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New York City Panel on Climate Change 2019 Report Chapter 7: Resilience Strategies for Critical Infrastructures and Their Interdependencies

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7.1 Introduction

Climate change poses many challenges to infrastructure in New York City. This chapter builds upon the work on climate change and critical infrastructure systems presented in the first and second New York Panel on Climate Change (NPCC) reports (NPCC, 2010, 2015), and provides new directions, updates, and considerations. Key concepts and definitions for resilience and vulnerability are found in Box 7.1. NPCC (2010) covered infrastructure by inventorying selected New York City facilities and their vulnerability to climate change. Vulnerabilities were described primarily in terms of outages and other disruptions, and covered a wide range of climate hazards, with a particular focus on exposure to sea level rise. NPCC2 (2015) did not have a separate chapter titled infrastructure, and infrastructure dimensions were distributed throughout the report.

In addition to building upon the previous work of the NPCC, many other New York City efforts are integrated in this chapter and others such as *PlaNYC* (City of New York, 2013), *OneNYC* (City of New York, 2015), the *1.5 Celsius Aligning NYC with the Paris Climate Agreement* report (City of New York, September, 2017), the NYC Mayor's Office of Recovery & Resiliency *Climate Resiliency Design Guidelines* (NYC Mayor's ORR, April 2018) summarized in Box 7.2, and the NYC Office of the Mayor *Mayor's Management Report* (2017, 2018). New York State reports particularly following Hurricane Sandy (e.g., NYS, 2013) and U.S. Department of Homeland Security (DHS) reports (U.S. DHS, 2013, 2015) are also key sources.

The goals of this chapter on critical infrastructures are to:

- Place climate change challenges in the context of current infrastructure usage and condition in New York City as these characteristics contribute to infrastructure vulnerability
- Provide insights on dependency and interdependency among NYC's infrastructure systems
- Present case studies of how infrastructure and climate change intersect at the community level
- Explore insurance and finance issues related to infrastructure resiliency in the face of climate change

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Box 7.1. Resilience and vulnerability in the context of infrastructure

Resilience: Resilience is a core concept throughout the infrastructure and climate change theme. Resilience generally refers to the ability of systems, whether networked, interdependent, or independent, to return to some state after experiencing a disturbance and/or adopting processes that promote those readjustments. That state can either be the state prior to the disturbance or to a different state that can resist adverse effects of disturbances (Vale, 2014), resist change altogether, or prepare, respond, and recover from disturbances (NYC Mayor's Office of Recovery and Resiliency (ORR) 2018 Climate Resiliency Design Guidelines; City of New York, 2013). Resilience is often associated with vulnerability.

Vulnerability: A review of the concept of vulnerability by Adger (2006: 268) defined vulnerability in the context of changing conditions or threats as "the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt" referencing both processes and outcomes. For infrastructure, aspects of vulnerability emphasized in this chapter are: its initial condition and its usage relative to its capacity, both of which influence the extent to which infrastructure is exposed to a threat and can resist or adapt to it maintaining at least its initial functions (Gallopín, 2006; Farmani and Butler, 2013; Zimmerman, 2016).

- Link resiliency to mitigation of greenhouse gas (GHG) emissions as well as to adaptation

This chapter focuses on infrastructure categories, typically referred to as "lifelines," for example, energy, transportation, telecommunications, water, and waste and sewers, that are considered "essential to the operation of most critical infrastructure sectors" (U.S. DHS, 2013: 17) and social infrastructure. Dependencies and interdependencies among infrastructures are another dimension addressed in addition to the individual sectors, and are defined in Box 7.3.

Selected infrastructure properties that create potential vulnerabilities for infrastructure in the context of climate change are described in Box 7.4.

This chapter on critical infrastructures is closely linked to Chapter 8, Indicators and Monitoring, and provides additional detailed references for that chapter. This chapter sets forth vulnerabilities of the critical infrastructure systems in New York City to key climate extremes, and Chapter 8 describes how to track those vulnerabilities and proposes the creation of the New York Climate Resiliency Indicators and Monitoring System to do so.

In Section 7.2, infrastructure issues are examined with regard to the climate variables that are described in Chapters 2–4: (1) extreme heat, (2) cold snaps, (3) heavy downpours, (4) drought, (5) sea level rise and coastal flooding, and (6) extreme winds. This list of variables updates those that were identified in NPCC1 (NPCC, 2010). The impacts identified in this chapter provide the basis for and are directly linked to the infrastructure indicators and metrics in Chapter 8. In Section 7.3, key infrastructure vulnerabilities are addressed, first for individual infrastructures, with and without

Box 7.2. NYC design guidelines for climate resiliency

NYC Climate Resiliency Design Guidelines: In April 2017, the NYC Mayor's ORR released a draft of its "Climate Resiliency Design Guidelines," which was finalized in 2018 (NYC Mayor's ORR, 2018). The Guidelines' purpose is to provide guidance on "how to use the range of climate projections in design" in order to promote resilience (NYC Mayor's ORR, 2018: 5) across the useful life of a facility in light of three climate elements: heat, precipitation, and sea level rise. The Guidelines indicate the need to coordinate with other guidance in connection with special funding and other requirements and considerations (NYC Mayor's ORR, 2018). Procedures are provided to select climate data, analyze risk, consider uncertainty, conduct sensitivity analyses, and identify and analyze design-related interventions depending on what the particular facility is, its useful life, and where it is located.

Box 7.3. Infrastructure dependencies and interdependencies

The concept of dependencies and interdependencies among infrastructure sectors and between infrastructure and the economy and society was identified by Rinaldi *et al.* (2001), expanded in subsequent literature, and has increasingly been drawing the attention of infrastructure managers, infrastructure finance organizations, and disaster management agencies. Infrastructure interdependencies may not always have appeared to be a direct component of climate-related infrastructure concerns; however, the focus on interdependencies is emerging in the examples, scenarios, and guidelines being used to connect climate and infrastructure.

According to Rinaldi *et al.* (2001), dependencies refer to a one-way relationship where one type of infrastructure depends on another but the reverse does not occur. Interdependencies connote at least a bi-directional relationship and can have a more complex structure when numerous infrastructure systems are involved. These concepts have since been carried forward into policy and planning documents, for example, into the sector-specific plans developed by the U.S. DHS for infrastructure (U.S. DHS, 2013; U.S. DHS, 2015). These documents and subsequent work have articulated various types of such interconnections involving, for example, spatial proximity, functional dependency, and information control, and the interconnections have formal properties that involve flows of people, goods, and information applicable to many infrastructure sectors (Rinaldi *et al.*, 2001; U.S. DHS, 2015). These different types of interdependencies often occur simultaneously.

The effects of these interconnections on system operations include what happens system-wide when a particular node (infrastructure component) or link (infrastructure route) upon which other systems rely becomes disabled. This partially explains why extreme events are a useful perspective for identifying infrastructure vulnerabilities. Metrics exist to characterize these relationships (which are addressed in Chapter 8: Indicators and Monitoring). Concepts and models for interdependencies have been developed and applied across a number of lifeline sectors, potentially applicable to climate change (Zimmerman *et al.*, 2016, 2017, 2018; Zimmerman *et al.*, 2017 and numerous references therein).

Interdependencies have typically started with electric power, since it is used by practically all sectors either directly or indirectly, and electric power in turn relies on those other sectors. Electricity is used by the transportation sector for road-based systems to power lights, signals, and fuel pumps, and for rail-based systems to power signals, switches, and third rails and catenary lines to power trains (Zimmerman and Restrepo, 2009). Energy is vital to the water sector for the operation of pumps for those portions of the water supply system not operating by gravity and for intermittent pumping operations to dewater equipment that is flooded. Transportation in turn enables workers and supplies to be transported to facilities and services that are critical components of electric power and other infrastructures. Water is needed for power production and other processing functions, where they occur, as well as providing water for worker consumption. Telecommunications connect with all critical infrastructures for purposes of detecting system states and anomalies, controlling and managing infrastructure systems, and communication of information to deploy resources, and in turn relies on other infrastructure, particularly electric power, to function.

climate change in Sections 7.3.1 and 7.3.2 and then for infrastructure dependencies and interdependencies with and without climate change, respectively, in Sections 7.3.3 and 7.3.4.

In Section 7.4, social infrastructure and related community issues are presented for two case studies that illustrate how infrastructure interfaces with communities, providing a model or benchmark for other cases. New finance and insurance mechanisms that have emerged to reduce vulnerability are introduced in Section 7.5. Section 7.6 briefly links infrastructure strategies to mitigation. In Section 7.7, conclusions and recommendations are presented that synthesize some of the major findings and suggest new directions.

Appendices present background information for selected New York City infrastructure sectors (Appendix 7.A), a compendium of adaptation measures (Appendix 7.B), acknowledging the need to balance risk, cost, and uncertainty in implementation decisions, and the progress toward NYC's commitment to reduce GHG emissions 80% by 2050 (Appendix 7.C). The section on adaptation reflects part of a trend toward innovative urban transformation emerging as a new direction for infrastructure adaptation (Solecki *et al.*, 2018).

Box 7.4. Selected infrastructure properties

Condition: The condition of infrastructure is assessed in many different ways, often constructed relative to or against needs and performance, and these dimensions of condition are interpreted or defined in many different ways depending on purpose, organizational mandates, and jurisdictions. For New York City, these are contained, for example, in the City of New York annual *Mayor's Management Report* (NYC Office of the Mayor, 2017, 2018), the *OneNYC* plan (City of New York, 2015), the National Academy of Sciences (2016) report that contained a New York City section, and other sector-specific documents. The American Society of Civil Engineers (ASCE) (2017) report card presented a number of measures for several of the city's infrastructure systems that reflect some potentially weakened conditions that could make parts of the system less resilient to the effects of climate change. Traditional condition measures, however, have not necessarily been linked directly to climate change, and Chapter 8: Indicators and Monitoring identifies some of the relationships that do exist. To make these linkages, inferences are required from underlying knowledge of conditions that potentially undermine the ability of infrastructure to withstand disruptions.
Usage: Usages of infrastructures or consumption of infrastructure services varies considerably depending on the type of infrastructure. Generically, they can be in the form of rates of use, temporal patterns of use, and purpose of use. Most significant, regardless of how usage is measured, is the ratio or comparison of infrastructure usage to capacity, where capacity information is available, since it reflects potential impacts of new stresses on infrastructure designed and managed for different tolerances.

Stakeholder engagement processes

Different forms of stakeholder engagement were undertaken to provide inputs to this chapter. This overlapped to some extent with the stakeholder engagement process for the Indicators and Monitoring Workgroup, since that chapter also focused on infrastructure.

One mechanism for stakeholder engagement was the New York City Climate Change Adaptation Task Force (CCATF). The city convened numerous city agencies and other organizations that oversee infrastructure through this venue covering the five lifeline infrastructure sectors in this report. A number of meetings in particular of the entire CCATF were attended by one or more of the coauthors of this chapter. These meetings were held on July 27, 2016, June 29, 2017, December 19, 2017, and July 26, 2018. Moreover, there were infrastructure-specific meetings, for example, several meetings of the CCATF Transportation Working Group that a representative of the infrastructure chapter attended.

In addition, members of the infrastructure chapter participated in a roundtable organized by the Indicators and Monitoring Workgroup on March 9, 2016 that consisted of a number of city infrastructure agencies. A member of the infrastructure chapter team met routinely with members of the Indicators and Monitoring Workgroup and participated in their ongoing meetings with a couple of city agencies. Details of this process are described in Chapter 8, Indicators and Monitoring.

Another mechanism consisted of informal engagement of members of infrastructure managers for specific portions of the work. The insurance and finance section authors, for example, took advantage of contacts with organizations relevant to that work. The staff of the NYC Mayor's Office of Recovery and Resiliency (ORR) provided important inputs on specific aspects of this chapter. Finally, informal contacts proved to be very valuable through venues such as professional society conferences and meetings (e.g., the ASCE) which afforded the opportunity not only to obtain information through formal presentations but as a basis for informal exchanges as well.

7.2 New York's critical infrastructure systems and updates from NPCC1

The New York City "infrastructure-shed" extends well beyond the borders of the city's approximately 300 square mile area. The term "infrastructure-shed" has been used in the context of climate change by Rosenzweig *et al.* (2011) referring to the scope of the 2010 NPCC (2010). The city both affects and is affected by the region beyond its borders. This is particularly true of its infrastructure.

Critical infrastructure is defined by the New York City CCATF and the NYC Panel on Climate Change 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, 2009:8, footnote 3)

The NPCC3 analyzes five key lifeline sectors plus social infrastructure systems that provide critical infrastructure to the New York metropolitan region: (1) energy, (2) transportation, (3) telecommunications, (4) water, (5) waste and sewers, and in addition (6) social infrastructure. The lifeline sectors as they pertain to NYC's infrastructure are described in more detail in Appendix 7.A. These lifeline sectors represent those that have been singled out by *OneNYC* (City of New York, 2015), PlaNYC SIRR (City of New York, 2013), and the National Infrastructure Advisory Council (NIAC) (2013), and are retained here for the purpose of consistency.

Other areas of infrastructure not specifically singled out in *OneNYC,* such as banking and other financial institutions and solid waste management that have been used by other agencies, such as the U.S. Department of Homeland Security, are not included here. The buildings sector, which cuts across many of these others, are a separate report and inventory of GHG emissions that the city undertakes (City of New York, 2017) and are not included here, except with respect to how the buildings sector connects with other infrastructure.

Each type of infrastructure has one or more technology dimensions or characteristics. Each technology has its own level of risk and resilience. New technologies are continually emerging that can change the nature of risk and resilience for each type of infrastructure.

In its 2010 analysis, the first New York City Panel on Climate Change (NPCC1) presented a table that listed potential infrastructure impacts from climate extremes (NPCC, 2010). NPCC1 dealt extensively with the relationship between key climate change risk factors–higher mean temperature, changes in precipitation, and sea level rise–and their effects on energy, transportation, water supply, wastewater, solid waste, and communications infrastructure (NPCC, 2010). In NPCC3 (NPCC, 2015), those relationships are summarized, and the 2010 table is now updated, appearing in this chapter as Tables 7.1a through 7.1e to incorporate additional climate extremes (see also, Chapters 2–4) and impacts.

In NPCC1 (NPCC, 2010), climate extremes, referred to as climate risk factors, were restricted to temperature, precipitation, and sea level rise. In NPCC3, extreme heat replaces temperature, heavy downpours replace precipitation, and sea level rise is combined with coastal flooding. In addition, cold snaps, drought, and extreme winds have been added.

Tables 7.1a through 7.1e set forth impacts that provide the basis for framing infrastructure indicators and metrics in Chapter 8. These climate extremes are described in more detail in earlier chapters. The impacts listed in Table 7.1a through 7.1e are meant to be illustrative rather than comprehensive.

7.3 Key vulnerabilities, dependencies, and interdependencies

This section describes infrastructure vulnerabilities in the current and future climate. Section 7.3.1 addresses infrastructure vulnerabilities irrespective of climate change (for individual infrastructures separately). Section 7.3.2 superimposes climate change on these vulnerabilities. Section 7.3.3 illustrates how these individual infrastructure sectors are interlinked by dependencies and interdependencies without climate change and Section 7.3.4 illustrates the dependencies and interdependencies with climate change. Energy and transportation infrastructure are emphasized, but other lifeline sectors are also discussed, namely water and telecommunications.

