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Developing Coastal Adaptation to Climate Change in the New York City Infrastructure-shed: Process, Approach, Tools, and Strategies[1]

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Abstract

While current rates of sea level rise and associated coastal flooding in the New York City region appear to be manageable by stakeholders responsible for communications, energy, transportation, and water infrastructure, projections for sea level rise and associated flooding in the future, especially those associated with rapid icemelt of the Greenland and West Antarctic Icesheets, may be beyond the range of current capacity because an extreme event might cause flooding and inundation beyond the planning and preparedness regimes. This paper describes the comprehensive process, approach, and tools developed by the New York City Panel on Climate Change (NPCC) in conjunction with the region's stakeholders who manage its critical infrastructure, much of which lies near the coast. It presents the adaptation approach and the sea-level rise and storm projections related to coastal risks developed through the stakeholder process. Climate change adaptation planning in New York City is characterized by a multi-jurisdictional stakeholder-scientist process, state-of-the-art scientific projections and mapping, and development of adaptation strategies based on a risk-management approach.

Introduction

Since the publication of *Climate Change and a Global City: The Potential Consequences of Climate Variability and Change,* part of the U.S. National Assessment of Climate Variability and Change (Rosenzweig and Solecki, 2001) and other early reports (e.g. Hill, 1996) accelerated sea level rise and exacerbated coastal flooding associated with climate change have been issues of critical concern for New York City and its surrounding region. With over 600 miles of coastline, this densely populated complex urban environment is already prone to losses from weather-related natural catastrophes, being in the top ten in terms of population vulnerable to coastal flooding worldwide and second only to Miami in assets exposed to coastal flooding. It is estimated that a direct hit by a major hurricane could cause $100s of billion in damages, with economic losses accounting for roughly two times the insured losses (LeBlanc and Linkin, 2010).

As part of PlaNYC (NYC Office of the Mayor, 2007), New York City's sustainability plan, Mayor Michael Bloomberg convened a panel of experts in 2008 to advise the government of

New York City on issues related to climate change and adaptation of critical infrastructure[2] (Rosenzweig and Solecki, 2010). The designated infrastructure systems included communications, energy, transportation, water, and waste. Since these critical infrastructure systems extend well beyond the boundaries of the five boroughs of New York City, the domain of the New York City Panel on Climate Change's work was thus the 'infrastructure-shed' of the region, with the water system encompassing the largest spatial area *(Figure 1).*

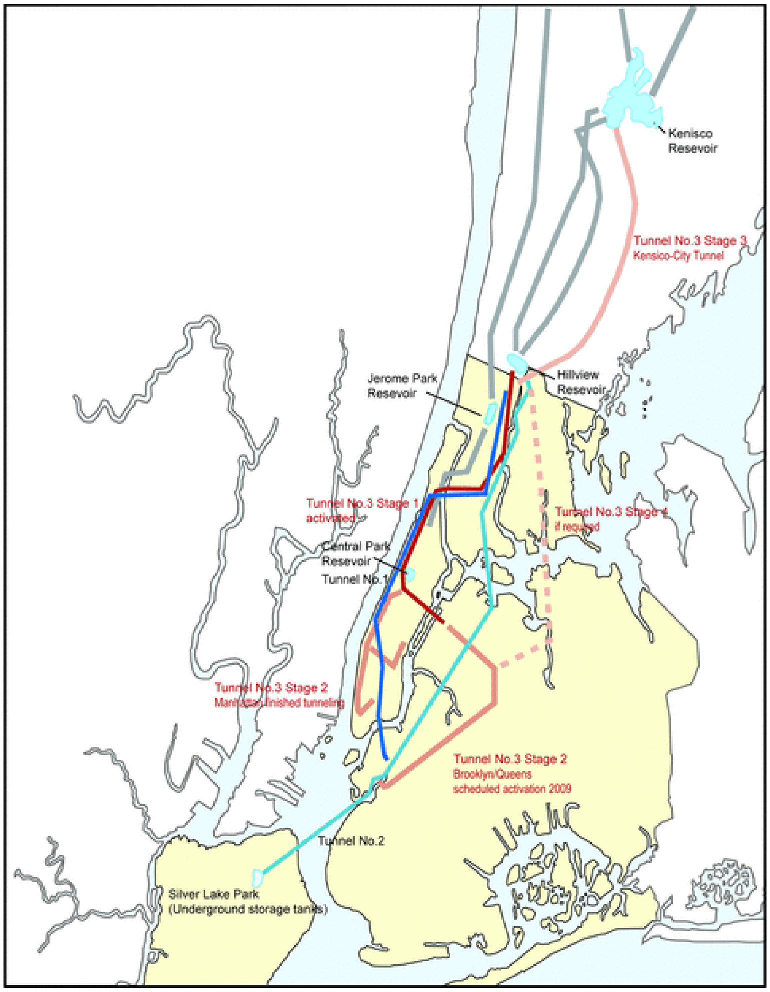

Figure 1. *New York City water supply distribution system and third water tunnel planned locations. Sources: PlaNYC, 2007; NPCC, 2010*

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[2] Critical infrastructure is defined as systems and assets (excluding residential and commercial buildings, which are addressed by other efforts) that support activities that are vital to the city and for which the diminished functioning or destruction of such systems and assets would have a debilitating impact on public safety and/or economic security (NPCC CRI, 2009).

The New York City Panel on Climate Change (NPCC)[3] consisted of academic experts covering a broad range of disciplines including physical climatology, geology, oceanography, as well as social science and economics, and private sector experts representing the fields of the law, insurance, and risk management. The aim of the NPCC was to achieve, at the local level, some of the scientific objectives that the Intergovernmental Panel on Climate Change (IPCC) Working Groups I and II achieve with their reports that focus on climate observations, projections, and adaptation assessment at the global and continental scales. The NPCC provided the stakeholders with both a broad range of information on climate change and adaptation approaches relevant to the critical infrastructure systems and a set of specific 'tools' that included developed down-scaled climate change projections for New York City and its surrounding region in order to help the region both understand and prepare for a changing climate. The cross-connection between significant coastal hazards and the fact that much of New York City's infrastructure is in the coastal zone made the water's edge a central focus of the NPCC's overall work on future climate risks and adaptation strategy development.

The development of adaptation to climate change in the New York City region is occurring in the context of other coastal cities in the U.S. and abroad that are taking up similar challenges (see e.g., Titus et al. 2009). For cities at the forefront of these efforts, it appears that strong input from scientists plays a role in that comprehensive impacts and adaptation assessments by scientists have contributed to building eventual policy outcomes. For example, the CLIMB and other impacts and adaptation assessments in Boston (Kirshen et al., 2008a,b) led to the development of the City of Boston's Climate Adaptation Work Group's formal recommendations in April 2010, which include a primary focus on preparing for sea level rise. Recommendations of the Boston group included supporting efforts to ensure that laws, codes, and regulations incorporate forward-looking climate change concerns and encouraging each city agency should conduct a formal review of potential effects and responses from sea level rise and other climate change effects (http://www.cityofboston.gov/Images_Documents/BCA_full_rprt_f2.pdf).

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[3] New York City Panel on Climate Change Members: Cynthia Rosenzweig (Co-Chair), William Solecki (Co-Chair), Reginald Blake, Malcolm Bowman, Craig Faris, Vivien Gornitz, Klaus Jacob, Alice LeBlanc, Robin Leichenko, Edna Sussman, Gary Yohe, Rae Zimmerman. NPCC Science Planning Team Members: Megan O'Grady, Lesley Patrick, David C. Major, Radley Horton, Daniel Bader, Richard Goldberg, Michael Brady.

Abroad, Lonsdale et al. (2008) have studied responses to the threat of rapid sea-level rise in the Thames Estuary, while the City of London Mayor's Climate Change Adaptation Strategy (2010) emphasizes both the current flooding hazard and that flood risk is projected to increase with climate change. Steps relevant to coastal adaptation presented in the City of London's strategy include obtaining better scientific understanding of flood risks, how climate change will affect the City's ability to manage the flood risks, identifying the most critical assets and vulnerable communities in London and concentrating flood management strategies in these areas, and increasing public awareness of flooding risks and enhancing individual and community recovery capacity (http://www.london.gov.uk/climatechange/sites/climatechange/staticdocs/Climiate_change_adaptation.pdf).

New York City's climate change adaptation efforts are similar to the efforts in other cities, but they offer a comprehensive set of specific contributions including the design of a multi-jurisdictional stakeholder-scientist process, the development of state-of-the-art scientific projections and mapping targeted to the needs of managers of critical infrastructure, and the development of a region-wide risk management approach to adaptation. While the full documentation of the NPCC's work can be found in Rosenzweig and Solecki 2010; the objectives of this paper are to bring together those parts of the NPCC work relevant to coastal adaptation and to describe NYC's contributions to climate change adaptation in urbanized areas. While the stakeholder process, approach, information and tools presented in the paper are specific to the management of critical infrastructure systems of the New York City region, we believe that the work can contribute to the development of climate change adaptation planning in cities more generally, and for coastal cities in particular.

Scientist-Stakeholder Process

The NPCC acted as a scientific advisory group to both the Mayor Bloomberg's Office of Long-term Planning and Sustainability and the New York City Climate Change Adaptation Task Force (Task Force), a stakeholder group of approximately 40 public agencies and private-sector organizations that manage the critical infrastructure of the region. The Task Force was organized in to five Work Groups: Energy, Communication, Transportation, Water and Waste, and Policy.

Key elements to emphasize in this scientist/multi-stakeholder process for climate change adaptation planning in a complex urban environment were: separation of functions between scientists and stakeholders; inclusion of public sector stakeholders from multiple jurisdictions as well as from the private sector; ‘buy-in from the top;’ a coordinating body; regular stakeholder-scientist interactions that engendered interactive tool-development; targeted sessions for specific issues; and communication of uncertainties.

Separation of functions between scientists and stakeholders. The formation of the NPCC as the scientific body advising the City and the Task Force separated the functions of knowledge provision and adaptation planning and action. Since the accomplishment of the latter depends on many social, economic, and political factors, the separation of the provision of science and information helped to clarify the roles and functions.

Inclusive and multi-jurisdictional participation: Because the critical infrastructure of the region is managed by a complex set of actors, an inclusive and multi-jurisdictional approach was undertaken in the creation of the Task Force by the City. Thus, public-sector representation on the Task Force included City, State, bi-state, and regional offices of federal agencies. Representatives from the energy and communications sectors were primarily from private corporations and utilities. The presence of such a wide range of actors facilitated discussion of infrastructure interdependencies and overlapping jurisdictions.

