment plant. A weighting scheme that considers the volume and toxicity of hazardous wastes handled and stored at sites might better represent the threat posed to the surrounding neighborhood. However the data necessary to employ this type of weighting scheme was not available for this work. And regardless, one element that cannot be quantified is the actual potential for leaks and spills of toxic materials at any given site due to flooding. For this reason it is assumed that all sites have equal potential to release hazardous materials during a flood event.

Circular Buffers

In the floodwater hazards index, circular buffers were constructed around facilities that store or handle hazardous wastes to approximate the movement and distribution of potential toxic releases during flood events. However, the use of buffers in this manner is overly simplistic in assuming that toxic wastes will disperse from their source in a manner that is equal and uniform when in fact they will likely be influenced by the direction of currents and disruptions presented
by infrastructure or other surface features. Thus, circular buffers are an unrealistic representation of both the movement of storm surge and the movement of point source hazardous wastes within storm surge but they are used for lack of a better alternative. The most accurate approximations of the movement of current and future storm surge in the open ocean and onto land are achieved through computational numeric hydrodynamic models, a process beyond the scope of this work.

**Omitted Data**

One aspect of this work that stands in contrast to other contemporary work on the topic is the omission from the index of critical facilities of police, fire, and emergency medical services (EMS) - all of which provide essential care to the community. The goal of the critical facilities index is to identify the population potentially affected by facility failure by identifying the spatial correlation between facility location and the area they serve. However, spatial information on emergency services facilities was limited to point locations of their stations without reference to the communities they respond to. In the case of NYC emergency services, a system of redundancy ensures that communities are served even when their primary station is compromised (see Section 5.2 for a more detailed discussion of emergency service networks in NYC). So the use of facilities location data (point data) would not have reflected the intent of critical facilities index and would have made inaccurate associations between facility locations and populations at-risk from their failure.

**Future Demographic Characteristics**

A significant limitation is the lack of knowledge regarding future population count, demographics and distribution, as well as changes to zoning, land use, and development in New
York City. Population characteristics for this study were derived from modern surveys using current population statistics that were applied to both current and future flood zones. Therefore this approach assumes that current and future populations will be equivalent in count and characteristics. This assumption is obviously inaccurate, however without the ability to model future demographics and population distribution it is also the default. It is difficult to discern how this assumption affects the results for future flood scenarios. For example, the current populations in the 100- and 500-year flood zones are not a clear over or underestimate of future population in those flood zones. Though the City of New York projects population to increase through the 21st century and speculates that much of the growth in residential units may occur along the coastal corridors, this process is emerging slowly and not yet clearly defined.

Uncertainty in Future Flood Shapefiles

There is inherent uncertainty in the flood extent shapefiles used to delineate future flood events. NPCC flood shapefiles contain numerous sources of potential error as a result of the datasets and methodologies used in their development. Error in the topographic elevation data, sea-level rise projections, and FEMA model outputs all contribute to this uncertainty and limit the accuracy of the shapefiles. The population, facilities, and infrastructure within the future flood zones inherit this uncertainty by virtue of being defined as ‘flooded’ by the shapefile extents. Though not quantified, the uncertainty of future flood areas is lowest near the coastline and greatest near the inland boundaries of the flood extents and it is possible that small changes to the flood extent boundary could result in large changes to the ‘flooded’ population. For this reason, where possible future work should consider using flood data that incorporates confidence intervals in their modeled results.
Uncertainties in Index Reliability

As mentioned in section 7.6, this work pushes forward the uses of multiple indices in the creation of an overall place-based flood risk index. The use of unique indices to represent aspects of geographic and social filters specific to NYC is a novel contribution to the hazards-of-place model and an innovative approach to developing a place-based storm surge risk index. Much of the subjectivity of the indices has been removed through the rational explanation of the decisions used in their construction, decisions based on expert judgment of the subject matter. Indices were constructed conservatively without weighting schemes and with care to select data that supports the intent of a given index. However eventually, in order to more objectively assess index reliability in measuring the intended parameter, future work should use external reference data where possible for validation of both the indices used in the creation of the overall flood risk index, and the overall flood risk index itself. Sensitivity analysis should also be applied to validate the indices internally and improve robustness by selecting the best data sets and construction methods. These efforts would prepare the indices for use as decision-making tools in scenarios of flood mitigation and resilience planning as well as emergency preparedness and response.