7.3.1 Vulnerabilities for individual infrastructure without climate change

Current vulnerabilities for individual infrastructure systems encompass a number of infrastructure attributes and their social dimensions. These include:

- Initial condition and performance (including designed capacity)
- Extent of use or dependency on the infrastructure, especially relative to capacity
- Accessibility and availability to users, and equity issues arising from differences in these characteristics
- Extent of or repeated exposure to hazard
- Ability to recover from hazard
- Existence of and access to alternative services to support immediate response during and following a disaster, for recovery, as well as to avoid damage at onset

Table 7.1a. Examples of potential illustrative infrastructure impacts from climate extremes: energy[a]

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
Energy (electricity)		(NYCDEP, 2008: 38; ClimAID, 2011: 260, 261, 450; NYC, 2013: 112, 120, 121, 126, 127; Anel *et al.*, 2017:3, 4, 5, 6; Bartos *et al.*, 2016: 6; Schaeffer *et al.*, 2012: 5, 8; U.S. DOE, 2013a,b; U.S. EPA, 2017a; NYC Mayor's ORR, 2018: 13)
Production		
	Extreme heat	- Increased user demand for and consumption of energy potentially straining capacity (U.S. DOE, 2013b: 5); ClimAID, 2011: 450; NYC, 2013: 112; Schaeffer *et al.*, 2012: 8; Anel *et al.*, 2017: 4; NYC Mayor's ORR, 2018: 13) - Increase in extreme energy use (peak load days) (ClimAID, 2011: 450; NYC, 2013: 112)-Increased potential for power interruptions (ClimAID, 2011: 450; NYC, 2013: 126; NYC Mayor's ORR, 2018: 13) - Overuse and strain on equipment, materials, efficiency, and performance, including cooling water needs increasing maintenance (U.S. DOE, 2013b: 2, 5); ClimAID, 2011: 450; NYC, 2013: 120; Schaeffer *et al.*, 2012: 5) - Equipment damage (ClimAID, 2011: 450; NYC, 2013: 120; Anel *et al.*, 2017: 5)
	Cold snaps	- Some production processes may slow down; equipment unprotected from low temperatures and snow and ice accumulation could be damaged depending on material tolerances and existence of icing conditions (ClimAID, 2011: 450)
	Heavy downpours	- Equipment damage from flooding (ClimAID, 2011: 261; NYC, 2013: 121)
	Drought	- Material and processes compromised if drought conditions are prolonged, especially processes dependent upon water inputs and maintenance of water intake levels; likelihood of increased fire risk and inability to fight fires due to insufficient water (NYCDEP, 2008: 38; ClimAID,2011: 310)
	Sea level rise and coastal flooding	- Equipment damage and potential damage to docks and marine-based infrastructure from flooding and corrosive effects of seawater (ClimAID, 2011: 446; NYC, 2013: 127)
	Extreme winds	- Potential production disruptions due to shut in facilities to avoid damage (ClimAID, 2011: 260; NYC, 2013: 121)
Transmission and distribution overhead and underground		
	Extreme heat	- Overuse and strain on equipment, materials, efficiency, and performance, increasing maintenance (ClimAID, 2011: 450) - Equipment damage (ClimAID, 2011: 450) - Increased sag of overhead lines and effects upon power transmission (ClimAID, 2011: 450; Bartos *et al.*, 2016: 6) - Increased downtime in provision of power (ClimAID, 2011: 450)
	Cold snaps	- Some transmission processes may slow down where unprotected equipment is damaged depending on material tolerances and existence of icing conditions (ClimAID, 2011: 450; Anel *et al.*, 2017: 5) - Increase in sag of overhead transmission lines; increased exposure of underground lines to freeze-thaw effects (ClimAID, 2011: 450; Anel *et al.*, 2014: 5)
	Heavy downpours	- Increase in number and duration of local outages from flooded and corroded equipment (ClimAID, 2011: 450)
	Drought	- Materials compromised if drought conditions are prolonged
	Sea level rise and coastal flooding	- Increase in number and duration of local outages from flooded and corroded equipment (ClimAID, 2011: 450)
	Extreme winds	- In areas with overhead lines, power disruption due to fallen lines as well as trees falling on the lines (ClimAID, 2011: 260; NYC, 2013: 126)

Table 7.1b. Examples of potential illustrative infrastructure impacts from climate extremes: transportation[a]

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
Transportation		(Kish and Samavedam, 2013; NYCDEP, 2008: 38, 41; ClimAID, 2011: 310, 311, 312, 341, 342, 345, 356, 450, 451; U.S. DOT Federal Transit Administration (FTA), 2011: 5, 10, 16, 19, 21, 30, 42, 102; NYC, 2013: 173–188; U.S. EPA, 2017b)
Roadways		
	Extreme heat	- Increased road material degradation, resulting in increased road maintenance (ClimAID, 2011: 451; Kish and Samavedam, 2013
	Cold snaps	- Some road surfaces could be damaged depending on material tolerances and resistance to effects of icing and snow accumulation (ClimAID, 2011: 451; U.S. DOT, FTA, 2011: 21)

Continued

Table 7.1b. ***Continued***

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
	Heavy downpours	- Declining serviceability of roadways due to flooding conditions (ClimAID, 2011: 451) - Increased travel delay from increased congestion during street flooding (ClimAID 2011: 451) - Increasing need for pumping capacity and associated increased energy use for additional pumping to remove excess water to prevent flooding (NYCDEP 2008: 41; ClimAID 2011: 342)
	Drought	- Increased road material degradation if drought is accompanied by heat (ClimAID, 2011: 451) - Likelihood of increased fire risk along roadway rights of way and inability to fight fires due to insufficient water (NYCDEP 2008: 38; ClimAID, 2011: 310)
	Sea level rise and coastal flooding	- Declining serviceability of roadways due to flooding conditions (ClimAID, 2011: 451) - Increased travel delay from increased congestion due to persistent high water levels (ClimAID, 2011: 451) - Increased need for ongoing pumping capacity and associated increased energy use for additional pumping to remove excess water continuously to prevent flooding (NYCDEP, 2008: 41; ClimAID, 2011: 342) - Corrosion of roadway support facilities by salt water (NYC 2013: 178)
	Extreme winds	- Increase in roadway accidents from vehicle collisions with road debris and vehicle instability (ClimAID, 2011: 311) - General potential impacts on transportation roadway and bridge structures and vehicles if winds exceed guidance and announced event-specific wind thresholds as it was for Hurricane Sandy, for example (I95 Corridor Coalition, 2013; NYS Office of the Governor, 2012a)
Transit		
	Extreme heat	- Increase in the use of cooling equipment due to increased underground station temperatures (ClimAID, 2011: 451; U.S. DOT, FTA, 2011: 21; NYC, 2013: 182) - Increased rail degradation and equipment deterioration, resulting in increased maintenance (ClimAID, 2011: 451; (Kish and Samavedam, 2013; U.S. DOT, FTA, 2011: 5) - For rail systems dependent on overhead catenaries for power, increase in transit accidents from train collisions with sagging overhead lines and increased potential risk of power outages (ClimAID, 2011: 450)
	Cold snaps	- Some rail components could be damaged depending on material tolerances and effects of icing and snow accumulation (ClimAID 2011: 451; U.S. DOT, FTA 2011: 21)
	Heavy downpours	- Increase in pumping capacity and associated increased energy use to remove excess water to prevent flooding (NYCDEP, 2008: 41; ClimAID, 2011: 342; NYC, 2013: 181) - Increase in train stoppages due to failed switches, signals, and potential third rail flood threats requiring power to be shut (ClimAID, 2011: 345; U.S. DOT, FTA, 2011: 16) - Increase in number of emergency stops due to flooding and power outages (ClimAID, 2011: 451; U.S. DOT, FTA, 2011: 19) - Increase in number of emergency evacuations (ClimAID, 2011: 356; U.S. DOT, FTA, 2011: 102)
	Drought	- Increase in rail and train material degradation if drought is accompanied by heat (ClimAID, 2011: 451; U.S. DOT, FTA, 2011: 10) - likelihood of increased fire risk along rail rights of way and inability to fight fires due to insufficient water (NYCDEP, 2008: 38; ClimAID, 2011: 310)
	Sea level rise and coastal flooding	- Increase in rail degradation and equipment deterioration from saltwater inundation, resulting in increased maintenance (ClimAID,2011: 451; U.S. DOT, FTA, 2011: 42; NYC, 2013: 178, 181)
	Extreme winds	- For commuter rail or elevated subway lines, increase in transit accidents from train collisions with track debris; operating disruptions where trains are required to cease operations (ClimAID, 2011: 312; U.S. DOT, FTA, 2011: 30)

Table 7.1c. Examples of potential illustrative infrastructure impacts from climate extremes: telecommunications[a]

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
Telecommunications		(ClimAID, 2011: 450, 452; NYC, 2013:161-172)
Supplies: facilities that provide electric power for telecommunications (corresponds to electric power above)		
	Extreme heat	- Power disruption/outage frequency and severity affects communication equipment, e.g., computerized controls for power systems (ClimAID, 2011: 452; NYC, 2013: 169)
	Cold snaps	- None expected for supply facilities, except as listed under energy
	Heavy downpours	- Equipment flooded and stored materials damaged (ClimAID, 2011: 452)
	Drought	- Water level and water supply inputs for electric power potentially affected (see electric power) (ClimAID, 2011: 450)
	Sea level rise and coastal flooding	- Increased flooding of electric power equipment and corrosion from salt water (ClimAID, 2011: 452)
	Extreme winds	- For production, disrupted power supply due to electric power production system disruptions (ClimAID, 2011: 450) - For transmission, in areas with overhead lines, power disruption due to fallen lines (ClimAID, 2011: 452; NYC, 2013: 169)
Equipment, for example: fiber optic cable, cell towers, internet, central and local offices, switching facilities, data centers, and telephone exchanges		
	Extreme heat	- Destruction of equipment and increased maintenance (ClimAID, 2011: 452)
	Cold snaps	- None expected for equipment, unless material tolerances and operational requirements are exceeded by reduced temperature and effects of icing and snow accumulation (ClimAID, 2011: 452)
	Heavy downpours	- Excessive precipitation flooding equipment (ClimAID, 2011: 452) - Line congestion, tower destruction, or loss of function (ClimAID, 2011: 452) - Call carrying capacity reduced, lost, or blocked (ClimAID, 2011: 452) - Internet traffic increases and accessibility declines (ClimAID, 2011: 452)
	Drought	- Prolonged drying conditions could affect telecommunication equipment and materials
	Sea level rise and coastal flooding	As in the case of heavy precipitation: - Increased flooding of equipment and corrosion from salt water from increased sea level rise (ClimAID, 2011: 457) - Line congestion, tower destruction, or loss of function (ClimAID, 2011: 457) - Call carrying capacity reduced, lost, or blocked (ClimAID, 2011: 457) - Internet traffic increases and accessibility declines (ClimAID, 2011: 457)
	Extreme winds	- Cell towers and exposed lines subject to toppling, hence disabling communications and electric power connections (ClimAID, 2011: 457)

Table 7.1d. Examples of potential illustrative infrastructure impacts from climate extremes: water, waste, and sewer[a]

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
Water, waste, and sewer		(NYCDEP, 2008: 9, 35, 38, 41, 45; ClimAID, 2011: 89, 104, 444, 445, 446; NYC, 2013: 205–218; 231, 232; AWWA, 2012)
Water supply		
Quantity		
	Extreme heat	- Increased water consumption or demand (NYCDEP, 2008: 9; ClimAID, 2011: 444) - Decline in groundwater and surface water supplies due to increased evaporation, where applicable in the watershed servicing NYC exceeding margins of safety (e.g., "safe yields") (NYCDEP, 2008: 45; ClimAID, 2011: 444) - Reservoir levels decline (NYCDEP, 2008: 35; ClimAID, 2011: 444) - Changes in watershed streamflow (e.g., early snowmelt) cause reservoirs to fill sooner in year and increase spill during Winter-Spring

Continued

Table 7.1d. ***Continued***

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
	Cold snaps	- None expected unless icing conditions exist that can potentially cause freezing in the water supply system components
	Heavy downpours	- Uncertain changes in precipitation producing variable and unpredictable water supplies (NYCDEP, 2008: 9; ClimAID, 2011: 444)
	Drought	- Decline in groundwater and surface water supplies due to lack of replenishment, exceeding margins of safety (e.g., "safe yields") (NYCDEP, 2008: 45; ClimAID, 2011: 444) (NYC is supplied by surface water, with some groundwater as backup supply) - Reservoir levels decline (NYCDEP, 2008: 35; ClimAID, 2011: 444) - Sustained high-volume reservoir stream releases while reservoir storage levels are reduced can lead to damage of release valves
	Sea level rise and coastal flooding	- Impact on emergency supply from salt front movement (NYCDEP, 2008: 9; ClimAID, 2011: 89) - Impact of salt front movement in lower Delaware River may add pressure to increase releases from City reservoirs
	Extreme winds	- Temporary disruption of operations due to operating restrictions in high winds
Distribution of water supply		
	Extreme heat	- Changes in characteristics of water flow through pipes - Material degradation resulting in the potential for more pipeline breaks and water leakage
	Cold snaps	- If icing conditions exist, water movement could be inhibited - Material degradation resulting in the potential for more pipeline breaks and water leakage
	Heavy downpours	- Pressure changes in water distribution system (NYCDEP, 2008: 38) - Increased corrosion (ClimAID, 2011: 446) - Increased water loss (ClimAID, 2011: 444)
	Drought	- Potential materials impairment in prolonged droughts
	Sea level rise and coastal flooding	- Increased flooding (infiltration and inflow) from flooded distribution lines (ClimAID, 2011: 446)
	Extreme winds	- Temporary disruption of operations due to operating restrictions in high winds
Quality		
	Extreme heat	- Increased evaporation in surface water supplies contributes to deteriorating water quality due to concentration of contaminants (ClimAID, 2011: 104) - Longer and more stable reservoir stratification, warmer water temperatures result in potentially significant increases in cyanobacteria/Harmful Algal Blooms (HABs)
	Cold snaps	- None expected unless treatment systems exist and processes are affected by cold
	Heavy downpours	- Impact on water quality from increased turbidity (NYCDEP, 2008: 9; ClimAID, 2011: 444) - Increased concentration of pollutants from pollutant release (ClimAID, 2011: 445)
	Drought	- Disruption of water-dependent collection and treatment processes (ClimAID, 2011: 444)
	Sea level rise and coastal flooding	- Impact on emergency supply from salt front movement (NYCDEP, 2008: 9; ClimAID, 2011: 89) - Potential increase in infiltration into distribution systems (ClimAID, 2011: 446)
	Extreme winds	- Temporary disruption of wastewater treatment operations due to restrictions on supply vehicles operating in high winds - Reservoir shoreline erosion due to high winds and wave action may increase turbidity
Waste		
Closed landfills		
	Extreme heat	- Alteration of chemical composition of contaminants below the surface, changing evaporation rates
	Cold snaps	- None expected unless freezing conditions exist that can threaten the integrity of landfill covers and liners through freeze-thaw cycles (Sterpi, 2015.)
	Heavy downpours	- Unexpected leaching of contaminants where precipitation penetrates the surface of closed landfills
	Drought	- Disturbance in landfill cover and integrity where design is contingent on the maintenance of humidity levels
	Sea level rise and coastal flooding	- Release of contaminants from unexpected inundation of landfills increasing public health concerns
	Extreme winds	- None relevant, assuming closure is secure
Marine transfer stations		
	Extreme heat	- Increased evaporation of contaminants from refuse
	Cold snaps	- None expected except for exposed facilities where temperatures below material tolerances and freeze-thaw cycles can potentially damage facility components