Buy-in from the top. Mayor Bloomberg convened both the Task Force and the NPCC in August of 2008, fulfilling the role of ‘climate change champion’ (NYC Office of the Mayor, 2008). The Task Force kick-off meeting was attended by the Mayor, Deputy Mayor, and Commissioners of the relevant agencies, which provided a clear signal of ‘buy-in from the top’ for the Task Force’s activities. The working members of the Task Force were from operations-focused divisions of the agencies and organizations.

Coordinating body. The Mayor's Office of Long-term Planning and Sustainability played a key role in coordinating the Task Force activities and in facilitating the communication between the Task Force and the NPCC. For the first six months of the joint activities, the Boston Consulting Group also contributed to coordinating the effort by helping to develop the structure of the Task Force activities and the NPCC adaptation products.

Regular stakeholder-scientist interactions. Over the period from August, 2008 to May, 2010, Task Force meetings were held on a quarterly basis and were attended by the NPCC Co-Chairs, who presented updates on the development of the climate risk information and other NPCC information products. This provided the opportunity for regular feedback from the Task Force as a whole on the NPCC work. The five working groups of the Task Force met on a monthly basis and at least one member of the NPCC attended each of the Working Group meetings, in order to share progress on the NPCC products and to get feedback from the stakeholders.

Targeted sessions. At various times during the one and a half years of the NPCC's work, special sessions were held with specific stakeholders regarding targeted issues. Examples of such targeted issues include the rapid ice melt sea level rise scenario of interest to the NYS Department of Environmental Conservation, legal issues with the NYC Legal Department, and coastal flood maps of interest to the NYC Office of Emergency Management.

Communication of uncertainties. The NPCC explicitly communicated with the stakeholders about a broad range of uncertainties related to climate change. Uncertainties discussed included reasons why future climate changes may not fall within the model-based range projected by the NPCC, due either to differing emission pathways or different sensitivity of the climate system to the greenhouse forcing. It was also discussed that observed greenhouse gas emissions to-date lie near the upper range of the emissions scenarios used, and that this could lead to an interpretation that the high-emission climate change scenarios may be more likely. The uncertainty related to icesheet melting in Greenland and West Antarctica was also included explicitly in the scenarios developed with and for the stakeholders. The potential for long-term climate change extending into the 22nd century was presented even though this timeframe is beyond most current infrastructure planning horizons, since some infrastructure intended to have a useful lifespan within the 21st century may remain operational beyond their planned lifetimes.

Framing a Risk Management Approach to Adaptation Planning

While current rates of sea level rise and associated coastal flooding in the region appear to be manageable, the projections for sea level rise and associated flooding in the future, especially those associated with rapid ice melt of the Greenland and West Antarctic Icesheets, may be beyond the range of current capacity because an extreme event might cause flooding and inundation beyond the planning and preparedness regimes. Thus, there is a need for establishment of an adaptation planning process. From ongoing discussions with the New York City Climate Change Adaptation Task Force over the year and a half of the NPCC's work, it emerged that a risk-management framework would be a useful approach, since such an approach is already taken within the stakeholder agencies in regard to current climate hazards and many other types of risks.

The risk-management approach developed by the NPCC is called Flexible Adaptation Pathways *(Figure 2)*, based in part on climate change adaptation planning for the updating of the Thames Barrier in London (Lowe et al., n.d.). The goal of the Flexible Adaptation Pathways approach is to foster climate change responses that evolve over time as understanding of climate change and impacts improves and that concurrently reflect local, national and global economic and social conditions.

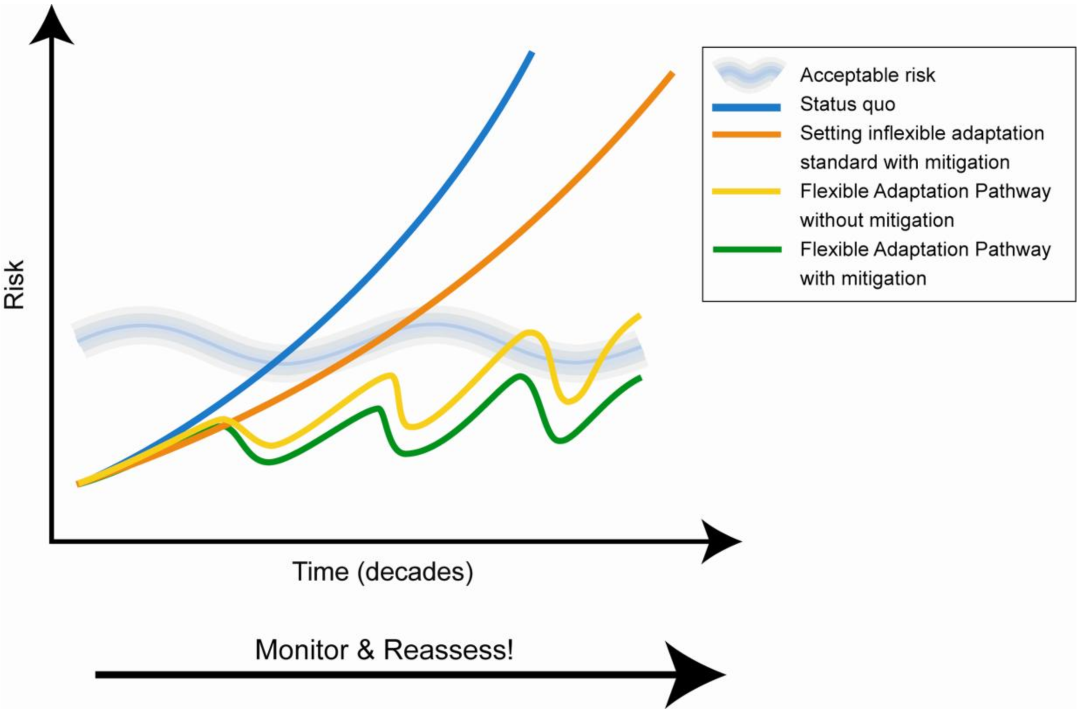

Figure 2. *Flexible Adaptation Pathways. Source: NPCC, 2010.*

Because climate change poses uncertain risks, the adaptation process should be characterized by a dynamic sequence of analysis and action followed by evaluation, further analysis, and refinement (i.e., learn, then act, then learn some more) (Yohe and Leichenko, 2010), an approach practiced by the Port Authority of New York and New Jersey and a wide set of city and regional agencies and organizations.

To guide the development of flexible adaptations through time, the NPCC, with inputs from the New York City Office of Long-term Planning and Sustainability, the Boston Consulting Group, and the New York City Climate Change Adaptation Task Force, developed an eight-step process designed explicitly to help stakeholders create an inventory of their at-risk infrastructure and to develop adaptation strategies with which they could address those risks *(Figure 3)* (Major and O'Grady, 2010). The steps outlined are intended to become integral parts of ongoing risk management, maintenance and operation, and capital planning processes of the agencies and organizations that manage and operate critical infrastructure.

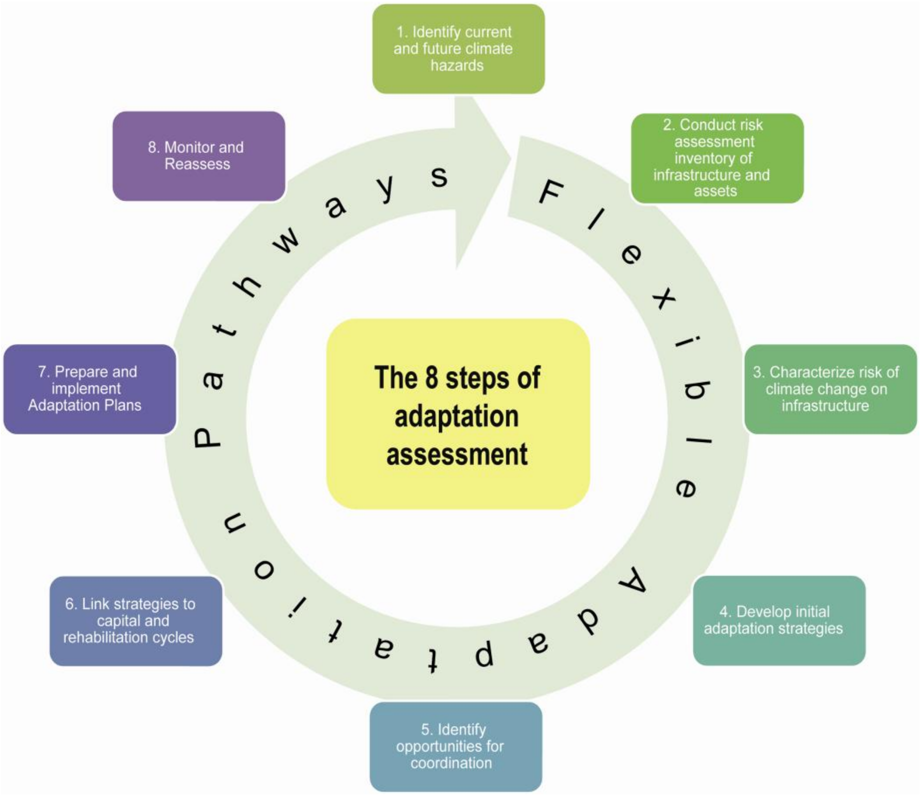

Figure 3. *Eight steps for adaptation assessment. Source: NPCC, 2010.*

Sea level rise and coastal flooding

In order to identify current and future climate hazards for that coastal areas of the New York City infrastructure-shed, the NPCC documented observed sea level rise and historical coastal storms, and developed a coordinated set of sea level rise and coastal storm projections. These were then used by all the stakeholders in the Task Force to conduct risk assessment inventories of infrastructure and assets, to characterize the risk of climate change on infrastructure, and to develop adaptation strategies.

Observed Sea Level Rise in the New York City Region

Prior to the industrial revolution, sea level had been rising along the East Cost of the United States at rates of 0.34 to 0.43 inches per decade, primarily because of regional subsidence as the Earth’s crust still slowly re-adjusts to the melting of the ice sheets since the end of the last ice age. Within the past 100 to 150 years however, as global temperatures have increased, regional sea level has been rising more rapidly than over the last thousand years (Gehrels, et al., 2005; Donnelly et al., 2004; Holgate and Woodworth, 2004).

Currently, rates of sea level rise in New York City range between 0.86 and 1.5 inches per decade, with a long-term rate since 1900 averaging 1.2 inches/decade, as seen in *Figure 4*. The sea level rise rates shown in Figure 4, measured by tide gauges, include both the effects of recent global warming and the residual crustal adjustments to the removal of the ice sheets.