8.2. Policy Implications for New York City

This research provides a methodology for a local-level analysis of areas and populations most at-risk to flood hazards in New York City, and illustrates the importance and influence of both the physical and social aspects of vulnerability in identifying the geographic areas (neighborhoods and communities) most likely to suffer during flood events. An understanding of the spatial
distribution of the components of flood risk is key in developing targeted hazard mitigation and climate change policies, and improving emergency preparedness and response.

Policies that protect coastal communities from flood hazards address both physical and social vulnerabilities. Two indices representative of physical vulnerability, the storm surge floodwater exposure and floodwater contaminants indices, are included in this work and describe both the location of physically vulnerable neighborhoods and the degree of vulnerability. This information can be used to develop place-based coastal resilience policies aimed at fortifying the physical environment as appropriate for that neighborhood. These measures may include installing or raising bulkheads, seawalls or other breakwater systems; creating systems of levees or dikes; nourishing scoured beaches; restoring or creating natural wetland buffer systems; and updating flood resistant construction codes to reflect future flood elevations and incorporate advances in design and engineering.

It should be noted that though this work considers the impacts of a storm surge flood event, future work might consider how the cumulative effect of storm surge combined with intense rainfall might impact the movement, timing, and drainage of floodwaters. Though coastal flooding dominates in NYC, fluvial and urban street flooding occurs during intense rainfall events resulting in overflows in residential and municipal drainage systems. Coastal flooding may reach greater extents and take longer to recede with storm drains already overfull. For these reasons a storm event that brings both heavy precipitation and high surge is potentially worthy of further study.
Two indices representative of social vulnerability, the social vulnerability and at-risk critical facilities indices, are also included in this work and describe the distribution of socially vulnerable neighborhoods and their degree of vulnerability. Coastal resilience incentives that address social vulnerabilities to hazards are non-structural in nature. They are often focused on fortifying local economies through a variety of means such as development and revitalization investment projects for low-income neighborhoods, the promotion and support of local merchants, and job creation and career services programs to diminish unemployment. Other strategies include offering flood hazard mitigation grants to nursing homes, adult care or other facilities in need, expanding community hazard response teams, and working with FEMA to allow greater access and options to property owners.

The City of New York released its post-Hurricane Sandy analysis and action plan in June of 2013. This report, *PlaNYC: A Stronger More Resilient New York*, includes strategies for community rebuilding and increasing resilience of major waterfront neighborhoods across the city. These strategies include measures and initiatives for protecting the coasts, buildings, and critical infrastructure, and for promoting community and economic recovery. Most of these initiatives are subject to available funding and involve physical changes to structures that would make them more resilient to floodwaters and a few are focused on reinforcing community networks and lifelines. However the report does not quantify the degree of protection offered by these new measures in terms of the future flood elevations to which neighborhoods will be subjected.

The intention of coastal resilience plans is to determine a level of exposure, in the context of sea-level rise, to which a given area can and should be protected now and in the future. Though this
level of exposure would manifest as various flood protection measures in different neighborhoods throughout the city, the aim is for all neighborhoods to be afforded the same level of protection. This research offers a means by which to create local targets for future flood protection and community resilience by accounting for multiple aspects of community vulnerabilities.
Chapter 9: Appendix

9.1. Appendix A: New York City Neighborhood Map
9.2. Appendix B: Flood Area and Population Calculations Citywide

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<th>Citywide</th>
<th>Area (mi²)</th>
<th>% Change Area</th>
<th>2010 Population</th>
<th>% Change Pop</th>
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<td>FEMA Original 100-Year Flood, 1983</td>
<td>30.6</td>
<td>-</td>
<td>189,386</td>
<td>-</td>
</tr>
<tr>
<td>FEMA WorkMap 100 Year Flood, 2013</td>
<td>44.9</td>
<td>47%</td>
<td>385,254</td>
<td>103%</td>
</tr>
<tr>
<td>NPCC2 100-Year Flood for the 2020s</td>
<td>58.8</td>
<td>31%</td>
<td>587,265</td>
<td>52%</td>
</tr>
<tr>
<td>NPCC2 100-Year Flood for the 2050s</td>
<td>71.2</td>
<td>21%</td>
<td>787,596</td>
<td>34%</td>
</tr>
<tr>
<td>FEMA WorkMap 500-Year Flood, 2013</td>
<td>63.4</td>
<td>-</td>
<td>687,733</td>
<td>-</td>
</tr>
<tr>
<td>NPCC2 500-Year Flood for the 2020s</td>
<td>82.1</td>
<td>29%</td>
<td>1,012,045</td>
<td>47%</td>
</tr>
<tr>
<td>NPCC2 500-Year Flood for the 2050s</td>
<td>89.5</td>
<td>9%</td>
<td>1,196,422</td>
<td>18%</td>
</tr>
</tbody>
</table>
9.3. Appendix C: Flood Area and Population Calculations by Borough