Continued

Table 7.1d. ***Continued***

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
	Heavy downpours	- Marine transportation impeded (NYC, 2013: 231)
	Drought	
	Sea level rise and coastal flooding	- Alignment of marine transfer station docking facilities with landside facilities affected (NYC, 2013: 232)
	Extreme winds	- Temporary disruption of operations due to restrictions on vessels operating in high winds (NYC, 2013: 232)
Curbside refuse		
	Extreme heat	- Increased evaporation of contaminants and decay of refuse, thereby increasing public health concerns from vermin and public nuisance from odors
	Cold snaps	- None expected
	Heavy downpours	- Increased damages to curbside refuse containment and releasing refuse, increasing public health concerns (NYC, 2013: 231)
	Drought	- None expected
	Sea level rise and coastal flooding	- Inundation of refuse from water releases contaminants to streets and waterways, increasing public health concerns (NYC, 2013: 232)
	Extreme winds	- Disturbance of refuge storage and unexpected uncontrolled release of refuse (NYC 2013: 231)
Sewer *(wastewater treatment and conveyance)*		
Quality		
	Extreme heat	- Treatment capability of wastewater treatment plants improved up to a point due to increased heat affecting biological processes but then declines tolerance limits are exceeded (NYCDEP, 2008: 41) - If substantial evaporation or drought occurs, quantity of wastewater becomes insufficient to sustain treatment processes
	Cold snaps	- Treatment systems and processes are compromised if they are affected by cold
	Heavy downpours	- Hydraulic capacity of sewers and wastewater treatment plants exceeded owing to increased flows (NYCDEP, 2008: 9; ClimaAID, 2011: 444; NYC Mayor's ORR, 2018: 15) - Combined sewer overflow facility capacity is overwhelmed and pollutants are discharged into sewer systems and waterways (, 2011: 445; NYC Mayor's ORR, 2018: 15) - Sewer backups (ClimAID, 2011: 444) - Treatment capacity of treatment plants exceeded from dilution from increased flows (ClimAID, 2011: 444) - Decline in water quality reflected in Clean Water Act standard variances (ClimAID, 2011: 446)
	Drought	- Insufficient water for sewer collection systems to operate - Saltwater intrusion (NYCDEP 2008: 9)
	Sea level rise and coastal flooding	- Reduced function of wastewater treatment plants and related infrastructure, including outfalls if sea level overwhelms plant facilities and other infrastructure through regular flooding and ponding upstream and downstream (NYCDEP, 2008: 9; ClimAID, 2011: 446;, October 2013; NYC Mayor's ORR, 2018: 15)
	Extreme winds	- Outdoor facility components can be damaged

Table 7.1e. Examples of potential illustrative infrastructure impacts from climate extremes: selected social infrastructure[a]

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
Social infrastructure		(NYCDEP, 2008: 9; ClimAID, 2011: 174, 449, 446, 450, 453; NYC, 2013: 143–160; Guenther and Balbus, 2014)
Hospitals		
	Extreme heat	- Power disruption/outage frequency and severity affects power-dependent operations; Given the use of electricity in hospitals (U.S. DOE, 2011; Christiansen *et al*., 2015.), increased use of electricity for cooling (ClimAID, 2011: 450) - Hospital and associated health facility capacity is overwhelmed due to increase in cases of mortality and injuries from heat stress, air quality degradation, vector-borne diseases, and other heat-related health effects (ClimAID, 2011: 453)

Continued

Table 7.1e. ***Continued***

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
	Cold snaps	- Given the use of electricity in hospitals (U.S. DOE, 2011; Christiansen *et al.*, 2015.), increased use of electric power for heating (ClimAID 2011: 450)
	Heavy downpours	- Equipment flooded and stored materials damaged (ClimAID, 2011: 450; Guenther and Balbus, 2014: 33)
	Drought	- Increased demand on water supply and electric power given the use of electricity in hospitals (NYCDEP, 2008: 9; ClimAID, 2011: 450)
	Sea level rise and coastal flooding	- Increased flooding of equipment upon which hospitals rely heavily (in particular, electric power used in hospitals and telecommunications) and corrosion from salt water (ClimAID, 2011: 446; Guenther and Balbus, 2014: 33)
	Extreme winds	- See sections on impacts of wind on electric power, telecommunications, and other infrastructure related to the functioning of hospitals
Parks and public spaces		
	Extreme heat	- Reduction in vegetation due to heat tolerance problems (ClimAID, 2011: 174)
	Cold snaps	- Reduction in vegetation due to cold tolerance problems (ClimAID, 2011: 174)
	Heavy downpours	- Reduction in vegetation from washouts and flooding of root systems (ClimAID, 2011: 449)
	Drought	- Reduction in vegetation due to water reduction, where supplemental irrigation is not available (ClimAID, 2011: 449)
	Sea level rise and coastal flooding	- Periodic or permanent inundation of vegetation potentially resulting in the transformation of species that can both positively and negatively impact the natural distribution of species (ClimAID, 2011: 446)
	Extreme winds	- Destruction of trees thus reducing tree canopies

Tables 7.1a–e

NOTES AND SOURCES

[a]This table is organized as in NPCC1 (Zimmerman and Faris, 2010, Table 4.1), with climate extremes expanded from 3 to 6 for NPCC3, and includes lifeline infrastructure systems Energy; Transportation; Telecommunications; Water, Waste, and Sewer with the addition of selected Social Infrastructure (hospital and parks subsectors only) as defined centrally for the NPCC3 report. The energy sector focuses on electricity.

[b]The six climate extremes listed here are those defined in Chapters 2–4: extreme heat, cold snaps, heavy downpours, drought, sea level rise and coastal flooding, and extreme winds.

[c]The impacts listed here are illustrative, and are not intended to be comprehensive. Factors other than climate extremes can contribute to impacts given. In some cases, references that pertain to other infrastructure sectors are listed where impacts to those other sectors are implied or mentioned in another sector. Many impacts are identified in or inferred from general literature, common use, and the impacts that occurred during Hurricane Sandy identified in plaNYC "A Stronger, More Resilient New York" (City of New York, 2013). No assignment of probability or level of impact is assumed. The potential illustrative infrastructure impacts as listed do not take into account adaptations or other actions to reduce or avoid the impacts, some of which appear in Appendix 7.B. They do not reflect temporal dimensions, that is, different impacts occur at different time periods. The potential infrastructure impacts are repeated in Chapter 8 (Tables 8.5 and 8.6) for the purpose of consistently linking indicators and their metrics to impacts. The references cited are not meant to be comprehensive, and tend to be specific to or applicable to NYC. Some impacts listed are worded directly as they appear in Table 4.1 in NPCC (2010) in order to maintain consistency.

Abbreviations for some of the references in the Potential Infrastructure Impacts column are:

- ClimAID: Rosenzweig *et al.*, 2011
- DEP: City of New York Environmental Protection, 2008
- NYC, 2013: City of New York, 2013. Strategic Initiative for Rebuilding and Resiliency (SIRR). A Stronger, More Resilient New York

References cited in Tables 7.1a–7.1e

Anel, J.A., M. Fernandez-Gonzalez, X. Labadeira, *et al.* 2017. Impact of cold waves and heat waves on the energy production sector, *Atmospere* 8: 1–13.

Bartos, M., M. Chester, N. Johnson, *et al.* 2016. Impacts of rising air temperatures on electric transmission ampacity and peak electricity load in the United States, Environ. Res. Lett. 11: 114008

City of New York. 2008. New York City DEP climate change program, assessment and action plan. New York, NY: NYCDEP. http://www.nyc.gov/html/dep/pdf/climate/climate_complete.pdf

City of New York. 2013. Strategic initiative for rebuilding and resiliency (SIRR). A stronger, more resilient New York. http://www.nyc.gov/html/sirr/html/report/report.shtmlhttp://s-media.nyc.gov/agencies/sirr/SIRR_singles_Lo_res.pdf.

City of New York. 2018. Progress report OneNYC 2018. https://onenyc.cityofnewyork.us/wp-content/uploads/2018/05/OneNYC_Progress_2018.pdf.

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Table 7.1e. *Continued*

Guenther, R. & J. Balbus. 2014. Primary protection: enhancing health care resilience for a changing climate. US Department of Health and Human Services. https://kresge.org/sites/default/files/Healthcare-Climate-Resilience-Guidance-HHS.pdf.

Jacob, K., R. Blake, *et al.* 2010. Indicators and monitoring, Chapter 7. In *Climate Change Adaptation in New York City: Building a Risk Management Response, New York City Panel on Climate Change* 2010 *Report.* C. Rosenzweig & W. Solecki, Eds.: 127–141. Prepared for use by the New York City Climate Change Adaptation Task Force. Annals of the New York Academy of Sciences, Vol. 1196. New York, NY: NY Academy of Sciences.

Kish, A. & G. Samavedam. 2013. Track buckling prevention: theory, safety concepts, and applications. U.S. Department of Transportation Federal Railroad Administration.

Lloyd, E. & A. Licata. Undated circa 2015. One New York City: one water sustainable water management for New York City's people and environment. http://www.nyc.gov/html/dep/pdf/climate/one-nyc-one-water.pdf.

New York City Mayor's Office of Recovery & Resiliency (ORR). 2018. Climate resiliency design guidelines. Version 2.0. New York, NY: NYC ORR. https://www1.nyc.gov/assets/orr/pdf/NYC_Climate_Resiliency_Design_Guidelines_v2-0.pdf.

New York City Office of the Mayor. 2017. Mayor's management report 2017. http://www1.nyc.gov/assets/operations/downloads/pdf/mmr2017/2017_mmr.pdf.

New York Panel on Climate Change. 2013. Climate risk information 2013 observations. Climate change projections, and maps. http://www.nyc.gov/html/planyc2030/downloads/pdf/npcc_climate_risk_information_2013_report.pdf.

New York State 2100 Commission. 2013. Recommendations to improve the strength and resilience of the empire state's infrastructure. http://www.governor.ny.gov/sites/governor.ny.gov/files/archive/assets/documents/NYS2100.pdf.

NYC Environmental Protection. 2013. NYC wastewater resiliency plan. Climate risk assessment and adaptation study. New York, NY: NYC DEP. http://www.nyc.gov/html/dep/pdf/climate/climate-plan-single-page.pdf.

Rosenzweig, C., W. Solecki, A. DeGaetano, *et al.*, Eds. 2011. Responding to climate change in New York State: the ClimAID integrated assessment for effective climate change adaptation. Technical Report. New York State Energy Research and Development Authority (NYSERDA), Albany, NY. www.nyserda.ny.gov; https://www.nyserda.ny.gov/About/Publications/Research%20and%20Development%20Technical%20Reports/Environmental%20Research%20and%20Development%20Technical%20Reports/Response%20to%20Climate%20Change%20in%20New%20York.

Schaeffer, R. *et al.* 2012. Energy sector vulnerability to climate change: a review. Energy 38: 1–12.

U.S. Department of Transportation, Federal Transit Administration. 2011. Flooded bus barns and buckled rails: public transportation and climate change adaptation. https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_0001_-_Flooded_Bus_Barns_and_Buckled_Rails.pdf.

U.S. Environmental Protection Agency. 2017a. Climate impacts on energy. https://19january2017snapshot.epa.gov/climate-impacts/climate-impacts-energy_.html#Supply%20and%20demand.

U.S. Environmental Protection Agency. 2017b. Climate impacts on transportation https://19january2017snapshot.epa.gov/climate-impacts/climate-impacts-transportation_.html#Land.

Zimmerman, R. & C. Faris. 2010. Infrastructure impacts and adaptation challenges, Chapter 4. In *Climate Change Adaptation in New York City: Building a Risk Management Response, New York City Panel on Climate Change* 2010 *Report.* C. Rosenzweig & W. Solecki, Eds.: 63–85. Prepared for use by the New York City Climate Change Adaptation Task Force. Annals of the New York Academy of Sciences, Vol. 1196. New York, NY: NY Academy of Sciences. Table 4.1. ISBN 978- 1- 57331- 800- 6. https://nyaspubs.onlinelibrary.wiley.com/doi/epdf/10.1111/j.1749-6632.2009.05318.x.

Each of these characteristics influences how an individual infrastructure system can resist stress. The first two vulnerabilities–condition and usage relative to capacity–are critical characteristics related to vulnerability and are singled out for greater discussion below.

7.3.1.1 Infrastructure condition. If infrastructure is weak to begin with, it will be less able to withstand stress. Table 7.2 presents the condition of selected infrastructure in New York City and in some cases in the region. Numerous organizations work together to maintain the highest level of performance of infrastructure in the region. These include government agencies at state and local levels, professional associations such as American Public Transportation Association (APTA) and the ASCE, and private and nonprofit entities. In New York City, government agencies include the New York City Office of Emergency Management (NYEM in connection with the hazard mitigation plan (NYCOEM, 2014) and other emergency functions), the New York City Mayor's Office of Recovery and Resiliency (NYCORR), NYC Office of the Comptroller, infrastructure owners and operators, and many of the city's community boards. Table 7.2 emphasizes selected illustrative characteristics of infrastructure condition.