Most of the observed current climate-related rise in sea level over the past century can be attributed to expansion of the oceans as they warm, although melting of land-based ice may become the dominant contributor to sea level rise during the 21st century (Church et al., 2008).

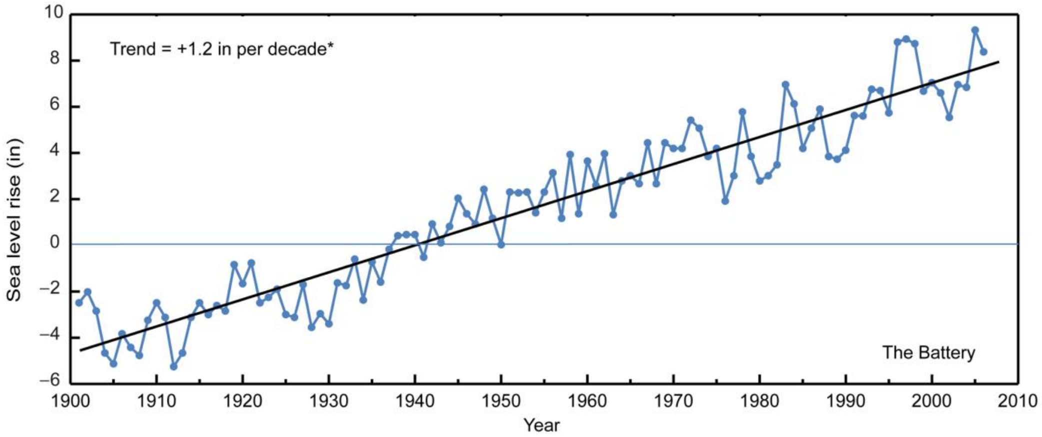

Figure 4. *Observed sea level at the Battery, New York City. *Trend is significant at the 95% level. Source: Horton and Rosenzweig, 2010.*

Coastal Storms in the New York City Region

The two types of storms with the largest influence on the region are hurricanes and nor'easters. Hurricanes strike New York very infrequently and can produce large storm surges and wind damage. Nor'easters are generally associated with smaller surges and weaker winds than those hurricanes that strike the region. Nevertheless, nor'easter effects can be large, in part because their long duration means an extended period of high winds and high water, often coinciding with high tides.

A large fraction of New York City and the surrounding infrastructure lies less than 10 feet above mean sea level; the infrastructure in these areas is vulnerable to coastal flooding during major storm events, both from inland flooding and from coastal storm surges[4]. The current 1-in-100 year flood produces a water level approximately 8.6 ft above designated vertical datum of New York City (Horton et al., 2010). Hurricanes, because they can be more intense, are more likely than nor'easters to cause 1-in-100 year and 1-in-500 year floods (10.7 ft above normal levels). Nor'easters are the main source of the 1-in-10 year coastal floods (6.3 ft above normal levels). Because the most extreme storms are by definition rare, documenting their occurrence over New York's longer-term history is challenging given reporting gaps and inconsistencies. Although no trend in observed storms is evident, characterizing historical storms is a critical first step in understanding future storms and their impacts, especially because rising sea levels will result in more severe coastal flooding when storm surges occur.

Sea Level Rise Projections

The NPCC climate projections focus on changes in both means and extremes in temperature, precipitation and sea level rise (for full description of methods of sea level rise projection development see Horton and Rosenzweig, 2010; Horton et al., 2010). The NPCC used two different sea level rise methods; both incorporating observed rates of local land subsidence, as well as global and regional projections from global climate models. The first method, referred to as the Intergovernmental Panel on Climate Change (IPCC)-based method (adapted from IPCC, 2007), projects (using the central range, or middle 67% of the model distribution) mean annual sea level rise in New York City as 2 to 5 inches by the 2020s; 7 to 12 inches by the 2050s; and

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[4] Surge is usually defined as the water level above that of the astronomical tide generated by a storm; flood level is the sum of the tide and the surge. NOAA tide gauges collect water level data at 6 min. intervals and results are usually averaged hourly. For this study, the highest surge and flood levels per 24 hrs (i.e. ,daily) were used to calculate 1-in-100 year floods.

12 to 23 inches by the 2080s. We report the central range because the Task Force stakeholders requested that this be calculated. (Both the full and the central range of the IPCC-based projections are shown in *Figure 5*; these are used to calculate the flooding recurrence intervals presented in *Table 1*).

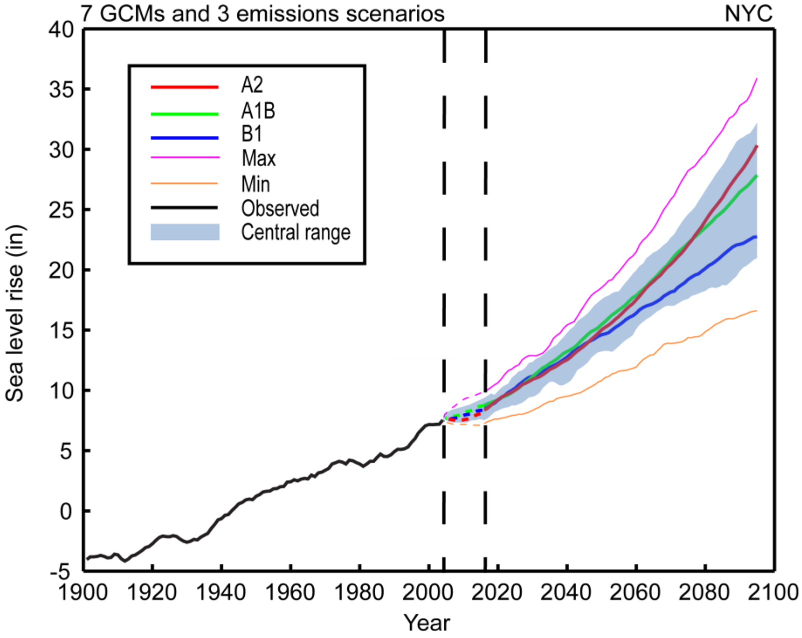

Figure 5. *Observed and projected sea level rise for New York City. Projections are based on global climate model simulations used in the IPCC Fourth Assessment Report Working Group I (2007). Projected changes through time are calculated on a yearly timescale and then displayed using a 10-yr filter. Source: Horton and Rosenzweig, 2010.*

Within the scientific community, there has been extensive discussion of the possibility that the IPCC (2007) approach to sea level rise may underestimate the range of possible increases, in large part because it does not fully consider the potential for land-based ice sheets to melt due to dynamical processes (e.g., Hansen et al., 2007, Horton et al., 2008). To address this possibility, an alternative method that incorporates observed and longer-term historical ice-melt rates is also included in the NPCC projections. The "rapid ice-melt" approach suggests sea level could rise by approximately 37 to 59 inches (with a central range of 41 to 55 inches) by the 2080s *(Figure 6).* The range in the rapid ice-melt scenario represents a combination of GCM model results and paleoclimatic uncertainties related to timing of deglaciation. The IPCC-based projections in

Figure 6 differ from those presented in Figure 5 because the former shows the average of the changes over the decade of the 2080s, while the latter was calculated on a yearly timescale with results presented with a 10-yr filter).

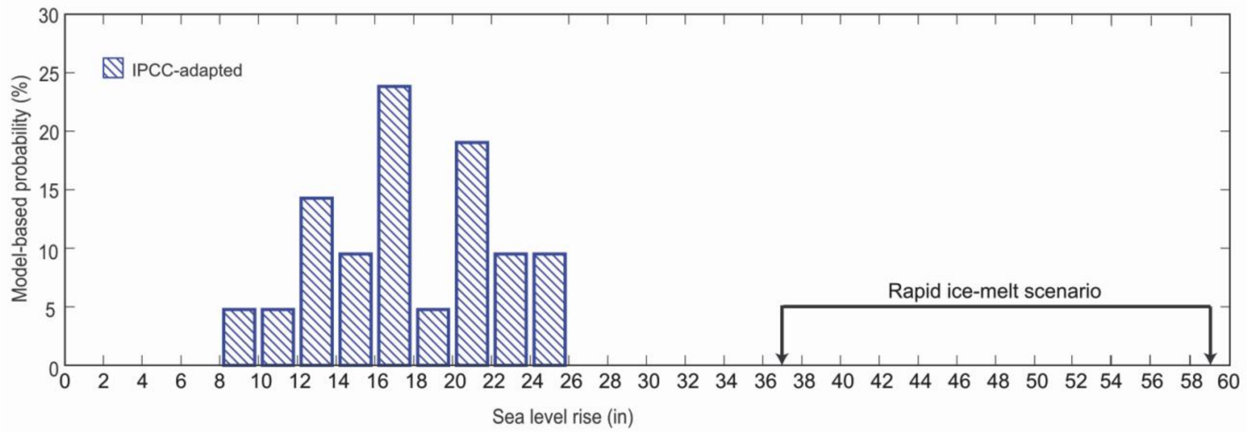

Figure 6. *Comparison of IPCC-based and rapid ice-melt sea level rise scenarios for New York City for the 2080s. Model-based probability refers to the suite of 7 GCMs and 3 emissions scenarios used to create the histogram. Note that the full range of projections, rather than solely the central range, is shown. Rapid ice-melt scenario does not have probabilities attached due to the high level of uncertainty. Source*: *Horton and Rosenzweig, 2010.*

Future Coastal Floods and Storms

As sea levels rise, coastal flooding associated with storms will very likely increase in intensity, frequency, and duration. The changes in coastal flood intensity shown here, however, are solely due to changes in sea level through time. Any increase in the frequency or intensity of storms themselves would result in even more frequent future flood occurrences relative to the current 1-in-10 and 1-in-100 year coastal flood events. By the end of the 21st century, sea level rise alone suggests that coastal flood levels which currently occur on average once per decade may occur once every one to three years (see *Table 2*).

The more severe current 1-in-100 year flood is less well characterized that than 1-in-10 year event due to the lack of long-term flood height data; thus there is the possibility that flood height may vary on century timescales or that storm behavior (intensity, frequency, storm tracks) may differ in the future from that experienced until now, but lack of data makes this hard to verify.

Assuming no change in storm characteristics, the NPCC estimates that due to sea level rise alone the 1-in-100 year flood may occur approximately four times as often by the end of the century. The current 1-in-500 year flood height is extremely uncertain since the historical record is much shorter than 500 years, but by extrapolation of current data we estimate that by the end of the century, the 1-in-500 year flood event may occur approximately once every 200 years.