<table>
<thead>
<tr>
<th>Borough</th>
<th>Area (mi²)</th>
<th>% Change Area</th>
<th>2010 Population</th>
<th>% Change Pop</th>
<th>% of Total Pop</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bronx</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FEMA Original 100-Year Flood, 1983</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FEMA WorkMap 100 Year Flood, 2013</td>
<td>3.8</td>
<td>-5%</td>
<td>11,446</td>
<td></td>
<td>0.83%</td>
</tr>
<tr>
<td>NPCC2 100-Year Flood for the 2020s</td>
<td>5.3</td>
<td>39%</td>
<td>19,513</td>
<td>70%</td>
<td>1.41%</td>
</tr>
<tr>
<td>NPCC2 100-Year Flood for the 2050s</td>
<td>6.6</td>
<td>25%</td>
<td>34,120</td>
<td>75%</td>
<td>2.46%</td>
</tr>
<tr>
<td>FEMA WorkMap 500-Year Flood, 2013</td>
<td>3.9</td>
<td>-</td>
<td>11,868</td>
<td>-</td>
<td>0.86%</td>
</tr>
<tr>
<td>NPCC2 500-Year Flood for the 2020s</td>
<td>8</td>
<td>105%</td>
<td>56,032</td>
<td>372%</td>
<td>4.05%</td>
</tr>
<tr>
<td>NPCC2 500-Year Flood for the 2050s</td>
<td>9.8</td>
<td>23%</td>
<td>95,898</td>
<td>71%</td>
<td>6.92%</td>
</tr>
<tr>
<td><strong>Brooklyn</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FEMA Original 100-Year Flood, 1983</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.85%</td>
</tr>
<tr>
<td>FEMA WorkMap 100 Year Flood, 2013</td>
<td>11.1</td>
<td>85%</td>
<td>171,504</td>
<td></td>
<td>9.93%</td>
</tr>
<tr>
<td>NPCC2 100-Year Flood for the 2020s</td>
<td>14.6</td>
<td>32%</td>
<td>248,702</td>
<td>45%</td>
<td>13.58%</td>
</tr>
<tr>
<td>NPCC2 100-Year Flood for the 2050s</td>
<td>18.9</td>
<td>29%</td>
<td>340,131</td>
<td>37%</td>
<td>13.58%</td>
</tr>
<tr>
<td>FEMA WorkMap 500-Year Flood, 2013</td>
<td>18.1</td>
<td>-</td>
<td>325,484</td>
<td>-</td>
<td>12.99%</td>
</tr>
<tr>
<td>NPCC2 500-Year Flood for the 2020s</td>
<td>24.1</td>
<td>33%</td>
<td>464,352</td>
<td>43%</td>
<td>18.54%</td>
</tr>
<tr>
<td>NPCC2 500-Year Flood for the 2050s</td>
<td>26.4</td>
<td>10%</td>
<td>534,153</td>
<td>15%</td>
<td>21.33%</td>
</tr>
<tr>
<td>Queens</td>
<td>Area (mi²)</td>
<td>% Change Area</td>
<td>2010 Population</td>
<td>% Change Pop</td>
<td>% of Total Pop</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
<td>---------------</td>
<td>-----------------</td>
<td>--------------</td>
<td>---------------</td>
</tr>
<tr>
<td>FEMA Original 100-Year Flood, 1983</td>
<td>11.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FEMA WorkMap 100 Year Flood, 2013</td>
<td>16.6</td>
<td>39%</td>
<td>96,079</td>
<td>44%</td>
<td>4.31%</td>
</tr>
<tr>
<td>NPCC2 100-Year Flood for the 2020s</td>
<td>22.6</td>
<td>36%</td>
<td>138,488</td>
<td>24%</td>
<td>6.21%</td>
</tr>
<tr>
<td>NPCC2 100-Year Flood for the 2050s</td>
<td>27.2</td>
<td>20%</td>
<td>171,563</td>
<td>24%</td>