Table 7.2. Selected illustrative characteristics of infrastructure condition in or affecting New York City

Infrastructure type and system	Description of condition element applicable to NYC	Selected potential consequences	Time period (if specified)	Reference
Energy				
Electric power				
	Some design, operational, and maintenance levels to meet functional needs, acknowledging that design protocols exist to address this	Frequent and often extensive outages (in terms of number of customers affected and infrastructure affected) in major storms, e.g., - Hurricane Irene: 6.69 million customer outages; - Hurricane Sandy: 8.66 million customer outages[a]	Approx. 2013	U.S. DOE (2013a: v); U.S. DOE (2013b)
Petroleum refining capacity				
	Condition of refining capacity may be affected during extreme weather events	Shutdown of refining capacity (expressed in barrels of oil per day) - Hurricane Irene: 238,000 - Hurricane Sandy: 308,000	Approx. 2013	U.S. DOE (2013a: v); U.S. DOE (2013b)
Transportation				
Transit				
	State of Good Repair (SGR) for New York City (ASCE) transit SGR expressed by component as percentages of components meeting SGR, corresponding to MTA capital plan categories: Meeting SGR - "Train cars, mainline tracks, and switches: 100%" - "Pumps, mainline signals, and stations"-89%, 74%, and 78%, respectively Failing SGR: - "Power 62% and high priority ventilation 60%, subway shops: 46%"	The lower the percentage meeting SGR, theoretically the greater the likelihood of more frequent equipment failures and hence delay and congestion for users; see Chapter 8 for transit indicators	Unspecified	ASCE (2015: 70); MTA (2013: 33)[b]
	- Age of subway components - - Subway cars: About 1/3 > 30 years old - Signals: About 40% > 50 years old	Age of older equipment relative to design lifetimes increases the likelihood that train service will become increasingly disrupted, that is, unable to run over their routes, at least temporarily, and hence rider inconvenience increases	2016	NYS Office of the Comptroller (2017: 1)
Roads				
	Pavement condition: −43% poor; −30% mediocre	Likelihood of inability to withstand water and wind-related effects of extreme events	circa 2015	ASCE (2015: 44)[c]
	Rough roads	Additional vehicle operating costs (per vehicle per year) $694	circa 2015	ASCE (2015: 5)

Continued

Table 7.2. ***Continued***

Infrastructure type and system	Description of condition element applicable to NYC	Selected potential consequences	Time period (if specified)	Reference
Aviation				
	Closeness to airport capacity JFK: expected to exceed current capacity by 130% LaGuardia: 103%	Likelihood of inability to withstand water and wind-related effects of extreme events	2030	ASCE (2015: 8)
Water				
Water supply				
	Water main strength - Number of breaks per year: 406, 513, 563, 397, 424, 520 - Number of breaks per 100 miles of water main (previous 12 months): 5.8, 7.3, 8.0, 5.7, 6.1 Outages and ability to restore water supply quickly: restoration time 4–5 h	Weaknesses in the water supply distribution system reflected in breakage rates could point to the likelihood of a greater inability of those systems to withstand pressures from flooding	Fiscal Year 2013–2017	NYC Office of the Mayor (2017:262-263; 2018:261)[d]; AWWA 2012
Wastewater treatment				
	Waterfront dependency for functionality versus flooding risk Exceedance of design life or "expected useful life" Maintenance of or compliance with water quality standards: effluent and instream Integrity and performance of facility components, e.g., outages, sewer backups, restoration times - Extent of existing impervious surfaces (72% of New York City land area) - Sewer configurations such as combined sewer systems (60% of the system) that can increase vulnerability to flooding	These conditions potentially lead to increased vulnerabilities to various extreme event impacts, particularly coastal flooding and sea level rise, extreme heat, and heavy downpours	Ongoing	NYC Environmental Protection (2013: 1; NYC 2013: 209); ASCE (2015: 75) ASCE (2015: 77); NYC Office of the Mayor (2017: 262, 263; 2018:261) ASCE (2015: 77); NYC Office of the Mayor (2017: 262, 263) NYCDEP (2018a:4; 2018b)

[a]Number of customers is not equivalent to number of people. Consequences are either for facility damage or deliberate shutdowns to avoid facility damage.
[b]Note: SGR determinations are required by the federal MAP-21 law and are implemented by individual transit systems (National Center for Transit Research, 2016: 3).
[c]These results are based upon the TRIP (2016) report that implies that the percentages refer to roadway mileage and that condition is based on pavement condition (TRIP, 2016).
[d]Water system leakages can reduce capacity; the major leak that the city is addressing is in the Delaware Aqueduct water transmission system. This will be addressed through construction of a bypass (NYC Water Board, 2016). In contrast to the NYC breakage rates, a U.S. Canada survey of 281 responding utilities found that "Between 2012 and this 2018 report, overall water main break rates increased by 27% from 11.0 to 14.0 breaks/(100 miles)/year" (Folkman, 2018: 4, 8). By comparison, the NYC Office of the Mayor MMR (2017: 262–263) indicates that NYC breaks per 100 miles are between 5.7 and 8.0 for FY13–FY17. FY18 (NYC Office of the Mayor, 2018: 261)

7.3.1.2 Infrastructure usage versus capacity. The comparison between the extent of use of an infrastructure and the capacity for which it has been designed and managed is a key indicator of infrastructure robustness. Where capacity is exceeded, the ability of an infrastructure to withstand the impacts of additional stresses is potentially diminished. The ratio of use to capacity is often used as an infrastructure indicator, for example, volume to capacity ratio for roadways.

Usage or consumption of electric power and water services and resources have been increasing nationally over time, though in the New York area usage has in some cases been at least stable and possibly intermittently declining in recent decades yet a comparison of usage against capacity is what is relevant for resilience. The transportation sector has generally experienced extensive growth in terms of vehicle miles of travel for road-based travel, bridge and tunnel crossings (NYS Comptroller, 2018: 3), and transit ridership (though transit ridership has shown some declines in the past 4 years (NYS Comptroller, 2018: 3)). Table 7.3 provides examples of some of these infrastructure usage characteristics that can be compared against capacity when such information on capacity becomes available.

7.3.2 Vulnerabilities for illustrative individual infrastructures with climate change

The previous discussion identified some infrastructure vulnerabilities in the absence of climate change. In this section, some specific examples of climate change attributes are introduced and related to selected infrastructure. The focus is primarily on vulnerabilities that arise in coastal areas due to two climate extremes: (1) sea level rise and coastal flooding and (2) temperature. These vulnerabilities contribute to impacts outlined in Tables 7.1a–e.

7.3.2.1 Sea level rise. Many of the components of the city's infrastructure assets and services are at risk from flooding, both directly and indirectly. Direct risk occurs in terms of elevation above sea level, extreme precipitation including flash flooding, and indirect risk to areas that are not in flood-prone areas but are connected to them physically or functionally. Most vulnerabilities relevant to climate change-related sea level rise pertain to location, and thus actual or potential exposure to sea level rise.

Figures 7.1a and 7.1b combined indicate the vulnerability to flooding for selected infrastructures in Lower Manhattan by virtue of flood plain delineations that existed following Hurricane Sandy. The following sections will zoom in on the impacts of flooding events on critical infrastructure sectors.

Transportation. The locations of NYC transportation systems that are commonly flooded or are routes for floodwaters have been known for some time from the histories of flash flooding and intense precipitation and studies of the elevations of these facilities relative to sea level.

A number of studies have identified locations for the most vulnerable components of the city's transit system. See the NYS ClimAID study, for example, Rosenzweig *et al.* (2011), MTA (2009), Jacob *et al.* (2009), Rosenzweig and Solecki (2010); the various components of the city's rail transit infrastructure within various sea level elevations (USACE, 1995; Zimmerman and Cusker, 2001; Zimmerman, 2003); and the subway lines and stations most vulnerable to flooding. See, for example, the August 2007 floods (MTA, 2007).

Zimmerman (2003) summarized the USACE (1995) findings for the elevations of major facilities and components in terms of the National Geodetic Vertical Datum (NGVD) of 1929:

- Amtrak, Metro-North Railroad, Long Island Rail Road: 10 stations were within 10 feet or less of sea level and 4 were between 10 and 12 feet;
- NYC subways and the PATH system: 17 components were within 10 feet and 3 were between 10 and 12 feet;
- Roads, bridges, and tunnels: 21 were within 10 feet and 9 were between 10 and 12 feet;
- Marine facilities: 6 were within 10 feet; and
- Airports: 2 were within 10 feet and 2 were within 10 and 12 feet.

In addition, many other facilities are threatened that are used for storage, cleaning, and maintenance of transportation infrastructure, as well as intermodal facilities for goods movement.

Energy. Historically, many electric power plants were located along shorelines for cooling water and greater access to waterborne transport of supplies. Selected locations were presented in Chapter 4 of

Table 7.3. Infrastructure usage characteristics: energy and transportation

Infrastructure type and system	Description of usage	Illustrative usage details	Time period (if specified)	Reference
Energy				
Electric power	Electricity use	Electricity use increased by 0.31% (GWh) equal to 53,653 GWh in 2016	2015–2016	NYS ISO (2017b: 13)
Transportation				
Roads	Congestion (time and cost of delay)	"New York has the highest daytime congestion rate on arterials and city streets among the major US cities studied" by INRIX	2017	INRIX (2017: 25)
Transit	Ridership	Highest usage volume on record in 2015	2015, based on 1948–2015 annual ridership	MTA (2016); NYS Comptroller (2018)
Transit	Ridership change	Increases in Average Weekday Ridership and Total Ridership were about 7% Declines occurred in Total Ridership due to Declines in Weekend Trips	2011–2016 2015–2016	MTA (2017a) MTA (2017a)

NOTE: Trends in each sector potentially signify stresses on the existing system unless capacity increases to cover it.

the 2010 NPCC report (NPCC, 2010). In addition to power plants, other energy components, in particular substations, were near enough to coastal areas to have been flooded in Hurricane Sandy. A comparison of Figures 7.1a and b illustrates some of the damages to electric power substations resulting from Hurricane Sandy.

Energy infrastructure in New York City includes power production equipment, transformers, and both underground and overhead distribution lines, each having different vulnerabilities depending on the hazard. Overhead lines are vulnerable to wind and tree damage. Underground distribution lines are vulnerable to salt-water intrusion and water corrosion in general. The operation of transformers and production equipment when directly exposed to water inundation becomes disabled as was apparent as a result of Hurricane Sandy and other similar storms.

A key learning experience is Hurricane Sandy and the associated storm surge that destroyed temporary protection barriers and inundated the Con Edison East 13th Street facility, causing massive flooding to two transmission substations and leading to an intense electric arc (City of New York, 2013).

Impacts from Sandy on the electric distribution system contributed to customers enduring blackout conditions for 4 days, some even lasting up to 2 weeks before power was restored. Much critical control equipment was submerged and damaged due to salt water corrosion. Many of Con Edison electric systems in Manhattan are in the floodplain close to the coastline and are buried underground making them more vulnerable to sea level rise and storm surge (City of New York, 2013). Hurricane Sandy caused catastrophic damage to critical underground systems causing many cascading effects to the electric system within and outside of Manhattan that are interdependent with each other (City of New York, 2013).

Wastewater. New York City's 14 wastewater treatment plants are located on or near the city's waterways, similar to power plants contributing to vulnerability to high water conditions. After Hurricane Sandy, the city conducted an extensive wastewater resiliency plan and analysis detailing the

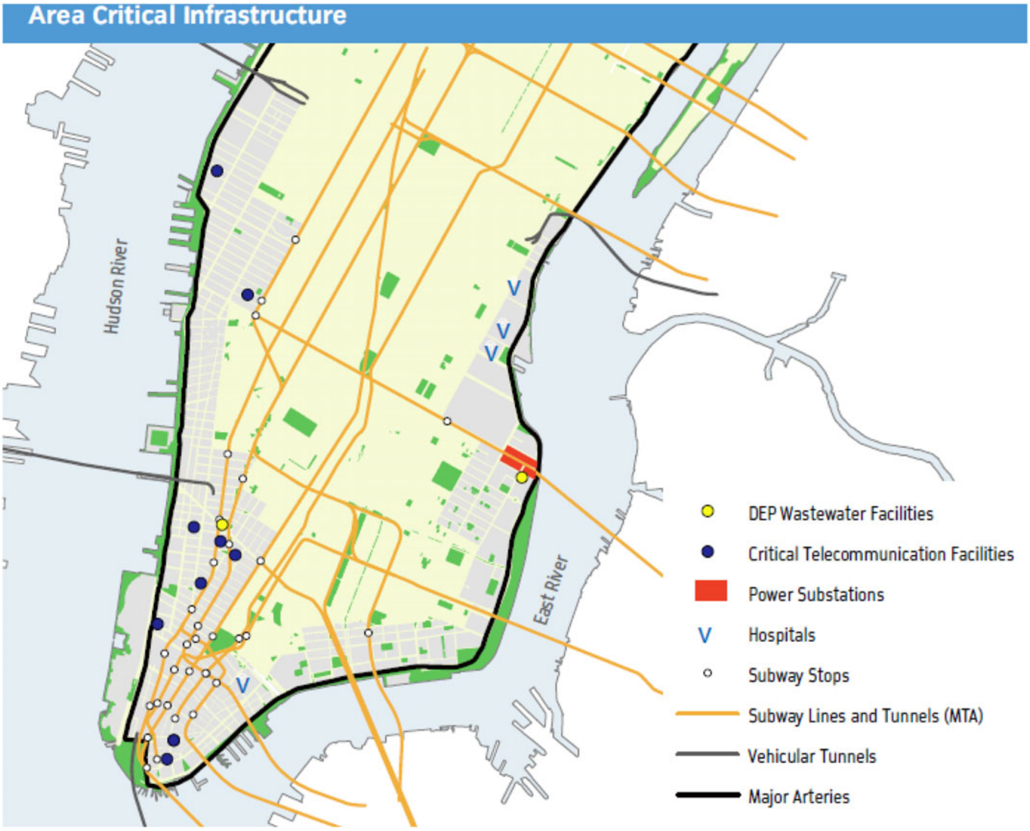

Figure 7.1a. Selected critical infrastructure systems located in or connected with facilities in flood inundation zones, Southern Manhattan, NYC. Source: City of New York, 2013.

components of the wastewater facility plants vulnerable to flooding (NYCDEP, 2013).

The NYC DEP's post-Sandy analysis in 2013 of the vulnerability of the city's wastewater treatment plants and their components to flooding indicated that all 14 of its wastewater treatment plants experienced such vulnerability (NYCDEP, 2013). In addition, the approximately 426 combined sewer overflow facilities (NYS DEC, 2012) and regulators that prevent the surrounding water from flooding city streets are extremely vulnerable to sea level rise and flooding, and their operations could be seriously affected.

These findings do not separate out many of the stresses associated with flooding such as hydrologic stress and undermining of structural supports and corrosion. Many of the vulnerabilities and the consequences associated with flooding are distinct from those associated with sea level rise. Sea level rise is a slow-onset hazard that causes saltwater intrusion damage to infrastructure, while coastal flooding can be acute yet cause intermittent damage.

7.3.2.2 Temperature. The NPCC 2010 report (NPCC, 2010: Table 4.1) sets forth impacts of temperature on the city's infrastructure and Tables 7.1a–e provide more current details. This section focuses primarily on the vulnerability of selected infrastructure sectors to temperature impacts primarily in terms of attributes of materials and structural characteristics, keeping in mind that temperature is measured in a number of different ways. A heat wave, for example, is defined for New York City as 3 or more consecutive days with maximum temperatures at or above 90°F (Horton *et al.*, 2015: Chapter 1).