The combination of intense storms (regardless of whether these change in frequency or intensity) and higher sea levels also increases the likelihood of coastal flooding. Projections with the current 1-in-100 year flood level under conditions of increasing ocean heights indicate a recurrence approximately once every 65 to 80 years by the 2020s on average, once every 35 to 55 years by the 2050s, and once every 15 to 35 years by the 2080s. These projections are based on the IPCC-based methods; the rapid ice melt scenario yields more frequent coastal flood events (*Table 2*). The flood heights associated with different flood frequencies vary from each other because the less-severe storms occur more frequently, while severe storms that cause high amounts of flooding are by definition rare. The flood heights shown in Table 2 correspond to the Battery in lower Manhattan. Flood heights can differ substantially over small spatial scales, due to a range of factors including coastal bathymetry and orientation of the coastline relative to storm trajectories. Some parts of New York City, such as the northernmost points where the Bronx and the Hudson River meet, currently experience lower flood heights than the Battery and many other exposed coastal locations (distances of 15 to 30 miles). These relative differences are expected to continue in the future.

Table 1. *Projections of coastal flood events in New York City Region.*

	Extreme Event	***Baseline (1971- 2000)***	**2020s**	**2050s**	**2080s**
Coastal Floods & Storms[4]	1-in-10 yr flood to reoccur, on average	*~once every 10 yrs*	~once every 8 (8 to 10) 10 yrs	~once every 3 (3 to 6) 8 yrs	~once every 1 (1 to 3) 3 yrs
	Flood heights (in ft) associated with 1-in-10 yr flood	*6.3*	6.5 (6.5 to 6.8) 6.8	6.8 (7.0 to 7.3) 7.5	7.1 (7.4 to 8.2) 8.5
	1-in-100 yr flood to reoccur, on average	*~once every 100 yrs*	~once every 60 (65 to 80) 85 yrs	~once every 30 (35 to 55) 75 yrs	~once every 15 (15 to 35) 45 yrs
	Flood heights (in ft) associated with 1-in-100 yr flood	*8.6*	8.7 (8.8 to 9.0) 9.1	9.0 (9.2 to 9.6) 9.7	9.4 (9.6 to 10.5) 10.7
	1-in-500 yr flood to reoccur, on average	*~once every 500 yrs*	~once every 370 (380 to 450) 470 yrs	~once every 240 (250 to 330) 380 yrs	~once every 100 (120 to 250) 300 yrs
	Flood heights (in ft) associated with 1-in-500 yr flood	*10.7*	10.9 (10.9 to 11.2) 11.2	11.2 (11.4 to 11.7) 11.9	11.5 (11.8 to 12.6) 12.9

Note: Does not include the rapid ice-melt scenario. Numbers inside parentheses indicate central range (67% of model-based distribution); numbers outside are full range. The sole source of variability, expressed by the range of frequencies and flood heights for the different flood recurrence intervals, is the range of sea level rise projections from the global climate models, which vary with emission scenario as well as sensitivity to greenhouse gas forcing. Variability can be large locally on shorter (sub-decadal) timescales. Source: Horton and Rosenzweig, 2010.

Table 2 presents qualitative projections for coastal storms. For these variables, quantitative projections are not possible due to insufficient information. This information was developed at the explicit request of the stakeholders managing the critical infrastructure of the New York City region, and is based on literature review and expert judgment (Horton et al., 2010).

Table 2. *Qualitative projections of changes in extreme events. Source: Horton and Rosenzweig, 2010.*

Extreme Event	**Probable Direction Throughout 21st Century**	**Likelihood**
Frequency of intense hurricanes	⇧	More likely than not
Frequency and intensity of nor'easters	*Unknown*	
Extreme winds	⇧	More likely than not

Note: These qualitative projections were made using a combination of literature review and expert judgment. The definitions of likelihood are based on IPCC (2007) to describe potential outcomes.

>99%	*Virtually certain*
>95%	*Extremely likely*
>90%	*Very likely*
>66%	*Likely*
>50%	*More likely than not*
33 to 66%	*About as likely as not*

Note: >50% is used when the likelihood can be estimated with reasonably good precision, and 33 to 66% is used when there is not high confidence in the likelihood estimate.

Coastal impacts on infrastructure.

New York City houses one of the densest infrastructures in the world. Because of its age and composition, some of this infrastructure and materials may not be able to withstand the projected strains and stresses from a changing climate. *Table 3* documents potential impacts of sea level rise and coastal flooding for energy, transportation, water and waste, and communications systems of the New York City region, four systems that comprise a large proportion of the infrastructure of the region especially near the coast. Coastal storms can cause increased street, basement, and sewer flooding in coastal areas; increased structural damage and impaired operations of communications, energy, transportation, and water and waste infrastructure; reduction of water quality through saltwater intrusion into aquifers; and inundation of low-lying areas and wetlands. If extreme climate events become more frequent as projected, there will be increased stress on all of these infrastructure systems as they play critical roles in emergency management. Furthermore, interdependencies, multiple owners, and complicated jurisdictions make coordination of adaptation planning especially challenging in the region (Zimmerman and Farris, 2010).

Energy. Presently, about two dozen power plants of varying sizes are operating within the borders of New York City, and over a dozen more were proposed as of 2005 *(Figure 7)*.[5] These facilities are owned and/or operated by a half-dozen entities. Traditionally power plants have required shoreline or close to shoreline locations for water intake structures and cooling water discharges thus a number of these existing production facilities are located at lower elevations and potentially sensitive to flooding due to sea level rise.

Transmission lines service the city from relatively few directions providing little flexibility should any one of these lines be compromised. The lines enter New York City primarily from Westchester to the north and secondarily from Long Island to the east and New Jersey to the west. Thus, any given disruption in one of these locations will have relatively widespread impacts. The distribution system, distinct from transmission, is one of the densest in the world, consisting of approximately 90,000 miles (145,000 kilometers) of underground distribution lines and 55 distribution networks within the city, each of which can operate independently of the other.[6]

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[5] K. Ascher, The Works, Penguin Press, 2005, p. 98

[6] T.D. O'Rourke, A. Lembo, and L. Nozick (2003) "Lessons Learned from the World Trade Center Disaster About Critical Utility Systems," in Beyond September 11th: An Account of Post-Disaster Research. Natural Hazards Research & Applications Information Center, Public Entity Risk Institute, and Institute for Civil Infrastructure Systems. Boulder, CO: University of Colorado, p. 275.

Figure 7. *Locations of New York City power plants relative to 10-foot elevation contour. Source: NPCC, 2010*

Transportation. The rail transit system serving New York City is the largest in the United States. Seven local and regional transit systems serve the city with a number of systems sharing track and other facilities. Three of them are managed by the Metropolitan Transportation Authority (MTA). First, New York City Transit has 660 passenger miles of track (840 in total) and serves 1.5 billion passengers annually within the five boroughs (see *Figures 8 and 9* for lines and station locations). Second, the Metro-North has 775 miles of track and services more than 80 million passengers annually running mainly to and from locations north of the city. The third MTA system is the Long Island Railroad that runs to and from Long Island east of the city and has 594 miles of track and services 82 million passengers per year.

The Port Authority of NY and NJ manages two transit systems that run between New Jersey and New York City. The Port Authority Trans Hudson system (PATH) has 43 miles of track and services 66.9 million passengers per year between locations within relatively close proximity to the Hudson River. NJ Transit runs further into New Jersey, has 643 miles of track and services 241.1 million passengers per year.

Many components and facilities of rail systems can potentially become vulnerable due flooding from increased precipitation and sea level rise. Although many rail components in New York City are at low elevations, there is a dramatic variation in height above sea level. These locations are well known for the New York area, which will help in identifying particularly vulnerable areas (U.S. Army Corps of Engineers, 1995; and summarized in Jacob, Edelblum and Arnold 2001; Jacob et al. 2007; Zimmerman 2003a; and Zimmerman and Cusker 2001). For example, within the New York City Transit system, the high point is the Smith and 9th Street station in Brooklyn, which is 91 feet high,[7] and the low point is about 180 feet below sea level in upper Manhattan. Subway stations also vary in the diversity and location of areas vulnerable to flooding such as public entrances and exits, ventilation facilities, and manholes.

A recent incident of heavy precipitation of short duration gives an example of how extensive flooding of the rail system can be. Massive area-wide flooding from the August 8, 2007 storm resulted in a system-wide outage of the MTA subways during the morning rush hour. The event also required the removal of 16,000 pounds of debris and the repair or replacement of induction stop motors, track relays, resistors, track transformers, and electric switch motors.[8] Such phenomena have periodically halted transit in New York City over the years (MTA 2007) necessitating the use of large and numerous pumps throughout the system. Storms such as these lend themselves to analogies to flooding from climate change in the future (Rosenzweig et al. 2007).

The flexibility of transit users to shift from one system to another is an important adaptation mechanism. An important factor influencing adaptation for rail transit facilities is the extent to which the configuration of transit networks consist of single extended rail lines that are not frequently interconnected with other lines, resulting in relatively little flexibility for shifting to

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[7] NYCSubway.org, June 24, 2005, http://www.nycsubway.org/perl/stations?207:2659, Accessed July 15, 2009.

[8] Metropolitan Transportation Authority (2007) August 8, 2007 Storm Report, September 20. New York, NY, p. 34.

another rail line if any one area of the line is disabled. Shifting to bus lines is often an option under such conditions. Portions of the New York City Transit and PATH systems are able to bypass bottlenecks depending on location, which was the case in both systems immediately following the September 11, 2001 attacks on the World Trade Center (Zimmerman and Simonoff 2009).

Although it is difficult to retrofit existing facilities, a number of very large new projects are being planned or are underway in New York City that provide an opportunity to incorporate climate change adaptations in the form of elevating, flood proofing, or providing heat resistant materials for transportation structures. These projects include among others Access to the Region's Core (ARC) for a new Hudson River commuter rail tunnel, the Second Avenue Subway, and Number 7 line extensions.