<td>7.69%</td>
</tr>
<tr>
<td>FEMA WorkMap 500-Year Flood, 2013</td>
<td>24.3</td>
<td>-</td>
<td>148,302</td>
<td>-</td>
<td>6.65%</td>
</tr>
<tr>
<td>NPCC2 500-Year Flood for the 2020s</td>
<td>29.2</td>
<td>20%</td>
<td>189,755</td>
<td>28%</td>
<td>8.51%</td>
</tr>
<tr>
<td>NPCC2 500-Year Flood for the 2050s</td>
<td>31.1</td>
<td>7%</td>
<td>212,534</td>
<td>12%</td>
<td>9.53%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manhattan</th>
<th>Area (mi²)</th>
<th>% Change Area</th>
<th>2010 Population</th>
<th>% Change Pop</th>
<th>% of Total Pop</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEMA Original 100-Year Flood, 1983</td>
<td>2.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FEMA WorkMap 100 Year Flood, 2013</td>
<td>3</td>
<td>25%</td>
<td>77,265</td>
<td>87%</td>
<td>4.87%</td>
</tr>
<tr>
<td>NPCC2 100-Year Flood for the 2020s</td>
<td>4.2</td>
<td>40%</td>
<td>144,154</td>
<td>37%</td>
<td>9.09%</td>
</tr>
<tr>
<td>NPCC2 100-Year Flood for the 2050s</td>
<td>5</td>
<td>19%</td>
<td>197,679</td>
<td>-</td>
<td>12.46%</td>
</tr>
<tr>
<td>FEMA WorkMap 500-Year Flood, 2013</td>
<td>4.4</td>
<td>-</td>
<td>157,057</td>
<td>-</td>
<td>9.90%</td>
</tr>
<tr>
<td>NPCC2 500-Year Flood for the 2020s</td>
<td>5.7</td>
<td>30%</td>
<td>245,662</td>
<td>56%</td>
<td>15.49%</td>
</tr>
<tr>
<td>NPCC2 500-Year Flood for the 2050s</td>
<td>6.3</td>
<td>11%</td>
<td>290,493</td>
<td>18%</td>
<td>18.32%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Staten Island</th>
<th>Area (mi²)</th>
<th>% Change Area</th>
<th>2010 Population</th>
<th>% Change Pop</th>
<th>% of Total Pop</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEMA Original 100-Year Flood, 1983</td>
<td>7.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FEMA WorkMap 100 Year Flood, 2013</td>
<td>10.3</td>
<td>30%</td>
<td>28,958</td>
<td>26%</td>
<td>6.18%</td>
</tr>
<tr>
<td>NPCC2 100-Year Flood for the 2020s</td>
<td>12.8</td>
<td>24%</td>
<td>36,407</td>
<td>21%</td>
<td>7.77%</td>
</tr>
<tr>
<td>NPCC2 100-Year Flood for the 2050s</td>
<td>13.5</td>
<td>5%</td>
<td>44,101</td>
<td>9.41%</td>
<td></td>
</tr>
<tr>
<td>FEMA WorkMap 500-Year Flood, 2013</td>
<td>12.7</td>
<td>-</td>
<td>45,020</td>
<td>-</td>
<td>9.60%</td>
</tr>
<tr>
<td>NPCC2 500-Year Flood for the 2020s</td>
<td>15.1</td>
<td>19%</td>
<td>56,243</td>
<td>25%</td>
<td>12.00%</td>
</tr>
<tr>
<td>NPCC2 500-Year Flood for the 2050s</td>
<td>15.9</td>
<td>5%</td>
<td>63,343</td>
<td>13%</td>
<td>13.51%</td>
</tr>
</tbody>
</table>
Bibliography


———. 2011. Citywide Environmental Justice coalition calls on Mayor and Governor to protect low-income waterfront communities from toxic exposures during hurricane storm surges.


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