New York City is experiencing increases in the number and intensity of extreme heat events that can be attributed to a warming climate (Horton *et al.*, 2015). NPCC2 presented these conditions in terms of heat waves (Horton *et al.*, 2015), and

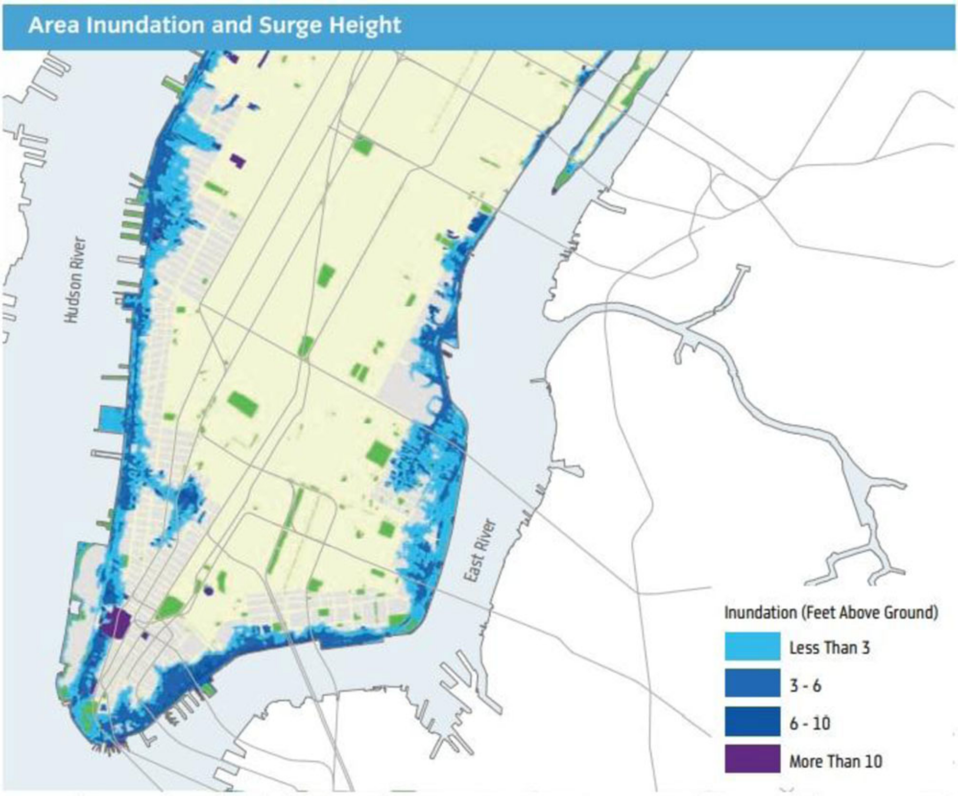

Figure 7.1b. Areas subjected to inundation and surge during Hurricane Sandy where selected critical infrastructure systems are located in or connected with facilities in flood inundation zones, Southern Manhattan, NYC.
Source: NYC SIRR (City of New York, 2013).

NPCC2 as well as future NPCC3 projections (as described in the climate sciences chapter) project these trends to remain throughout of the rest of the 21st century (Horton *et al.*, 2015). While the key physical drivers of extreme heat events are predominantly synoptic climate signals, the built environment of the complex urban core has a magnifier effect, the urban heat island, increasing the intensity of them (Ortiz *et al.*, 2018).

Transportation. Temperatures expressed as unusually high temperatures that are frequent or long duration (e.g., heat waves) have had the effect of deforming transportation materials, for example, concrete used for roadways and other supports such as bridges (Jacobs *et al.*, 2018), asphalt for roadways, and steel for transit rails and vehicle components (U.S. DOT, FTA, 2011). These phenomena are a combination of temperature levels, duration of the heat, environmental loads, usage (e.g., vehicular speed and weight), and the manner in which transportation materials have been installed in light of temperature constraints (Kish and Samevedam, 2013). The New York area transportation systems have experienced the effects of temperature on its operations, and some examples are noteworthy.

With respect to steel rail, the MTA's Metro-North system has experienced actual rail buckling and wheel distortions associated with high temperatures. A derailment near Poughkeepsie was potentially considered to be attributed to high temperatures (Cummings, 2017). This is potentially a system-wide problem and common to rail systems beyond the New York area (U.S. DOT, FTA, 2011) that needs to be addressed in the future, since rail transportation systems were not necessarily designed for such temperature extremes or to the delays associated with reductions in train speeds to reduce heat effects (Kish and Samevedam, 2013).

Furthermore, increased maintenance is often called for to compensate for such vulnerabilities (ClimAID, 2011: 451). The vulnerability of concrete to heat on roadways is also subject how roadways are designed to accommodate heat-related expansion (Jacobs *et al.*, 2018).

Energy. Heat waves can severely stress the electric power system that is built and operated for certain temperature tolerances (U.S. DOE, 2013; ClimAID 2011: 450). Records of past heat wave events indicate that peak loads and blackouts can be related to these extreme heat events. The way overhead transmission and distribution systems are designed can affect vulnerability to sagging, which is related to air temperature and the ability to reduce heat effects (Bartos *et al.*, 2016).

Water supply. A number of earlier studies have identified vulnerabilities of certain water supply components to temperature effects including the relationship between temperature and precipitation and temperature and water demand (NYCDEP, 2008). Water storage facilities are potentially threatened by increased evaporation rates which for New York City is a problem given that its storage facilities, such as reservoirs, are uncovered and are thus, generally vulnerable to evaporation. Increasing temperature can also affect water quality (NYCDEP, 2008).

Wastewater treatment. Following Hurricane Sandy, New York City studied selected effects of storm-related impacts on wastewater treatment (City of New York, 2013). In addition, other studies have noted that wastewater treatment processes which in NYC rely upon action by biological organisms can be affected given the limited tolerance of those organisms to heat.

7.3.3 Vulnerabilities for infrastructure dependencies and interdependencies without climate change

Dependencies and interdependencies among infrastructure systems contribute to vulnerabilities of interconnections when not anticipated, are unexpected, or are uncertain. To examine and address potential climate change risks to critical infrastructure, the City recently reconvened the CCATF in the fall of 2015 to review risks based upon the most recent NPCC2 climate projections for New York City and to develop and coordinate potential mitigation strategies.

As part of CCATF, the city through the Mayor's Office of Recovery and Resiliency (ORR) is working with the U.S. Department of Homeland Security (DHS) and Argonne National Laboratories to focus in particular on risks associated with interdependencies among critical infrastructure sectors. The goals are to better understand the risks posed to networked systems such as energy, telecom, and transportation, in addition to asset-level vulnerabilities, and examine potential asset- and neighborhood-level infrastructure resilience strategies.

Table 7.4 gives examples of infrastructure interdependencies and dependencies among infrastructure sectors that begin to identify some of those directions (Zimmerman and Restrepo, 2009). Although these are in the absence of climate change, they provide a foundation for understanding climate change effects.

7.3.4 Vulnerabilities for infrastructure dependencies and interdependencies with climate change

Table 7.5 briefly illustrates conceptually the nature of infrastructure dependencies and interdependencies relevant to climate change exemplified by electric power as the initiator of the effects and interactions with water and transportation. Key cases applicable to New York City or its region follow, first in terms of dependencies and then extended generally to interdependencies.

Some cases specific to New York City are given below for dependencies and interdependencies. Though the climate change connections were not usually made, ways in which climate change could be related are suggested or inferred.

7.3.4.1 Dependencies for energy and transportation potentially associated with climate change. Under climate change, impacts from heat could exacerbate power outages and lead to transit impacts. Below are examples of electric-transportation sector dependencies in New York City that might be expected:

- 2016–2017 Transit Disruptions from Electric Power Outages. The city's transit system relies upon Con Edison as a power supply. In late 2016, subways were disrupted by a midtown manhole fire and the New York City Transit system experienced outages on several subway lines for about a day (Honan, 2016), which exemplified the power-transit connectivity in NYC. This was one of a series of such outages reflecting the power-transit connections that continued through the following year, for example, on April 21, May 7 and 9 (New York

Table 7.4. Illustrative examples of generic infrastructure interdependencies

Sector providing the service	Sector receiving the service				
	Energy: oil and gas	Energy: electricity	Transportation	Water	Communications
Energy: oil and gas		Fuel to operate power plant motors and generators	Fuel to operate transport vehicles	Fuel to operate pumps and treatment processes	Fuel to maintain temperatures for equipment; fuel for backup power
Energy: electricity	Electricity for extraction and transport (pumps, generators)		Power for overhead and underground transit lines, switches, signals, and lighting	Electric power to operate pumps and treatment processes	Energy to run cell towers and other transmission equipment
Transportation	Delivery of goods, food, raw materials, fuels, and general supplies, workers, and residuals removal; pipelines for energy material transport	Delivery of supplies and workers, and the removal of residuals		Delivery of supplies and workers, and the removal of residuals	Delivery of supplies and workers, and the removal of residuals
Water	Production process water	Cooling and production processes water	Water for vehicular operation; cleaning		Water for equipment and cleaning
Telecommunications	Breakage and leak detection and remote control of operations	Detection and maintenance of operations and electric transmission	Identification and location of disabled vehicles, rails, roads; user service information and processing	Detection and control of water supply and quality	

SOURCE: Modified and expanded from Zimmerman and Restrepo (2009).
NOTES: Exchanges or interconnections within each sector also occur, but are not shown here. These examples are illustrative and not intended to be comprehensive. Cases of dependencies and interdependencies specific to New York City are presented in the context of climate change below.

State Office of the Governor, August 9, 2017), and September 17, 2017.

- 2003 U.S.–Canada Blackout. The extensive 2003 blackout was not a particularly extreme heat event however; it underscores the dependency of transportation on electric services in the event of a disruption. A 2006 study showed that during the 2003 blackout, transit in New York City took about 1.3 times as long to recover and traffic signals 2.6 times as long to recover compared to the length of time it took for power recovery (Zimmerman and Restrepo, 2006).
- September 2016 Power Distribution to the MTA Metro-North Railroad. A high-voltage feeder cable powering the MTA's Metro-North Railroad commuter rail transit system was taken offline, but during that process the adjacent backup unit was disabled, disrupting Metro-North commuter rail service for over a week (Flegenheimer, 2013). The problem was investigated and ensuring the robustness of

Table 7.5. Infrastructure dependencies, interdependencies, and selected climate impacts: illustrated for energy, water, and transportation

Dominant infrastructure (example)	Dependency 1: transportation (transit) dependence on energy	Dependency 2: water dependence on energy	Interdependency: energy-transportation-water
Energy (electric power)	Transportation (transit) depends upon energy for operational controls (signals, switches, lighting) and vehicular power in the case of transit Climate impact: Heat, sea level rise, and storms can disable energy which in turn can disable transportation (transit)	Water supply depends on energy for water conveyance (via pumps) and to provide power for treatment processes, where applicable Climate impact: Heat, sea level rise, and storms can disable energy which in turn can disable water supply systems	Electric power outages affect transportation and water (see dependencies 1 and 2) and then electric power is affected since it depends on water for production processes and transportation for access to resources Climate impact: Heat, sea level rise, and storms can disable interdependent energy, transportation, and water systems, potentially with more severe consequences given the interdependencies

Source: Based on Zimmerman (2018–2019) and Zhu and Zimmerman (September 20, 2018).
Note: This hypothetical example portrays energy infrastructure only as electric power. This example covers only the disabling of transportation and water supply from electric power outages; disabling also occurs from direct effects of climate change as well as indirect effects through electric power outages.

power supply to a large transit system suggests operational and managerial control needs.

In each of these examples, commuters heading to work and other transit users were affected by power outages that unexpectedly halted train service. Some solutions are for New York State and New York City to ensure electric power reliability for subway signals, switches, and third rail systems and to improve signaling and switch capabilities. The Governor directed the NYS Public Service Commission (2016) to investigate (NYS Office of the Governor, 2017), and Con Edison has scheduled improvements (Con Edison, May 26, 2017). In the future, these considerations should be expanded to components of the MTA system other than trains but related to train service.

7.3.4.2 Interdependencies potentially associated with climate change. The effects of sea level rise and temperature on individual infrastructures are heightened where several infrastructures are connected. In New York City, water supply distribution lines and electric power lines are often colocated in the same conduits or corridors for cost-saving. Drainage pipes are often located on the underside of highway overpasses or bridges. Under such conditions, sea level rise and high temperatures will affect more than one infrastructure.

Some examples illustrate selected interdependency and climate change phenomena relevant to NYC:

- *Energy and Transportation:* This case is identical to the one above for New York City transit subways in the absence of climate change except that the climate change phenomenon can be specified. First, when heat or sea level rise causes power outages and separately also impairs rail lines and disrupts train operations, then transit riders may shift to other travel modes (e.g., road-based transit that can cause excess roadway congestion). Such congestion will likely prevent electric utility workers from accessing utility equipment (e.g., electric power, water) causing delays in equipment repair (Zimmerman, 2018-2019; Zhu and Zimmerman, September 20, 2018).

  Second, when heat impairs rail travel by distorting the rail lines or when sea level rise floods rail lines and disrupts train operations, not only will transit be directly affected but electrical lines that run near the rail lines will in turn also become impaired.

- *Combined Sewer Overflow (CSO) Facilities and Transportation.* New York City has 426 combined sewer overflow facilities at shoreline locations (NYS DEC, 2012: 1–2). Those CSOs operate in the following way (NYCDEP, 2018b; U.S. EPA, 2017b): when the tide is below the level of the CSO, the CSO regulators can open thus discharging excess water from streets into the waterways surrounding NYC. When the tide increases the regulators close. This is an important mechanism for removing water from land surfaces, including streets.

  Under rising sea level conditions, depending on the height, the regulators could be permanently shut, thereby preventing them to function for street and land surface drainage. When streets are flooded due to CSO interruption, the streets can in turn disrupt water drainage infrastructure further through uncontrolled water discharges from the streets.
- *Energy and Information Technology (IT).* As a result of Hurricane Sandy, IT components were disabled in part due to their connectivity to electric power, estimated to be the major cause of IT outages (City of New York, 2013; Rosenzweig *et al.*, 2011; NYS 2100 Commission, 2013).

  This dependency becomes an interdependency when an electric power outage causes an IT system outage, which in turn prevents the IT-enabled electric power systems to operate. The IT connections to electric power systems occur in several different forms, as computers, sensors, cell towers, etc.
- *Energy and Water Supply.* Water supply delivery to housing units in buildings above six stories relies on power supplies to operate the pumps, and electric power can be vulnerable to the effects of climate change and extreme events. Such units and their locations have been estimated for New York City as a basis for adaptation strategies to avoid interruptible water supplies (Zimmerman *et al.*, 2015).

  Likewise, water supply outages caused by electric power outages can in turn affect energy infrastructure that is dependent upon water for cleaning, operations, cooling, and other functions. When these other infrastructures are deprived of water, they may cease to function especially where water is needed for cooling.
- *Water and Transportation.* Water usage is pervasive across infrastructures, and in turn, water infrastructure relies upon electric power to run pumps and other machinery and transportation to provide water system supplies. Downstate transit depends upon water for potable use and washing operations for its facilities.

  The MTA reported 2.6 billion gallons of water consumed in 2006 for potable purposes across the entire MTA downstate system, and of that, 1.9 billion gallons of water was used for washing as indicated in the report of the Blue Ribbon Commission on Sustainability: Water Sustainability (MTA, 2008). The New York City transit system alone uses about three-quarters of the potable water system used throughout MTA and over 80% of the washwater (2006 water use data) (MTA, 2008).

  Thus, if electric power to these water and transportation systems is disabled (separately to each system), it can produce impacts across both water and transit systems; that is, once the power is disabled to both systems, the impacts will be felt across both. Ultimately, electric power can in turn be affected by transportation and water services.

7.4 Community and infrastructure resilience case studies

Community issues are potentially pervasive in many areas in terms of the extent to which differential impacts and remediation are experienced by communities of different types. The cases in connection with infrastructure, including dependencies and interdependencies among them, associated with electric power, transportation, water, and telecommunications introduced in the previous section provide a context for the cases here.