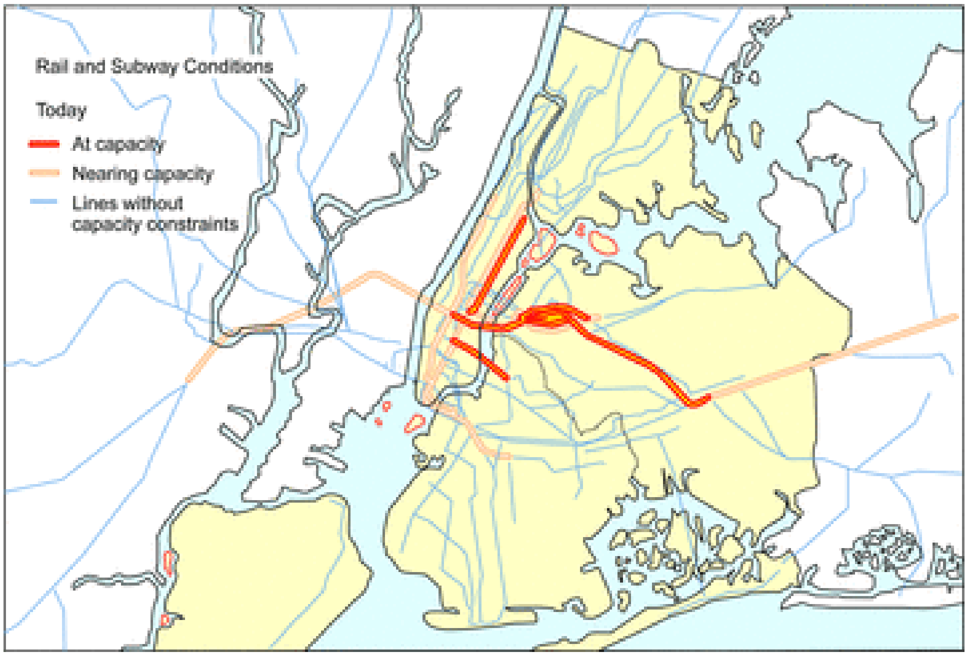
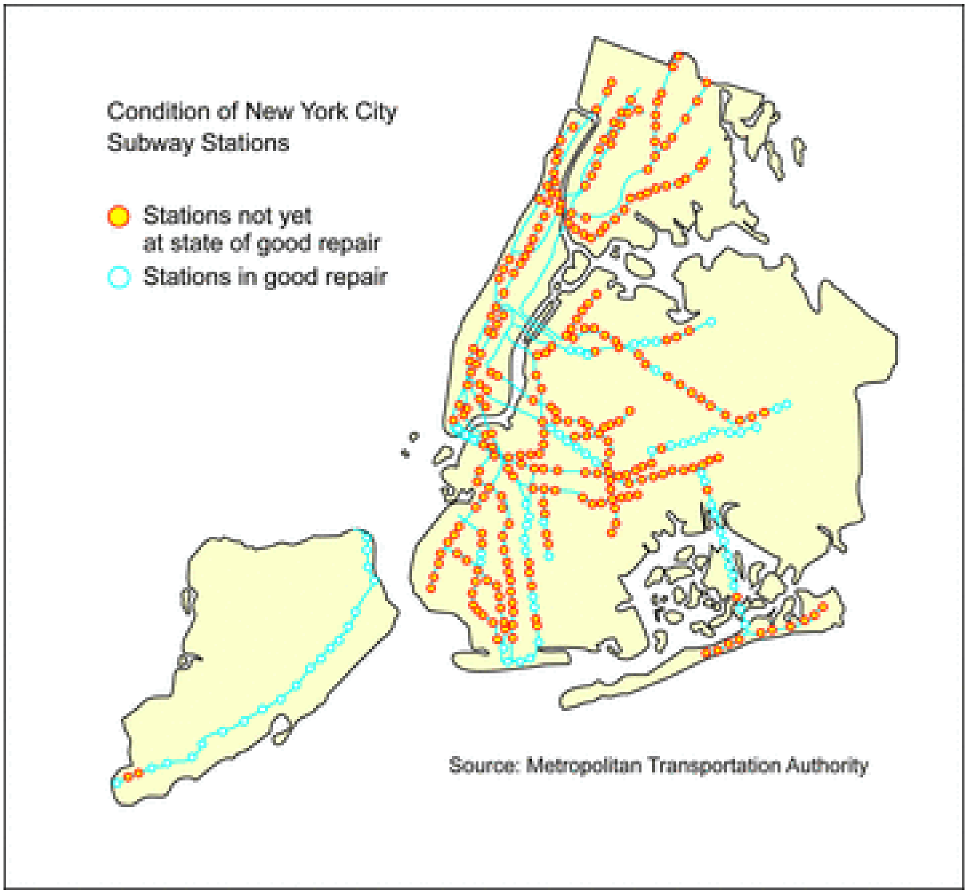


Figure 8. *Location and capacity constraints of New York City rail and subways. Sources: PlaNYC, 2007; NPCC, 2010*



Source: Metropolitan Transportation Authority

Figure 9. *Location and condition of New York City subway stations. Sources: PlaNYC, 2007; NPCC, 2010*

Water and waste. The New York City water supply system supplies about 1.1 billion gallons a day from a 1,972 square mile watershed that extends to 125 miles from the city's borders. The Catskill and Delaware watersheds provide 90% of this water.[9] This flow to the city travels through an extensive network consisting of aqueducts, dams, reservoirs, and distribution lines along with pumping and other support facilities. To capture the supply, for example, there are 4 reservoirs and an aqueduct in the Delaware system; 4 reservoirs, an aqueduct and a tunnel in the Catskill System; and 14 reservoirs including the Jerome and Central Park Reservoirs, three controlled lakes, and an aqueduct in the Croton System. The construction of a treatment plant for the Croton System is underway in the Bronx. The capital budget of the New York City Department of Environmental Protection over the next ten years is $20 billion (NYC DEP, 2008, p. 73).

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[9] NYC, Sustainable Stormwater Management, Main Report, 2008, p. 34.

Within the city's water distribution system there are two water tunnels and over 6,000 miles of water distribution pipe.[10] The city is planning to introduce redundancy into its in-city water supply distribution system and also improve the ability for system maintenance through the completion of a 60 mile-long water tunnel, Water Tunnel No. 3, in four stages.

The wastewater collection and distribution system consists of "6,600 miles of sewer, 130,000 catch basins, almost 100 pumping stations, and 14 water pollution control plants (WPCPs)" *(Figure 10).*[11] The wastewater treatment plants, by virtue of the way they are intended to operate with discharges to waterways, are primarily located along the City's shorelines, where the lowest elevations above sea level occur. During dry weather, the wastewater treatment plants are designed to fully treat one and a half times their design capacity and can partially treat about two times their design capacity. Where flows exceed that amount, for example, during wet weather conditions, water is discharged through the City's wastewater collection system – through combined sewer overflows (CSOs).

The City of New York currently "recycles or disposes of 15,500 tons per day (tpd) or 4, 000,000 tons per year (tpy) of DSNY-managed waste generated in the City generated by its curbside and containerized collection and recycling activity in FY2006.[12]" It transports most of the solid wastes that are not recycled outside of the City via marine transport stations for its treatment and/or ultimate disposal rather than relying on disposal sites within the City *(Figure 11).* In the past, New York City has used landfills within the City's borders for this purpose, but these have now been closed, since efforts to convert solid wastes into usable materials within the City have not succeeded.

Waste facilities sited in low-lying areas including closed landfills are also subject to flooding that could result in increased contamination of water bodies. If inundated by sea level rise, these facilities could create water quality problems, since many of them are located near shorelines and

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[10] *NYC, PlaNYC, 2007, pp. 63-65.*

[11] *New York City Department of Environmental Protection (2008) Climate Change Program. Assessment and Action Plan, May, p. 39. http://www.nyc.gov/html/dep/pdf/climate/climate_complete.pdf.*

[12] *New York City Department of Sanitation, Solid Waste Management Plan. September 2006, p. 1-2.*

relied on closure technologies that did not take into account the current knowledge around climate changes.

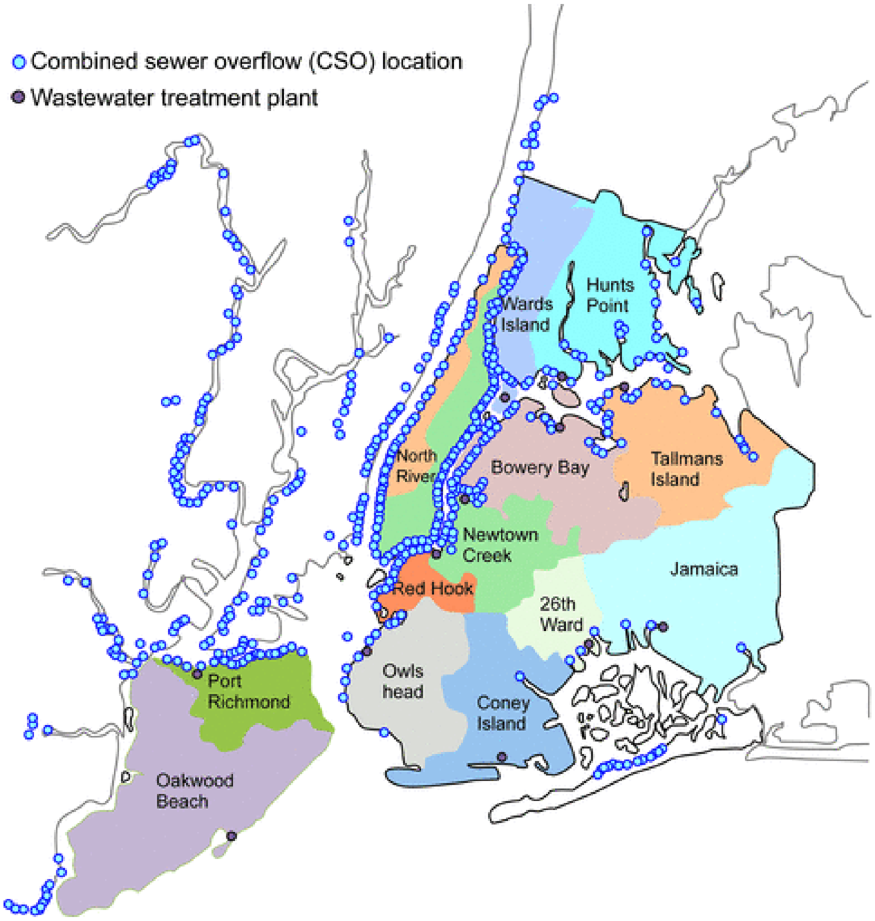

Figure 10. *Locations of Water Pollution Control Plants, CSO Outfalls, and Drainage Areas in the NYC area, 2008. Sources: PlaNYC, 2007; NPCC, 2010*

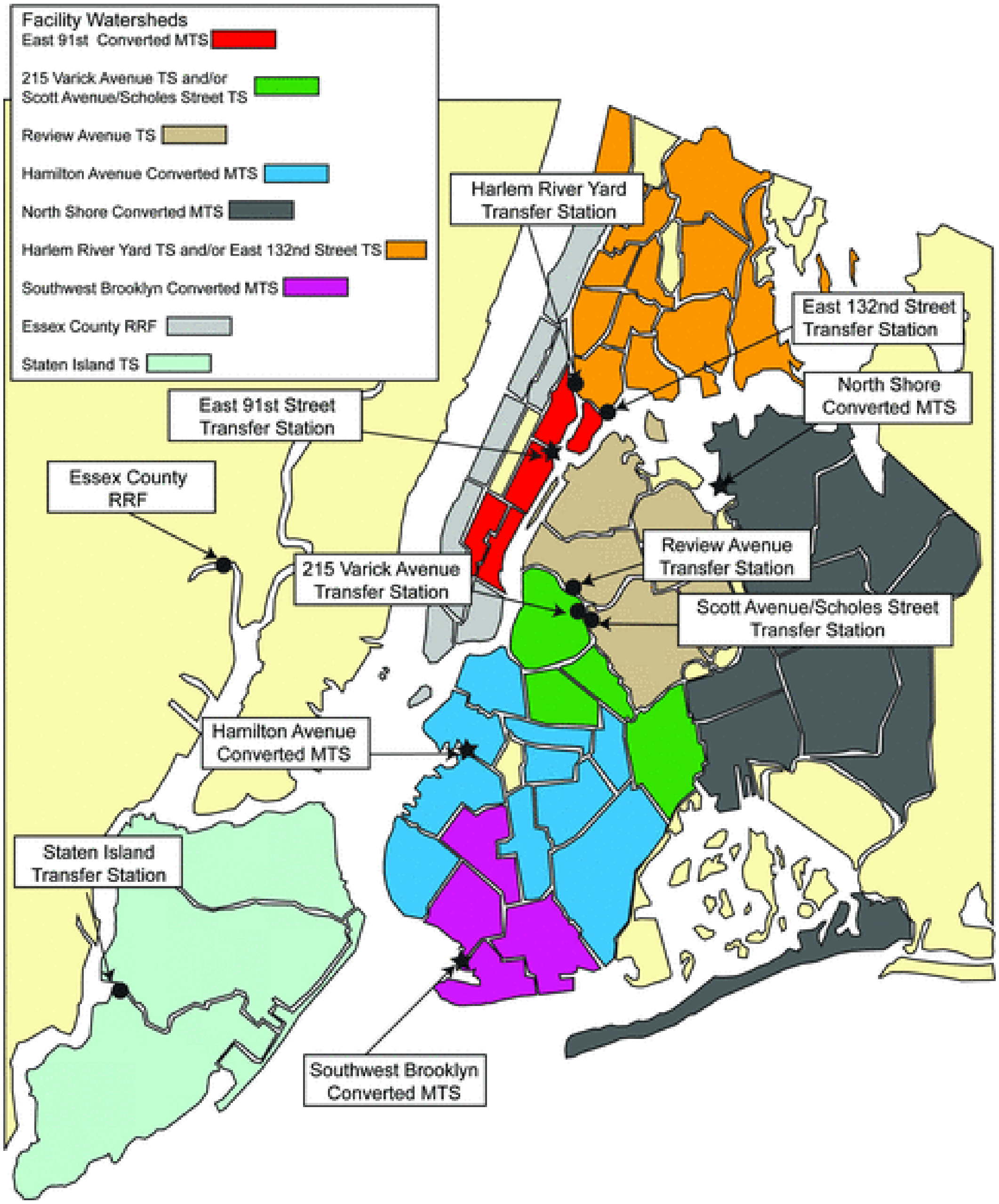

Figure 11. *Long-Term Export Facilities and Watersheds. Location of solid waste marine transfer stations. Source: NPCC, 2010*

Communications. The New York City communications infrastructure consists of a vast network of fixed structures to support communication and computing, consisting of voice lines, data circuits, fiber optic cable, switching stations, backbone structures, domain name servers, cell towers, satellites, computers, telephones (landlines), televisions, radios, and many more

(Zimmerman 2003b). Numerous private communications providers serve New York City including AT&T, Verizon, T-Mobile and many others.

Table 3. *Impacts of sea level rise, coastal floods, and storms on critical coastal infrastructure by sector. Sources: Horton and Rosenzweig, 2010; Zimmerman and Faris, 2010*

Communications	**Energy**	**Transportation**	**Water and Waste**
Higher average sea level			
• Increased salt water encroachment and damage to low-lying communications infrastructure not built to withstand saltwater exposure • Increased rates of coastal erosion and/or permanent inundation of low-lying areas, causing increased maintenance costs and shortened replacement cycles • Tower destruction or loss of function	• Increased rates of coastal erosion and/or permanent inundation of low-lying areas, threatening coastal power plants • Increased equipment damage from corrosive effects of salt water encroachment resulting in higher maintenance costs and shorter replacement cycles	• Increased salt water encroachment and damage to infrastructure not built to withstand saltwater exposure • Increased rates of coastal erosion and/or permanent inundation of low-lying areas, resulting in increased maintenance costs and shorter replacement cycles • Decrease clearance levels under bridges	• Increased salt water encroachment and damage to water and waste infrastructure not built to withstand saltwater exposure • Increased release of pollution and contaminant runoff from sewer systems, treatment plants, brownsfields and waste storage facilities • Permanent inundation of low-lying areas, wetlands, piers, and marine transfer stations • Increased salt water infiltration into distribution systems
More frequent and intense coastal flooding			
• Increased need for emergency management actions with high demand on communications infrastructure • Increased damage to communications equipment and infrastructure in low-lying areas	• Increased need for emergency management actions • Exacerbated flooding of low-lying power plants and equipment, as well as structural damage to infrastructure due to wave action • Increased use of energy to control floodwaters • Increased number and duration of local outages	• Increased need for emergency management actions • Exacerbated flooding of streets, subways, tunnel and bridge entrances, as well as structural damage to infrastructure due to wave action • Decreased levels of service from flooded roadways; increased	• Increased need for emergency management actions • Exacerbated street, basement and sewer flooding, leading to structural damage to infrastructure • Episodic inundation of low-lying areas, wetlands, piers, and marine transfer stations

	due to flooded and corroded equipment	hours of delay from congestion during street flooding episodes - Increased energy use for pumping	

Adaptation Strategies

Adaptation strategies can involve operations and management, investments in infrastructure, and policy solutions. Strategies can be at the sector or regional or citywide scales. Storm surge barriers, adaptive land management, coastal zone policies, and revised standards and regulations offer the potential for citywide protection against enhanced flooding associated with sea level rise. Effective adaptation measures can bring near-term benefits such as increased resource use efficiency.

Operations and Management

There is a great potential, at least in the near term, for adaptation measures related to current operations and management to deal with sea level rise and storms. For the transportation sector with assets and operations near the coast, adaptation strategies include improving pumping capacity and increasing backup emergency equipment so that service can be maintained during storms, while incorporating better storm information and forecasting can help managers prepare personnel and riders for events before and as they occur. For the water sector, which in New York City operates 14 wastewater pollution control plants (WPCPs) that discharge into the Estuary, adaptation strategies related to operations and management include repairing leaks in water supply pipes so that rising saltwater doesn't flow into the system and ensuring functioning of tidegates so that they maintain the gravity-driven outflows as efficiently as possible until sea levels rise beyond their elevations.

Investments in Infrastructure

Infrastructure adaptation strategies include both ‘hard’ and ‘soft’ measures.

Hard Measures In response to projected rates of sea-level rise, especially if rates follow the rapid icemelt scenario, existing hard structures in the New York City region will need to be strengthened and elevated over time (Gornitz, 2001). Shoreline armoring is typically applied where substantial assets are at risk. Hard structures in the New York City region include seawalls, groins, jetties, breakwaters, bulkheads, and piers. Seawalls and bulkheads, a common form of shore protection in the region, often intercept wave energy, increasing erosion at their bases, which eventually undermines them. Erosion can be reduced by placing rubble at the toe of the seawall. Groins, often built in series, intercept littoral sand moved by longshore current, but may enhance beach erosion further downdrift, if improperly placed. Similarly, jetties, designed to stabilize inlets or to protect harbors, may lead to erosion. Individually engineered solutions can also be achieved by raising individual structures and systems or critical system components to higher elevations (Jacob et al., 2001). This may be done without moving them to higher ground.

The Port Authority of New York and New Jersey at the La Guardia Airport has already surrounded the exposed structures with local sea-walls and dykes (Jacob et al., 2001). Specific measures described by the the New York City Department of Environmental Protection in their Assessment and Action Plan (NYCDEP, 2008) include raising elevations of key infrastructure components, constructing watertight containment for critical equipment and control rooms, using submersible pumps, augmenting reserves of backup emergency management equipment; and installing local protective barriers. The NYCDEP plans to consider estimates of the range of future sea and tide levels in sewer design and siting of outlets (NYCDEP, 2008).

Storm-surge Barriers One possible long-term ‘hard measure’ that has been suggested for New York City would be barriers designed to protect against high water levels, which would increase in height as sea-level rises (and possibly also through increasing intensity of storms) (Zimmerman and Faris, 2010; Aerts et al., 2009). Such barriers are in place in the Thames in London (UK Environment Agency, 2010) and Rotterdam (Aerts et al., 2009). The risk of future casualties and damage from hurricanes and nor’easters might be reduced by barriers placed across vulnerable openings to the sea. Each barrier would require large open navigation channels for ships and a porous cross section allowing sufficient tidal exchange and river discharge from New York Harbor to maintain ship passage and water quality *(Figure 12).*

Figure 12. *Conceptual Design of a Storm Surge Barrier in NYC. Source: Aerts et al., 2009*

At present, storm surge barriers are under discussion as a possible way to deal with the increasing risks of storm surge in New York City and the surrounding region in the era of climate change (Aerts et al., 2009), but they have not been accepted by the City government as a current response. Storm-surge barriers might be relevant as part of a long-term, staged response to rising sea levels and flooding, especially if rising sea levels and enhanced flooding proceed at the higher end of the projections. A key point is that those risks still need to be better characterized in regard to the efficacy of citywide measures. Such options, which would entail significant economic, environmental, and social costs, would require very extensive study before being regarded as appropriate for implementation, especially as alternative robust approaches to adaptation are available.

New York could protect against some levels of surge with a combination of local measures (such as flood walls and reclaimed natural barriers), improved storm information and forecasting to help managers of power plants, airports and stations, and wastewater treatment plants to prepare for extreme events before they occur, and evacuation plans for at least the next several decades. Moreover, barriers would not protect all neighborhoods, nor would they protect against other substantial damages from wind and rain that often accompany hurricanes in the New York City region. The surge barrier concept outlined here would at most protect part but not all of NYC (e.g., Queens and Brooklyn) and possibly adjacent parts of New Jersey. Environmental effects on the estuary would also need to be studied in detail.