Two case areas are presented that illustrate the role of infrastructure and its interdependencies and the nature of community and citywide decisions to improve resilience: health care, in particular, hospital row in New York City, and the New York City Housing Authority (NYCHA) in connection with Hurricane Sandy. For each of the cases, key infrastructure interdependencies, specific effects on community, and solutions in terms of current city programs and recommended solutions are the focus.

The cases below are illustrative of social infrastructure. The City of New York (2015: 237) specifically defines social infrastructure as "infrastructure that strengthens communities, such as hospitals, community centers, libraries, and schools, . . . [that] . . . can enhance social resiliency and assist in immediate response after a disruptive event." While Chapter 6 Community-Based Assessments of Adaptation and Equity addresses these directly, the relationships for two examples of these types of social infrastructure to lifeline infrastructures are described here.

7.4.1 Intersection of social and critical infrastructure in hospitals

Health facilities can be particularly vulnerable during extreme weather events, and, like most other types of social infrastructure, rely on and are connected to a vast network of infrastructure services: transportation for access, environmental facilities for cleanliness, and electric power and water to support essential services. To illustrate the interrelationships between social and critical infrastructure, this section will focus on New York City's hospital row. Hospital row is an area along the East River shore of Manhattan, between East 20th to 30th Streets and First Avenue, where many hospitals are located, including three out of the five acute-care hospitals evacuated during hurricane Sandy.

7.4.1.1 Vulnerability. A variety of different types of health facilities are part of the city's healthcare system encompassing hospitals, rehabilitation/long-term care, ambulatory care, pharmacy, and home care settings, and all of these interact with one another. New York City has 62 active hospitals with a total capacity of 26,451 beds (NYC Independent Budget Office (IBO), 2012; Commission on Health Care Facilities in the 21st Century, 2006; New York University Langone web site, 2012).

The NYC Health and Hospitals Corporation (HHC) also known as NYC Health + Hospitals operates the public hospitals and clinics in NYC. NYC Health + Hospitals is the largest municipal health system in the country and it serves more than 1.2 million city residents annually (City of New York, 2015). The NYC Health and Hospitals operates 11 hospitals, 44 neighborhood health centers and 5 postacute/long-term care centers across the five boroughs (NYC Health and Hospitals, undated web site). All of these facilities are dependent upon transportation, electric power, and water for resilience during normal as well as emergency conditions.

During emergencies, maintaining the functioning of acute healthcare facilities is of the highest priority. Evacuation can be life threatening to vulnerable individuals (McGinty, 2015). For example, a study of nursing home residents with dementia reported that evacuation increased the risk of death 30 and 90 days after relocation (Brown *et al.*, 2012).

Because patients in hospitals are ideally expected to shelter in place to minimize the risks to vulnerable patients during most emergencies including extreme weather events such as heat waves and storms, they are heavily dependent on the availability of a reliable backup electricity supply in case of electrical grid failure. The adequate flood protection of critical electrical infrastructure within these facilities is also vital for ensuring the continuity of services.

A report by the U.S. Department of Health and Human Services concluded that "without exception, the loss of (or lack of) emergency power following the loss of municipal grid power was the primary reason that hospitals, adult care facilities, and nursing homes evacuated. Flooded critical infrastructure, such as ground floors, electrical switchgear, and heating/cooling systems, was the secondary reason. In ambulatory settings, the disruption to staff and patient travel became the primary reason for disruption, followed by loss of communication/IT systems" (Guenther and Balbus, 2014: 33).

The Pace Energy & Climate Center (c2013) also emphasized the disabling of hospitals due to electric power outages in the Hurricane: "Approximately half of New York City hospitals' generators malfunctioned during the blackout [citing U.S. EPA CHP], and many other hospitals were unable to sterilize equipment due to insufficient steam pressure [citing the NYC Emergency Response Task Force, October 28, 2003)]".

The vulnerability of these facilities to climate-related extreme events is reflected in some of the effects that Hurricane Sandy had on them. Specifically, five acute-care hospitals shut down in New York City due to Hurricane Sandy, two of which evacuated before and three of which were evacuated after the storm hit (Kinney *et al.*, 2015; Teperman, 2013). Since some hospitals were unable

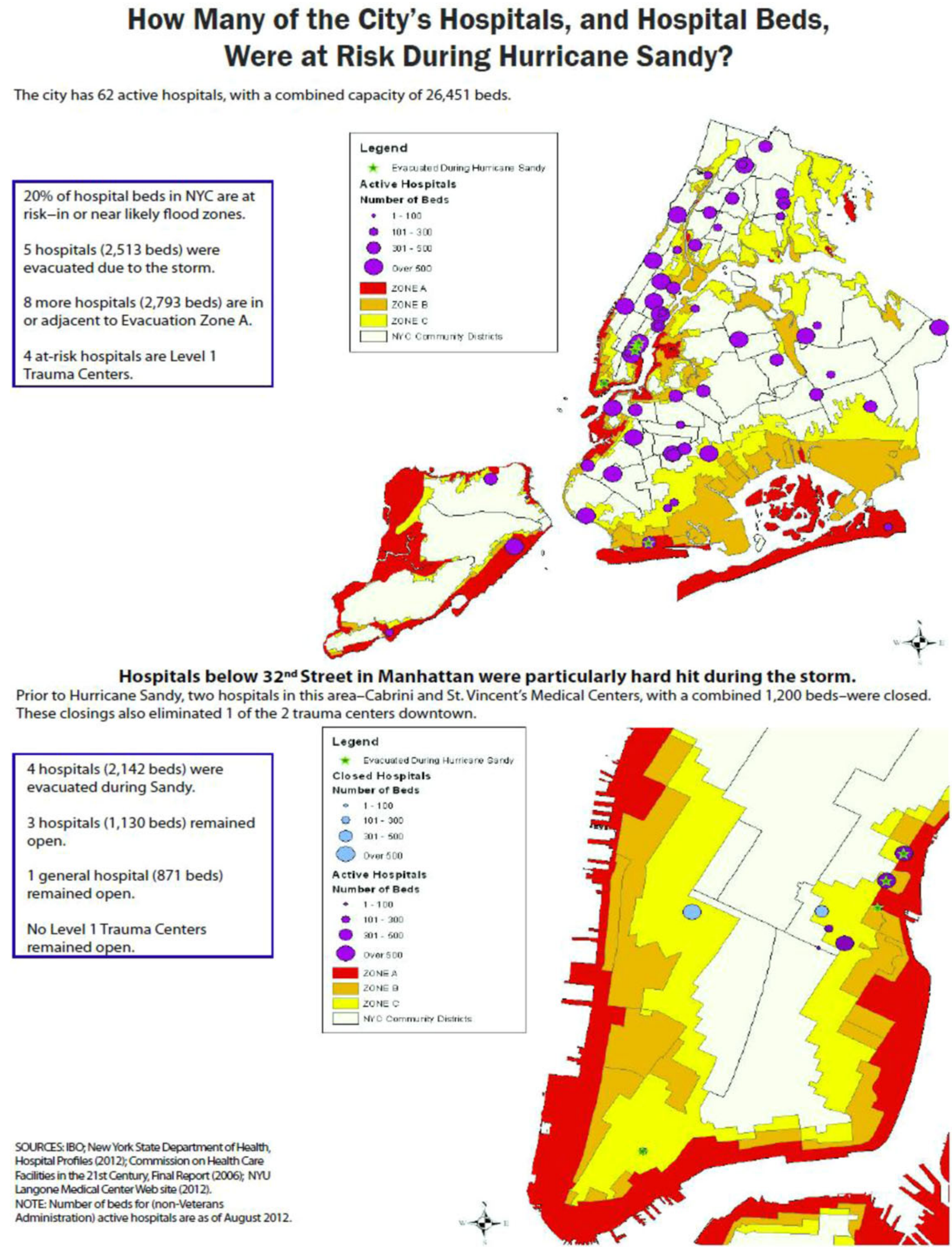

Figure 7.2. Risk to hospitals and hospital beds during Hurricane Sandy.

to ensure continuity of operations, there were substantial delays in returning to normal functions (Powell *et al.*, 2012). Bellevue Hospital, which evacuated patients and staff after the storm hit, did not restore inpatient wards until 2 weeks later (Teperman, 2013). The locations of hospitals and hospital beds considered at risk during Hurricane Sandy are shown in Figure 7.2 along with the city's zone designations for flood hazard at the time (NYC IBO, 2012; NYS Department of Health, 2012; Commission on Health Care Facilities in the 21st Century, 2006).

In 2014, the city announced $1.6 billion in funds from FEMA for hospital repairs, particularly noting repairs for four of the city's hospitals, which are Coney Island, Bellevue, Metropolitan, and Coler (City of New York, 2014). The destruction experienced by the NYU Langone Center illustrates particularly well the magnitude of impacts experienced by the communities served by the Center as a result of infrastructure disruptions.

According to FEMA (U.S. DHS, FEMA, 2017b, c), The NYU Langone Medical Center which is a private nonprofit facility consisting of the NYU School of Medicine, three hospitals, and specialized centers, experienced severe damages to its electrical infrastructure, backup power systems, and communications due to flooding related to storm surge conditions during Hurricane Sandy. The electric power and communications systems are interconnected as well, each relying on the other to function.

Public and private financial support enabled surgery units to open on December 27, 2012, pediatric services to open in January 2013, and emergency services to be available by April 2014. Subsequent funding for repairs supported long-term resilience and key resilience investments included the relocation of electrical equipment, drinking water, and fuel pumps to higher levels, as well as building flood walls aimed at protecting critical infrastructure on hospital campuses to the 500-year flood level (U.S. DHS, FEMA, 2017b,c).

The NYC Independent Budget Office summarized federal financial commitments for hospital repairs. From the nearly 1.6 billion in disaster relief funds, $1.3 billion were added to the city's capital budget and $260.5 million were added to the operating budget (NYC IBO, June 2016). NYC Health + Hospitals (2017) received $231.5 million in federal funds for repair and reconstruction projects, including improved protection from future storms. Of these funds, $208.8 million are planned for 2020 projects.

According to the City of New York Sandy Funding Tracker (NYC Recovery, 2018), some medical facilities where repairs are currently or recently underway include Jacobi Medical Center, Metropolitan Hospital, Roberto Clemente Family Guidance Center, and Bellevue Hospital. Examples of repair projects include "install[ing] pre-connections for external generators, temp boilers, and temp chillers" (Metropolitan Hospital), "build[ing] a floodwall and relocate[ing] the Emergency Department (ED) & critical infrastructure above the 500-year floodplain (Bellevue Hospital)," and strengthening the soffit support system to provide a "rigid system capable of resisting uplift loads experienced during Sandy" (Jacobi Medical Center).

7.4.1.2 Social impacts. Emergency hospital closures during disasters can have a myriad of short- and long-term consequences for the populations they serve and the healthcare system in general. For example, hospital evacuations, the process of moving patients from an at-risk location to a safer zone within the hospital or to another facility (Tekin *et al.*, 2017), may put critically ill patients at increased risk (King *et al.*, 2016) and pose a number of operational challenges for the medical facilities received by patients from evacuating hospitals (Adalja *et al.*, 2014).

According to reports, nearly 2000 patients were evacuated as a result of hospitals closings in the aftermath of Hurricane Sandy and transferred to medical facilities that struggled to meet their needs (City of New York, 2013: 16). One estimate was made by the NYC SIRR (City of New York, 2013) of the total costs to New York City hospitals associated with the emergency response to Hurricane Sandy (City of New York, 2013: 148) but revenue losses or the costs associated with restoring normal operations were probably not included.

The short-term challenges related to patient evacuation and absorbing citywide patient surge only highlight the most immediate social impacts of physical damage to hospitals, and secondary hospital "surge" issues need to be addressed. Studies have demonstrated that some of the greatest effects of a disaster on healthcare services utilization occur in the months and years following the immediate impact (Bell *et al.*, 2018; McQuade *et al.*, 2018; Sharp *et al.*, 2016). According to one analysis, "disasters create a secondary surge in casualties because of the sudden increased need for long-term health care" (Runkle *et al.*, 2012).

Although the mechanism through which disasters may affect long-term demand for healthcare services is not completely understood, it is well established that exposure to disasters poses particular challenges to individuals suffering from chronic health conditions such as heart disease, cancer, chronic respiratory, and diabetes (Mensah *et al.*, 2005; Sharp *et al.*, 2016). Therefore, hospital closures will likely have substantial and long-term consequences for the populations they serve.

7.4.1.3 Recommended adaptation measures. Hurricane Sandy resulted in around $3.1 billion dollars in estimated total healthcare damages, a substantial fraction of which likely reflects damages to hospitals (NYS Office of the Governor, 2012b). Improving the infrastructure resiliency of hospital facilities to climate-related extreme events will be essential for ensuring the continuity of healthcare services and reducing the adverse health impacts of disasters, particularly among the already vulnerable.

Adaptation planning with consideration of the hospital capacity and lifeline infrastructure in vulnerable areas will be essential for minimizing costs and damages to health institutions associated with future extreme weather events. For instance, four of the hospitals that evacuated during Hurricane Sandy New York Downtown Hospital, Manhattan VA Medical Center, Bellevue Hospital, and NYU Langone, are located in low lying areas in the southern portion of Manhattan. The southern portion of Manhattan is characterized by a high concentration of critical infrastructure, such as Con Edison's East 13th Street complex, in addition to a large number of hospitals, including those located in hospital row (City of New York, 2013: Chapter 18).

Health facilities and infrastructure in such vulnerable areas often serve communities well beyond their geographical scope. According to the NYS Department of Health, 20% of all New York City hospital beds are located in or near likely flood zones. Very importantly, a substantial amount of hospitals with over 500 beds are at risk, including Manhattan VA Medical Center, Bellevue Hospital, and NYU Langone (NYC Independent Budget Office, 2012).

Improving the resiliency of healthcare infrastructure is one of the most critical steps necessary to prevent human health and safety impacts during future weather events (Powell *et al.*, 2012; Redlener and Reilly, 2012). This will be especially critical in light of the increasing risk of flooding due to sea level rise. According to one estimate based on NPCC high-end sea level rise projections, "a total of 1000 New York City healthcare facilities will be in the 100-year floodplain by the 2050s (City of New York, 2013: 149)." Although estimates may vary depending on sea level rise scenarios used, this assessment highlights the vulnerability of the city's healthcare infrastructures and prompts urgent resilience measures.

The City of New York has already committed to ensuring better preparedness for future extreme weather events by enacting improved flood protection building codes and implementing emergency power systems resiliency measures (City of New York, 2013). Such measures, together with improved emergency preparedness plans at healthcare facilities, will be critical for ensuring the continuity of operations during climate and weather emergencies.

7.4.2 New York City Housing Authority and access to energy after Hurricane Sandy

The case of the New York City Housing Authority's (NYCHA) experiences in rethinking access to renewable energy during normal and emergency conditions illustrates many of the challenges this affordable housing resource faces in light of climate change and related extreme weather events. NYCHA's course of decision making and its projects also elevate the complexities embedded in Mayor Bill de Blasio's strategic focus on the intersection of equity, with an emphasis on inclusive growth that reduces poverty and expands job opportunities, and climate action designed to reduce risks and vulnerability while building sustainability and resilience at all scales (household, neighborhood, borough, and citywide) according to the OneNYC Progress Report (City of New York, 2018). (See Appendix 7.C for a fuller discussion of equity and climate related to critical infrastructure in New York City.)