Soft Measures Because the New York City coastline has extensive beaches and coastal wetlands as well as built-up areas, and because erosion problems often associated with hard structures along the coast, 'softer' approaches involving wetland and dune restoration and beach nourishment have emerged as a viable method of shoreline protection, where possible. Beaches, including Coney Island, Brighton Beach, and the Far Rockaways, are maintained for public recreational use, while the Gateway National Recreation Area is an important nature reserve and bird migration stopover site. Beach nourishment or restoration consists of placing sand that has usually been dredged from offshore or other locations onto the upper part of the beach. Beach nourishment needs to be repeated over time since the erosional processes at work are continual. Under sea level rise and associated enhanced coastal flooding, beaches will require additional sand replenishment to be maintained (Gornitz, 2001).

Another 'soft' approach is to enhance and expand the Staten Island Bluebelt (NYCDEP, 2008) *(Figure 13).* The Bluebelt is a stormwater mangement system covering about one third of the island. The program preserves natural drainage corridors, including streams, ponds, and other wetland areas. By preserving these wetlands, they are able to perform ecosystem functions of conveying, storing, and filtering stormwater, while providing open space and diverse wildlife habitats.

Figure 13. *Staten Island Bluebelt Source: NYCDEP, 2008*

Policy Solutions

Adaptive land use management and changes in zoning, design standards, and regulations are mechanisms by which coastal zone adaptation can proceed through policies. (Titus, 1998; Titus et al., 2009) categorized policy options for dealing with sea level rise as ‘protect, retreat, or abandon.’ Adaptive Land Use Management could involve the development of erosion/flood setbacks; limiting new high-density construction in high hazard zones; and rezoning for low density and recreation uses. Creative land use, as is being considered in Rotterdam, could raise buildings on stilts, use ground floors for communal activities and parking, and design parks or open green spaces as water-absorbing areas.

Potential adaptations related to land use management being considered by The NYCDEP include developing plans allowing for coastal inundation in defined areas; strengthen building codes for construction of more «storm-proof» buildings (with the caveat that the public needs to know that no building can be made ‘fail-safe’ indefinitely); and gradually retreating from the most at-risk areas or using these areas differently, such as for parkland that could provide food with minimal damage (there are some community gardens in parks that provide food today) (NYCDEP, 2008). This could entail obtaining vacant coastal land to act as buffers against flooding and storm damage, and/or to allow for inland migration of coastal wetlands. At the time of this article, these continue to be ‘potential’ adaptation strategies.

To effectively adapt to climate change laws and regulations, as well as some basic legal frameworks that govern infrastructure, must also adapt[13]. Sussman and Major et al. (2010) consider the potential for zoning changes, and limiting or even curtailing new construction in high hazard zones. They examined a wide range of current environmental laws and regulations at all levels relevant to New York City to determine their applicability to adaptation efforts. Laws applicable to New York City are enacted by legislative bodies, the U.S. Congress, the New York State Legislature and the New York City Council. Regulations are issued by governmental agencies or authorities which often having the force of law and may be issued in many forms including rules, orders, procedures and administrative codes *(Table 4).*

Table 4. *Examples of Laws, Regulations and Standards relevant to land use in the New York City region Source: Sussman and Major et al., 2010*[14]

Sector	Sources of law and regulation	Jurisdiction	Examples	
Land Use	Law	Federal	National Environmental Policy Act (NEPA)	US Congress
	Law	State	NYS Environmental Quality Review Act (SEQRA)	NYS legislature
	Regulation	State	DEC SEQRA Regulations	NYS Department of Environmental Conservation
	Law and regulation	Local	City Environmental Quality Review (CEQR)	NYC Office of Environmental Coordination
	Law	Local	NYC Zoning Resolution	NYC Council

Sussman and Major et al. (2010) analyzed law and regulation related to land use—a body of law and regulation that determines much of the how, where and what of the built environment and can significantly influence the degree of vulnerability of infrastructure. Legal avenues can foster adaptation by reducing vulnerability, increasing resilience, enabling effective preparation for disasters and increasing capacity to respond to disasters. They suggested a broad range of policies that can strengthen adaptation in the coastal zones of the New York City region. These include: a mandate for evacuation plans that focus on surface mass transit in flood-prone areas;

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[13] Laws applicable to New York City are enacted by legislative bodies, the U.S. Congress, the New York State Legislature and the New York City Council. Regulations, as the term is used in this paper, are issued by governmental agencies or authorities which often having the force of law and may be issued in many forms including rules, orders, procedures and administrative codes.

[14] There are thousands of relevant laws, regulations, standards and policies. This table is only intended to illustrate the multiplicity and multi-jurisdictional nature of the relevant legal provisions.

stricter rules for variances inconsistent with adaptation goals; zoning and special permitting could include a finding discussing how adaptation to climate change is being addressed in that project; regularly updated information on precipitation, flooding and stormwater to guide the planners' decisions; incorporation into zoning best practices for on-site stormwater management; as is already planned by New York City, all new developments and enlargements can be required to have a program for on-site stormwater retention; restriction of the use of the basement and ground floor space, and guidelines for the location of generation, mechanical and safety equipment in flood-prone districts; barring of certain uses of vulnerable populations (such as nursing homes) from lower floors; zoning revisions requiring on-site evacuation plans and equipment; legislation for a comprehensive "bluebelt program" such as Staten Island's Bluebelt program, for other suitable areas within the city limits; revised coastal plans that take into account climate change-related coastal flooding; modified zoning rules for a systematic retreat from vulnerable areas, to allow for migration of beaches, and fostering natural wetlands in undeveloped coastal areas; rolling easements to prevent property owners from holding back the sea but otherwise do not alter what they can do with the property; an expanded coastal property assessment form; and revision of the Technical Guidance for the city, the DEC, and the CEQR Technical manuals to include climate change impacts upon the proposed project or action under consideration.

Case Study: New York City 1-in-100-year Flood Zone Levels

Climate protection levels (CPLs) were defined by the NPCC as socially-determined measures to protect critical infrastructure, particularly assets that are determined to be at risk to climate change (Solecki et al., 2010). CPL measures are achieved through the application of design and performance standards to which the infrastructure are managed and built in order to ensure that these infrastructure elements remain viable and operational under specified conditions.

The NPCC identified key existing design and/or performance standards relevant to critical infrastructure in the New York City region; reviewed these standards in light of the climate change projections, and highlighted those standards that may be compromised by climate change or need further study to determine whether Climate Protection Levels are necessary to facilitate climate resiliency. The single most significant CPL recommendation for coastal flooding and sea level rise is for FEMA to update the Flood Insurance Rate Maps (FIRMs) to incorporate into the current 1-in-100 year flood zone projections of rapid ice melt sea level rise through the 2080s as an upper bound.

The primary design and performance standard for coastal flooding and storm surge is the Federal Emergency Management Agency (FEMA) defined 1-in-100 year flood, also known as the 1% flood. The 1-in-100 yr flood is defined as a flood that has a 1% chance of being equaled or exceeded in any given year. For nearly 40 years, the 1-in-100 year flood zone has been considered a high risk flooding area and subject to special building codes, and insurance and environmental regulations (ASFPM, 2004)

The Federal Emergency Management Agency (FEMA) is responsible for creating and maintaining Flood Insurance Rate Maps (FIRMs) that delineate the 1-in-100 year flood zone for all communities that participate in the National Flood Insurance Program (LeBlanc and Linkin, 2010). The 1-in-100 year flood zone, also known as the Special Flood Hazard Area (SFHA), is identified on these maps as well as site-specific base flood elevations (BFEs), also known as the 100-year flood elevation. These maps are used by federal agencies to determine if flood insurance is required when banks provide federally insured loans or grants towards new construction that is located within this zone. In New York State, compliance with the National Flood Insurance Program is mandatory for all flood-prone jurisdictions. To participate in the NFIP, a community agrees to adopt and submit flood plain management regulations that meet or exceed the minimum federal floodplain management requirements. . 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). State and federal requirements manifest as zoning and subdivision ordinance, building requirements, sanitary regulations, and special-purpose floodplain ordinances, and are specified for each community based on the flood hazard data provided by FEMA (FEMA, 2005).

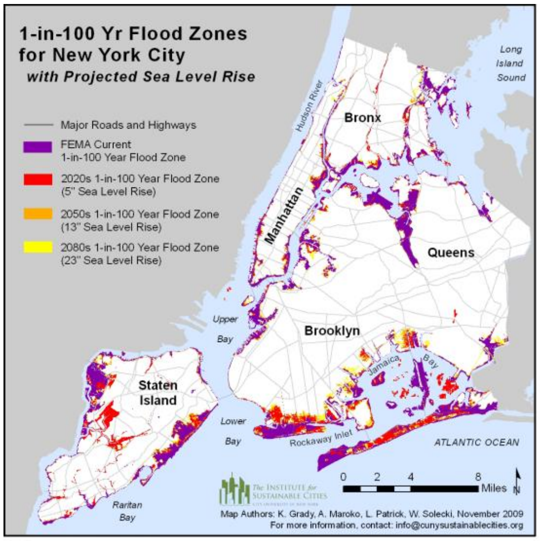
Development activity within the FEMA 1-in-100 year flood zone is subject to special permitting procedures due to the high flood risk. The 1-in-100 year flood zone for New York City is based on peak stormwater discharge flow rates defined by NYSDEC extreme flood control criteria.

Figures 14 and 15 illustrate the potential impact of sea level rise on current FEMA 1-in-100 year flood zone and the projected 1-in-100 year flood zone, based on the IPCC-derived and rapid icemelt methods (see above). The projected 1-in-100 year flood zone was created by adding projected SLR elevations to the FEMA 1-in-100 year base flood elevations to generate new base flood elevations for a storm of equal magnitude in the 2080s. These projections add 23 inches of SLR (method 1) and 53 inches of SLR (method 2) to the existing 1-in-100 year FEMA base flood elevations.

The maps illustrate ever-expanding areas of flooding associated with increased amounts of sea level rise; however it should be noted that they also include limitations of modeling, GIS mapping, and data source that should be considered upon interpretation. For example, the FEMA 1-in-100 year floodplain for New York City was modeled over 25 years ago and has yet to be revised. Many of the modeling methods FEMA originally used have since been replaced and supplemented with more modern techniques that account for processes such as wave setup and erosion. In addition, a huge assumption and source of error that all methodologies use is that FEMA's base flood elevations roughly equate to topographic elevation. They do not, yet this is a major approximation we have to use in order to translate between flood elevations and topographic elevations. Finally, the vertical accuracy of the digital elevation model used as the foundation of this map was in some cases less than the elevation intervals being mapped, resulting in wide margins of vertical error. Therefore while the maps do not reflect specific locations of flooding, they do illustrate areas currently outside the 1-in-100 year flood zone likely to be included within it in the future.

After concerted expert deliberation, the NPCC decided that the 90th percentile of rapid ice-melt sea level rise elevation should be adopted as the climate protection level for the city. This corresponds roughly to 4 ft of sea level rise for the region. The NPCC did not make this a formal recommendation because further study and a more comprehensive social process are needed for such a formal statement to be made. The NPCC chose this level because using the 90th percentile of sea level rise elevation based on the rapid ice melt scenario in the 2080s as an upper bound provides a very high probability that critical infrastructure will be protected with respect to 90% of the possible range of future climate risk defined under the model-based probability curve. Furthermore, should sea level rise prove lower by the 2080s, the CPL would provide a buffer for rare but larger storm surges than those defined by the 1-in-100 year flood. Should sea level rise be lower than the CPL, and the 1-in-100 year flood prove lower than the currently defined 1-in-100 year flood, the CPL can be thought of as providing: 1) protection for sea level rise beyond the 2080s, and 2) protection against low probability yet high consequence storms up until the time when sea level rise exceeds the CPL.

Figure 15 in particular highlights the dramatic landward progression of the 1-in-100 year flood zone, specifically in the Greater Jamaica Bay area of Brooklyn and Queens, under a rapid ice melt regime in the 2080s. The implications of including this update on future sea level trends would be far reaching, highlighting new communities for potential inclusion in the National Flood Insurance Program (NFIP) and changing the extent and base flood elevations of the New York City Flood Insurance Rate Maps.



*Note.*This map is subject to limitations in accuracy as a result of the quantitative models, datasets, and methodology used in its development. The map and data should not be used to assess actual coastal hazards, insurance requirements, or property values or be used in lieu of Flood Insurance Rate Maps issued by FEMA.

Interpretation. The floodplains delineated above in no way represent precise flood boundaries but rather illustrate three distinct areas of interest: 1) areas currently subject to the 1-in-100 year flood that will continue to be subject to flooding in the future, 2) areas that do not currently flood but are expected to potentially experience the 1-in-100 year flood in the future, and 3) areas that do not currently flood and are unlikely to do so in the timeline of the climate projection scenarios used in this research (end of the current century).

Figure 14. *Citywide 1-in-100 year flood projections for the 2080s for IPCC-based sea level rise of 22.8 inches. Source: Solecki et al., 2010.*

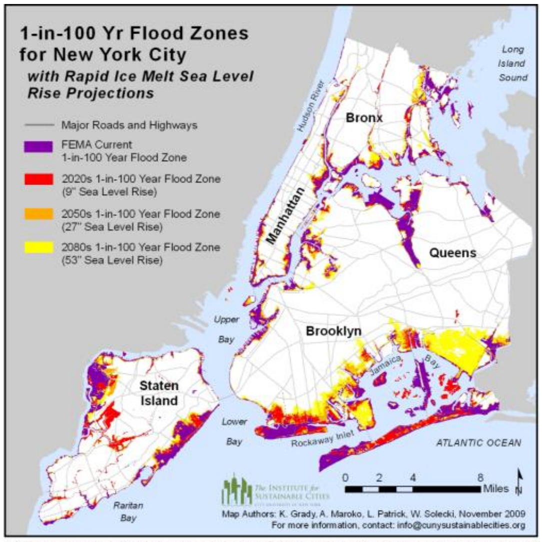


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Figure 15. *Citywide 1-in-100 year flood projections for the 2080s for 'Rapid Ice-Melt' sea level rise scenario of 53.0 inches. Source: Solecki et al., 2010.*

The NPCC specifically encourages the updating of the 1-in-100 year flood zone to reflect rapid ice melt sea level rise. More generally, it also encourages that other design standards be examined so they can transition into benchmark CPLs by incorporating emerging projections of climate risk thus allowing for the maintenance of current protection levels for the region's critical infrastructure under future climate regimes. Stakeholders need to work together to establish a process by which the region periodically updates the NYC 1-in-100 year flood zone to reflect emerging climate change hazards and risks.

Indicators and Monitoring

A key recommendation of the NPCC is that climate change, impacts and adaptation strategies should be regularly monitored and reassessed as part of any climate change adaptation strategy (Jacob and Blake, 2010). These should be done taking into account changes in climate science, impacts, and adaptation strategies, as well as other factors such as population growth rates and technological advancements that will also influence infrastructure in the region.

In order to successfully monitor future climate and climate impacts related to developing New York City's coastal adaptation strategy, specific indicators to be tracked must be identified in advance. These indicators are of two types. First, climate indicators such as global and regional sea level rise, can provide an indication of whether climate changes are occurring outside the projected range.[15] Given the large uncertainties in climate projections, monitoring of climate indicators can play a critical role in refining future projections and reducing uncertainties. Second, climate-related coastal impact indicators provide a way to identify consequences of sea level rise and enhanced coastal flooding as they emerge. For example, transportation disruption is a climate-related impact of coastal storms.

Sea level rise and coastal flood-related indicators include mean sea level, high water levels, and extreme wind events. Additional larger-scale climate indicators should include tropical storms over the entire North Atlantic basin, as well as climatic conditions (including upper ocean temperatures) that support tropical cyclones and variability patterns that influence the region, such as the North Atlantic Oscillation (NAO) and the El Niño Southern Oscillation (ENSO). The

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later indicators are needed not only to improve global and regional climate models, but to provide perspective on changes in regional weather if and as they occur.

The possibility of rapid climate change in general, and sea level rise in particular, are two areas where the importance of monitoring and reassessment has been well documented. Indicators of rapid ice melt to monitor could include, but should not be limited to the status of the ice sheets; the changes in sea ice area and volume; global and regional sea level; and polar upper-ocean temperatures. Climate variables cause certain climate-related impacts, which will also need to be monitored. These impacts include shoreline erosion and biological and chemical composition of coastal waters.

Infrastructure can be impacted either directly by a climate risk factor (such as sea level rise) or by a climate-related impact (such as shoreline erosion). Infrastructure-specific impacts which may result from these climate indicators or climate-related impacts are likely to include but are not limited to: infrastructure damage from climate-related factors; impacts on operations, including transportation delays; communications disruptions; combined sewer overflow events (CSOs); and coastal storm-related power outages.

In addition to monitoring climate and impacts, advances in scientific understanding, technology and adaptation strategies should also be monitored. Technological advances, such as those in materials science and engineering, could influence design and planning, and potentially result in cost savings.

Monitoring adaptation plans in the region should be done both to determine if they are meeting their intended objectives and to discern any unforeseen consequences of the adaptation strategies. The NYC Office of Long-term Planning and Sustainability has been playing a coordinating role and could usefully continue to ensure that the objectives and strategies of separate plans or adaptation efforts of the 40 organizations involved in the New York City Climate Change Task Force are consistent with, and not contradictory to, each other. Some adaptation strategies will also have to be reassessed in the context of non-climatic factors that are themselves based on uncertain projections. For example, by monitoring trends in population, economic growth, technology, and material costs, infrastructure managers can tailor future climate change adaptation strategies to ensure they remain consistent with broader citywide objectives. Monitoring and reassessment of climate science, technology and adaptation strategies will no doubt reveal additional indicators to track in the future.

One potential pitfall of monitoring over short timescales, especially for small regions, is that it is easy to mistake natural variability for a long-term trend. Creating an effective climate-monitoring program is a long-term commitment, and requires different methods over a much longer timescale than more common short-term monitoring efforts. The NPCC has recommended that such a monitoring program be established and maintained. To accomplish this, it could be useful for federal and local partnerships to be established such as between New York City and NOAA's RISA, Regional Climate Centers, and nascent Climate Services programs.

Adaptation Outcomes and Moving Forward

There is at least one specific adaptation outcome that has already emerged from the work of the Task Force and the NPCC. The NYC Department of Environmental Protection (NYC DEP) is raising the pumps and electrical equipment in its Far Rockaway Wastewater Treatment Plant from below sea level to 14ft above sea level based on the NPCC projections (NYC Office of the Mayor, 2009). The NYC DEP has also commissioned an in-depth analysis of how climate change would affect its upstate watersheds, utilizing detailed hydrologic reservoir and planning models (NYCDEP, 2008).

More generally, the Task Force is preparing a report that sets forth its approach to building a 'climate-resilient' city, a concept that they are embracing because they believe that it sends a useful signal to the citizens of the region that the impacts of climate hazards will not necessarily be avoided but that the city as a whole will be working to improve its ability to respond.

For the long term, New York City Local Law 17 of 2008 (City of New York, 2008) establishes an ongoing sustainability effort that will continue in subsequent administrations. Responding to climate change in regard to both mitigation and adaptation is an integral part of PlaNYC. The expectation is that climate change adaptation in the New York City will proceed in an effective way based on the process, approach, and tools described in this paper.

Conclusions

As demonstrated by the interactions of climate change and the New York City region, climate change presents significant challenges for coastal cities throughout the world. Coastal cities face a specific set of challenges that require a unique set of adaptation strategies due to their concentration of people and critical infrastructure in low-lying coastal zones, inability to easily shift locales, overlapping regulatory jurisdictions, and especially the variety and complexity of infrastructure and the population's dependence on it. While specifically designed for New York City, the comprehensive approaches, methods, and tools developed here can be modified and applied to many urban areas both coastal and non-coastal. These approaches, methods, and tools include a multi-jurisdictional stakeholder-scientist process, state-of-the-art scientific projections and mapping, and development of a range of types of adaptation strategies based on an overarching risk-management approach.

Although climate change will exacerbate existing urban challenges and environmental stressors, it also provides an opportunity for cities by encouraging infrastructure investments and improving urban planning and regulation. While most U.S. cities are struggling to finance the existing investments in infrastructure required in the absence of consideration of climate change, climate change adaptation can provide additional incentives for funding from local, state, and federal sources. If cities respond wisely, they will create better climate management for their citizens and for the infrastructure that enables their comfort and movement. Effective adaptation measures can also bring near-term benefits such as improved efficiency and reduced emergency costs, through, for example increased subway station pumping capacity, better-functioning water supply pipes and tidegates, and greater backup emergency equipment supplies.

Building on the work of the NPCC and efforts by other researchers, the First Assessment Report on Climate Change in Cities (ARC3) was launched by the Urban Climate Change Research Network (UCCRN) in November 2008 with the goal of building the scientific basis for city action in both the mitigation of and adaptation to climate change. The first ARC3 report is due out in 2010. Cities can thus share ‘best practices’ on climate change adaptation throughout the world.

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