Late October 2018 marked the sixth anniversary of Hurricane Sandy, which affected about 60,000 residents and damaged over 200 New York City

Housing Authority buildings. The infrastructure systems of these residential building sustained significant damage—residents had to endure the loss of electricity, elevators, heat, and hot water (Goodson *et al.*, 2016).

More than 400 NYCHA buildings throughout New York City were affected by the hurricane; 402 of those NYCHA buildings lost power, which also disabled elevator and compactor service, and 386 of those buildings lost heat and hot water (New York City CDBG-DR, November 2013; NYS CDBG April 2013). NYCHA housing stock in Coney Island, Brooklyn, sustained significant damage from sand and saltwater infiltration, while damage to other NYCHA housing stock was mostly the result of flooding.

U.S. DHS, FEMA (2015: 23) noted in connection with a New York City application to upgrade various facilities for portions of NYCHA housing and others that:

> The revised information depicted on the P-FIRMs has increased the number of NYCHA buildings located within the 100-year flood zone as compared to pre-Hurricane Sandy conditions. With one exception (Gowanus, located in Shaded Zone X), all NYCHA developments included in this PEA [Programmatic Environmental Assessment] are located in Zone AE.

In Figure 7.3, the location of NYCHA developments are shown with respect to 2015 Preliminary FIRM flood zones, and provided by NYCHA.

In the fall of 2017, NYCHA forecasted that projects designed to repair, fortify systems, and in NYCHA's terms "build back better," will be in construction through 2021 (Honan, 2017). Like almost all residential buildings in New York City, NYCHA infrastructure systems for heat, hot water, elevators, trash compacting, and other functions depend on grid-connected electrical power (U.S. DHS, FEMA, 2015: 7).

NYCHA (2017) is currently incorporating distributed energy resources (DERs) into its $3 billion Sandy Recovery and Resilience program, including one campus-scale microgrid. When complete, over 200 NYCHA buildings will benefit from emergency back-up power for full building loads (rather than critical building functions only). After evaluating generation technologies including combined heat and power (CHP) and solar PV, NYCHA chose to install gas-powered emergency back-up generators connected to a centrally controlled demand management system. NYCHA plans to off-set the maintenance cost of this infrastructure with revenues generated from peak shaving and demand response programs.

NYCHA is building a campus microgrid for more than 6000 residents of its Red Hook East and Red Hook West Houses (Red Hook NY, 2014). The Red Hook Houses back-up electric system may also allow the possibility for future integration with the Red Hook Community Micro-grid, another DER project under the auspices of the New York State Energy Research and Development Authority (NYSERDA) and the New York Power Authority (NYPA); this community-wide microgrid has listed solar and wind as its preferred sources of low-carbon power and natural gas as a backup alternative.

Looking beyond projects directly developed by NYCHA to NYCHA's participation in DER proposals and projects advanced by private entities illustrates the challenges and opportunities involved in designing DER projects that simultaneously meet goals for mitigation, resilience, and public benefit for the housing authority as well as technical viability and financial success for the private-sector partner. Since 2015, NYCHA has provided letters of interest to six DER (microgrid) projects led by private DER developers that in aggregate encompass 13,700 apartments and more than 13 million square feet of public housing. None of these projects have progressed beyond the concept phase.

In 2016, One City Block, a unit of Google, proposed the Eighth Avenue Microgrid, a DER that would include three natural gas–fired CHP microturbines to be located in NYCHA's Robert Fulton Houses, a solar array and a back pressure turbine to be located on the Google building in Chelsea, a West Side Manhattan neighborhood south of NY Pennsylvania Station (NY Prize Stage I Feasibility Study, Eight Avenue Microgrid, ERS, April 2016) (NYSERDA, 2016).

During normal, everyday operation, this DER would provide electricity to One City Block (the Google campus in former Port Authority buildings) and a substantial share of the steam needs of Fulton House's 945 apartments in 11 buildings. During an emergency, this DER would be "islanded' and would provide power for Google and the Fulton Houses apartments for approximately 7 days. This proposal won a first-round planning grant from NYSERDA,

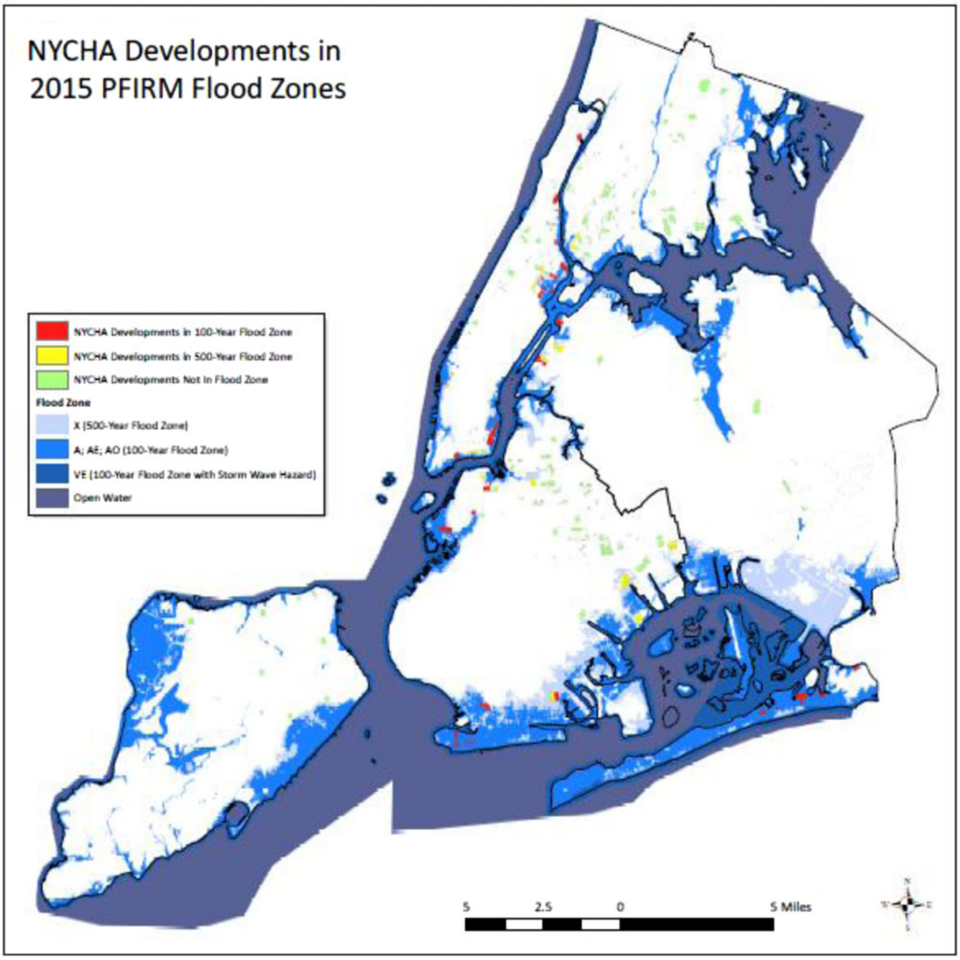

Figure 7.3. NYCHA developments and selected flood zone locations. Source: NYCHA with FEMA 2015 Preliminary FIRM.

but the proposal failed to advance to later stages of the NYSERDA competition. Though this is a single project, it is an important model.

In 2016, NYCHA began to evaluate development options for solar PV-based DERs, informed both by the need to provide emergency back-up power for critical building systems and by its Sustainability Agenda goals (NYCHA, 2017). In light of NYCHA's electric supply contract with the New York Power Authority, capital constraints, and regulatory and rate-structure limitations in its ability to participate in remote net metering and as an off-taker in community distributed solar, NYCHA ultimately came to the conclusion that the currently economically viable solar development option is limited to leasing rooftops and parking canopy space to private solar developers.

Accordingly, NYCHA released two solicitations for solar development: in 2017, for commercial-scale solar projects, and in 2018 for its small buildings. NYCHA seeks to site 25 megawatts of renewables on NYCHA property by 2026; however, it is yet to be seen whether any of these projects could be structured to provide an emergency back-up function for NYCHA's critical building systems.

NYCHA's DER projects, both those led by NYCHA and those in which it is a public-sector participant in a public–private partnership (P3), underscore the substantial, near-term challenges that New York City and New York State face in rightsizing DER projects and designing viable P3s. In addition to the mitigation and resilience benefits of viable DER projects, New York City at a variety of scales—City Hall, borough, neighborhood—should continue to advocate policies that highlight the economic benefits and co-benefits of DERs.

Two incumbent DER operations—one at Co-op City in the Bronx and the other at New York University's Greenwich Village campus—may provide lessons learned as New York City builds out its DERs policy and projects. Building connected to New York University's microgrid on its Greenwich Village campus continued to provide electricity during and after Hurricane Sandy. In the Bronx, Co-op City, home to 60,000 people in 35 high-rise buildings and seven sets of townhouses used its microgrid to continue supplying electricity for heat, hot water, and air conditioning, while nearby neighborhoods went without power (Leonhardt *et al.*, 2015).

New York City and the Empire State's transition to low-carbon and zero-carbon feedstocks for energy by 2050 will transform energy generation, transmission, and delivery as energy users in all sectors (public, private, and independent) move from reliance on utility-scale grid-based power to a system where a growing share of power needs under normal conditions and during emergencies will flow from distributed energy sources linked to battery storage units. This emerging structural shift in the sources and assets for energy, as well as other elements of mitigation, adaptation, and resilience, is creating new challenges, opportunities, economic benefits, and cobenefits in all sectors and many communities, including low-income, low-wealth communities.

7.5 Insurance and finance strategies for citywide resilience

Insurance and finance are key dimensions in achieving infrastructure resilience.

7.5.1 Insurance[a]

Economic and insured losses from hurricanes and floods have increased significantly over the last several decades and are likely to increase further in the future from more intense hurricanes and sea level rise. There is general consensus that improvement in resilience to reduce future disruptions is a smart investment. Research is being conducted to improve understanding of infrastructure resilience from a climate change perspective along with other threats such as cyberattacks. However, the economic and financial considerations of resilience remain less explored.

The insurance industry can catalyze infrastructure resilience by encouraging investment in loss reduction measures prior to a disaster through a reduction in premiums to reflect lower claim payments. Losses from both natural disasters like hurricanes and floods and man-made disaster such as accidents, terrorism, and cyberattacks are often insured through traditional insurance products. Newer financial instruments like catastrophe bonds also facilitate the transfer of a portion of the risk from these types of hazards to investors.

Certain barriers prevent wider use of insurance-related instruments and other market-based incentives for improving infrastructure resilience. For example, government disaster relief can deter both the purchase of insurance and other risk-transfer instruments and investment in mitigation measures, thus increasing the reliance on taxpayers' money to aid the recovery process following severe losses from future disasters.

Addressing the following questions will help facilitate better understanding of the economic and financial facets of resilience:

- Who will pay for cost-effective mitigation measures that enhance resilience against future disasters?
- "What is the best way to finance resilience in the short-term and long-term?" (Kunreuther *et al.*, 2016: 3)
- How can we transfer more risk to the private sector to reduce reliance on post disaster taxpayers' money?

To answer these questions, it is critical to understand the nature of federal disaster relief, economic constraints, and behavioral limitations that need to be overcome. Two infrastructure sectors are the focus of this work: energy utilities and transportation.

7.5.1.1 Nature of federal disaster relief and its relationships to insurance. Governments often serve as the insurer of last resort (King *et al.*, 2013, Pidot, 2007), and the role that the federal

[a]Some of the material in this section is taken from Kunreuther *et al.* (2016). Partial support for this research comes from a grant to Wharton Risk Center from the National Critical Infrastructure Resilience Center of Excellence through the University of Illinois 2015-ST-061-CIRC01, "Identifying and Reducing Barriers to Infrastructure Insurance."

government plays in disaster relief has been continually growing. The Stafford Disaster Relief and Emergency Assistance Act (Public law 100–707) plays a key role in providing emergency funds following disasters that impact public sector infrastructure by providing funds to cover at least 75% of the cost of recovery and repair following a Presidentially declared disaster (it was 100% after Hurricane Katrina). Further details on federal disaster relief funding are discussed in the next section under financing, and this section addresses its relationship to insurance.

While the Stafford Act supports community recovery following a disaster, it can also inhibit infrastructure resiliency in a couple of ways. First, with the knowledge that federal funds may be available following a disaster should their facilities incur damage, infrastructure managers may have less of a financial motivation to invest in loss mitigation measures or to purchase insurance to make their systems more resilient in light of potential future disasters. Second, Stafford Act funding typically only covers the costs to restore an infrastructure system to its predisaster design. It generally does not pay for the costs associated with improving an infrastructure system's resilience to future disasters. When other sources of resiliency funds are available, improvements can be made in conjunction with restoration, but this is often infeasible given budget limitations (Kunreuther *et al.*, 2016).

Though the Stafford Act in its current form serves in some ways as a deterrent to infrastructure resilience, it could potentially be modified to encourage communities and infrastructure managers to exhibit greater financial responsibility and to undertake adaptation measures to reduce losses prior to a future disaster. One revision that FEMA proposed to the Stafford Act would compel a state to meet a disaster deductible prior to receiving recovery funds. The deductible could take on a variety of forms such as emergency savings or predisaster mitigation measures. Such modifications could reduce the reliance of infrastructure systems on federal disaster relief funds and could encourage increased insurance and mitigation (U.S. DHS, FEMA, 2016).

Reliance on federal disaster relief also potentially hinders the ability of the insurance market to effectively price and share risks (King *et al.*, 2013, Pidot, 2007). Improvements to the Stafford Act could potentially address this concern. With reduced reliance on federal disaster relief funds, infrastructure managers will be incentivized to purchase sufficient insurance to cover losses should a disaster occur.

Insurance can also serve as a tool to incentivize mitigation, wherein an infrastructure system could receive a premium discount or improved policy terms if they employ mitigation measures to reduce the potential losses from a natural disaster and insurance premiums reflect this reduction in risk. When evaluating mitigation measures and insurance policies, one also needs to take into account how climate change will impact the environment (e.g., sea level rise). This is important in determining ways to protect existing infrastructure (e.g., sea walls) and in designing insurance mechanisms to support these measures.

In addition to federal disaster relief posing a disincentive to insurance purchase and risk reduction investment, other challenges also limit infrastructure system resiliency. One challenge is a lack of information sharing among critical infrastructure organizations. Due to security concerns, sharing of information about system vulnerabilities between infrastructure organizations typically does not occur. However, this information could be helpful for preparedness planning and for understanding risks associated with infrastructure interdependencies.

A second challenge is a lack of direct experience with major disasters on the part of many infrastructure managers, which may limit the understanding of vulnerabilities in their systems. While some infrastructure managers may gain insight from disasters experienced in other places or by other infrastructure systems, they may be limited in their understanding of necessary investments to reduce future losses and improve system resiliency toward disasters. For these reasons, and in light of budget limitations, decisions and expenditures for improving infrastructure resiliency for the future are often delayed in the absence of economic incentives in the present (Chang *et al.*, 2014).

7.5.1.2 Insurance for specific infrastructure sectors. Insurance needs and policies vary for infrastructure systems based on the type of system, risks faced, funding sources, and other factors. In this section, we consider insurance for electric utilities and transit infrastructure.

Insurance for Damage or Disruption of Electric Utilities. Electric utilities are typically insured, and the cost of the premium is embedded in the electricity rates paid by customers. Insurance needs vary for electricity producers and distributors. Electricity producers are typically insured against property damage and business interruption. Electricity distributors usually also have coverage for business interruption; however, property damage coverage is limited for distribution systems due to the significant exposure of their transmission and distribution lines.

Newer insurance products available to electric utilities provide coverage against losses associated with adverse weather events such as warm winters that impact profits. Separate business interruption insurance for losses associated with compromised or lost data due to operator error and cyber risk from hackers, data malware, and other malicious cyber risks is also available (Bruch *et al.*, 2011).

Transit/Rail Infrastructure Insurance. Rail organizations generally seek private insurance for catastrophe risks. Considerations in insurance coverage for rail companies include the class and size of the railway as well as local laws. Coverage is typically first party on an all-risk, replacement cost basis through companies such as Lexington (AIG), Lloyds, and the continental European market.

The amount of coverage that insured parties received following Hurricane Sandy depended on whether the damage was attributed to flooding or to storm surge. Flood coverage is usually subject to an aggregate limit, whereas storm surge coverage is not. For some infrastructure systems, recovery and restoration after a disaster is a long process, and it can take the insured a long time to recoup their losses as was true following Hurricane Sandy (Kunreuther *et al.*, 2016).

Public transit operators generally have some combination of self-insurance and commercial insurance for their systems, but coverage types and amounts vary greatly between different organizations. Due to budgetary limitations and a focus on insurance needs for other risks, as noted in the prior section, many transit infrastructure systems are not sufficiently insured against natural hazards and other catastrophic risks and are reliant on federal relief funds to recover from catastrophic disruptions.

The U.S. DOT Federal Transit Administration's (FTA) Emergency Relief Program (ERP) provides assistance to public transit operators in the aftermath of an emergency or major disaster, and eligibility for such funding relates in some ways to insurance requirements. The FTA program has helped states and public transportation systems fund the protection, repair, or replacement of equipment and facilities that are damaged due to emergencies and natural disasters (U.S. DOT, FTA, 2018a).

The ERP was established under the Moving Ahead for Progress in the 21st Century (MAP-21) Act, and seeks to improve U.S. DOT and U.S. DHS coordination for the purpose of expediting emergency assistance to public transit systems (U.S. House of Representatives, 2015). The ERP funds emergency relief projects including emergency operations, protective measures, emergency repairs, permanent repairs, resilience improvements, and the purchase of spare parts. Disaster relief resources provided by the FTA are separate from those provided by FEMA.

Flood insurance is required for transit-related buildings and stations and terminals that are situated above-ground and within a FEMA Special Flood Hazard Area (SFHA), also known as the mapped 100-year floodplain. Certain facilities do not require flood insurance, for example, "underground subway facilities, tunnels, ferry docks, or any transit facilities located outside of a SFHA" (Kunreuther *et al.*, 2016: 34).

If a building in the SFHA is uninsured at the time of a disaster and has previously received prior federal funding, the FTA (U.S. DOT, FTA, 2018b) will only fund a reduced amount of disaster assistance. The eligible amount is established by subtracting the maximum limit of coverage ($500,000) available under the National Flood Insurance Program (NFIP) or the amount of prior federal funding received, whichever is less, from the total restoration cost. The ERP received $10.9 billion from the Disaster Relief Appropriations Act of 2013 for Hurricane Sandy recovery (U.S. DOT, FTA, 2018a, b).

The Metropolitan Transportation Authority (MTA): Insurance and Government Relief. Hurricane Sandy provides a good illustration of costs and disruptions to taxpayers associated with insufficient infrastructure resilience. Congress allocated more than $50 billion in funds for Hurricane Sandy recovery efforts across the entire affected area, and more than $17 billion of this funding was allocated for projects in New York City (NYC Sandy Recovery, 2018). A substantial amount of this funding was allocated to infrastructure, including transportation infrastructure systems. The MTA is a public benefit corporation that is responsible for public transportation. MTA experienced more than $5 billion in damage during Hurricane Sandy, including substantial damage to rail and subway systems. The MTA's property insurance paid out at the policy limit of $1.1 billion for Hurricane Sandy, which only covered a fraction of MTA's losses.

The MTA also received $4.2 billion in federal relief from the U.S. Department of Transportation Federal Transportation Administration (FTA) under the ERF. This $4.2 billion included $900 million for resilience improvements. FEMA also provided $3.7 million for emergency repairs to equipment and facilities such as damaged tracks, signals, power lines, communication links, and stations (Kunreuther *et al.*, 2016; Czajkowski *et al.*, 2017).

Following Sandy, the MTA established a Sandy Recovery and Resiliency Division, with a key goal being to protect the many places where their subway system is prone to future flooding (Metropolitan Transportation Authority, 2016).

Following Sandy, the MTA was unable to renew its annual insurance policy under predisaster terms. They were offered only a policy that halved their coverage and doubled premiums, so they sought other forms of risk transfer. In July 2013, the MTA issued a $200 million catastrophe bond with stable premiums over the next 3 years in order to transfer a portion of its exposure to future storm surges to the financial markets. The bond would pay the MTA $200 million if specified storm surge conditions occurred during that period; the funding would be provided rapidly after storm surge damage estimates were completed (Kunreuther and Michel-Kerjan, 2013).

The extensive cost to taxpayers plus the substantial business interruption that occurred in the aftermath of Hurricane Sandy illustrate the need for infrastructure resiliency improvements. Financial and insurance mechanisms, along with regulatory mechanisms, can be used to facilitate resilience via mitigation and insurance. In addition to substantial federal disaster relief expenditures, there was a substantial cost to the insurance industry associated with Hurricane Sandy. Total insured losses equaled around $37 billion. $20 to $25 billion of this cost was incurred by private insurers, with the rest incurred by the NFIP (Kunreuther *et al.*, 2016).

7.5.1.3 Proposals for utilizing insurance to enhance infrastructure resilience. Interactions and interviews with leaders of the insurance and reinsurance industry involved in risk management for rail, transit, air, and marine transportation infrastructure revealed that enhancements to infrastructure resilience and insurance are needed to address the challenge of increasing losses associated with catastrophic events.

Seven recommendations for utilizing insurance to foster resilience in critical infrastructure in the New York metropolitan region as well as other parts of the country emerged from these interviews and a review of the existing literature that are detailed in Czajkowski *et al.* (2017: 2).

The recommendations are (1) continue working toward revisions of the Stafford Act; (2) promote alternative funding vehicles for pre-event resiliency investments linked to discounts in insurance premiums; (3) facilitate catastrophic risk data collection, availability, and analysis to better relate resilience improvements to insurance premiums and cost savings; (4) encourage the development of resilience metrics; (5) support research pertaining to emerging catastrophic risks such as cyber and climate change; (6) consider a redefinition of terrorism for coverage under the Terrorism Risk Insurance Act (TRIA); and (7) promote the comprehensive benefits, beyond a straightforward loss backstop, of catastrophic risk insurance coverage for infrastructure systems (Czajkowski *et al.*, 2017).

7.5.2 Infrastructure finance

A robust and sustainable infrastructure financing system is at the core of infrastructure resilience. A 2016 study of spending in global megacities for resilience and adaptation indicated that New York City ranked first in total spending, ranked second in spending per capita, and tied for third for spending per dollar of GDP for climate change adaptation (Georgeson *et al.*, 2016).

Estimates of infrastructure needs are a useful prerequisite for investment. Needs are usually linked to performance standards, some of which are incorporating resilience in the face of climate change and extreme events, including GHG mitigation measures either directly or indirectly associated with climate change. Chapter 7, Indicators and

Monitoring, of the 2010 NPCC report (Jacob *et al.*, 2010) addressed these metrics, and some are also revisited in Chapter 8, Indicators and Monitoring. For U.S. infrastructure, investment needs have been estimated by the ASCE (2017) as over 4 trillion dollars nationwide for the period from 2015 to 2025 (ASCE, 2017: 8). Needs assessments do not always explicitly or directly include climate change requirements for resilient infrastructure.

The financing mechanisms that support New York City's infrastructure draw from diverse financing sources, in particular with respect to the public and private mix, level of government, and the conditions or applicability, and type of infrastructure. With respect to level of government, one example for transportation is the New York Metropolitan Transportation Council (NYMTC; NYMTC, undated web site), whose functions include "decisions on the use of federal transportation funds for its planning" that encompasses New York City. The mechanisms can also change under different conditions and over time. This section focuses on three financial mechanisms: (1) Federal Disaster Assistance, (2) Bonds, and (3) Green Infrastructure Grant and Loan Opportunities.

7.5.2.1 Federal disaster assistance. Federal disaster assistance is a major source of federal funding available to aid in infrastructure restoration following certain disasters. Some aspects of federal disaster assistance were addressed above in connection with infrastructure and insurance, and this section provides a general coverage of the program as it pertains to extreme events that are relevant to New York City. Moody's Investor Service (2017) used Hurricane Sandy to illustrate the diversity of funds that were provided for emergency relief and recovery, and in particular reflected FEMA's role and the changing nature of its financial resources.

General coverage included:

- Typical FEMA coverage for "emergency response and debris cleanup": minimum 75%
- Usual coverage: 90% or more

Hurricane Sandy coverage included:

- FEMA: 100% "of certain emergency response and cleanup costs"
- Additional disaster relief from Congress: supplements for $48 billion
- Additional sources were: "Community Development Block Grants, FEMA, and National Flood Insurance Program housing aid, other supplemental federal funds and the Sandy supplemental measure" (Moody's Investor Service, 2017: 15). More details on these are provided below.

Disaster assistance for Hurricane Sandy came from the following federal agencies: FEMA (23%), Housing and Urban Development (HUD) (32%), the Department of Defense (DOD) (11%), the Department of Transportation (DOT) (26%), and other Federal agencies (8%). Involvement of Federal agencies besides FEMA and HUD typically depends on the source and scale of the disaster and what types of entities are affected. For instance, the DOT is generally involved when a disaster has a significant impact on transportation infrastructure. Certain sources of federal relief require a Presidential Disaster Declaration under the Stafford Act, while some do not. Additionally, some types of federal funding can be applied to resilience improvements, while others are solely allocated for restoration or replacement in-kind (Kunreuther *et al.*, 2016).

As indicated above in connection with hurricanes, disaster assistance levels administered by FEMA can be expanded and adapted to specific events and targeted for infrastructure. For example, the 2018 California wildfires are a case in point. The linkage between the wildfires and climate change has not been well developed though it is believed to be related in part to the extensive drought period that preceded the fires in California. In response to the southern California fires, FEMA's authority to fund infrastructure improvements was expanded by Congress on November 28, 2017 (U.S. DHS, FEMA, 2017c).

Emergency conditions open up a range of other funding options, such as state and federal disaster relief funds administered, for example, by FEMA and U.S. DOT programs for transportation-related recovery at the federal level to fund state and local areas, including dedicated emergency funds that have had caps (Zimmerman, 2012).

Agencies have made grant provisions for infrastructure that potentially can apply to climate change needs (see, for example, U.S. EPA, 2017a). FEMA also issues hazard mitigation grants (U.S. DHS, FEMA, 2017a).

7.5.2.2 Bonds. Bonds issued for infrastructure include general obligation bonds, revenue bonds, and special purpose bonds such as green bonds, and as indicated in the section on insurance, catastrophe bonds, for example, for the MTA. Catastrophe bonds are issued by reinsurance companies and recently by FEMA in connection with the National Flood Insurance Program (Friedman, 2018). Green bonds are of increasing importance, especially for green infrastructure support (City of New York Office of the Comptroller, April 2015).

Green bonds operate like traditional municipal bonds, but unlike traditional municipal bonds, they are used exclusively to fund environmentally friendly or climate mitigating projects and are often synonymous with climate bonds.

According to the New York City Office of Management and Budget (OMB) information (NYC OMB, December 14, 2018 for these and following quotations), the NYC OMB has indicated that "to date, the City of New York has funded all of its environmentally friendly or climate mitigating projects with traditional municipal bonds, after determining, in consultation with participants in the green bonds market, that green bonds do not provide cost savings to the city and actually include complex reporting requirements that could be administratively burdensome.

Additionally, the investor base for municipal green bonds remains small. The city, as a frequent issuer, minimizes borrowing costs by tapping a broad pool of investors that participates in the larger, more mature traditional municipal bond market."

An example of climate bonds being used in New York City is the MTA Transportation Revenue Green Bonds (The Climate Bonds Initiative, 2018). These bonds were first issued in February 2016 and have resulted in $5,489,500,000 for subway infrastructure renewal and upgrade, including electrification (The Climate Bonds Initiative, 2018). The MTA worked with the Climate Bonds Initiative (2018) to certify the bonds using the Low Carbon Transport criteria.

According to information provided by the NYC OMB, "The decision to issue green bonds does not in and of itself mean that additional funds are available to fund environmentally friendly or climate mitigating projects."

Bond ratings, covered in Chapter 8 on Indicators and Monitoring, are fundamental indicators for the strength of bonds as a financing mechanism. Chapter 8 addresses how bond ratings can reflect climate change considerations. Moody's, Standard & Poor, and Fitch are among the major bond rating organizations, and have generally consistently rated New York City bonds high.

According to information provided by the NYC OMB, NYC OMB has indicated that "Further, both bond rating organizations and investors have consistently commented that the City of New York's disclosure in its offering documents is among the best with regards to its comprehensive discussion of the potential impacts of climate change."

Different public authorities issue bonds separately. Some of the authorities relevant to infrastructure for New York City are the Metropolitan Transportation Authority (MTA) and the Port Authority of NY and NJ for the transportation sector, and the New York City Municipal Water Finance Authority for the water sector.

7.5.2.3 New York State green infrastructure loan and grant programs and New York City climate change needs.

NYS State Revolving Fund (SRF) program

State revolving funds were set up by Congress separately for clean water and drinking water as amendments to the U.S. Clean Water Act in 1987 (U.S. EPA, 2018a) and U.S. Safe Drinking Water Act in 1996 (U.S. EPA, May 8, 2018b), respectively. Eligibility under the Clean Water State Revolving Fund (CWSRF) program has gradually been expanded under various amendments (U.S. EPA, April 18, 2018) to include green infrastructure (U.S. EPA, April 23, 2018; U.S. EPA, May 2016; Environmental Finance Center Network, 2017).

The U.S. Code of Federal Regulations (2011: Article 35.3135(b) indicates that funds are provided by the federal government with at least a 20% state match (U.S. EPA, March 6, 2018). According to the U.S. EPA (2016), green infrastructure projects are eligible for financing for water management, and green infrastructure projects include: stormwater and wet weather issues, energy efficiency, water efficiency, and innovative approaches to managing water resources. "Climate resilience" is explicitly a criterion for funding under SRF (U.S. EPA, 2016: 8) and planning activities connected with climate change are eligible for funding.

As summarized by the U.S. EPA (March 6, 2018), the CWSRF offers a variety of different types of financial support including loans, loan guarantees, purchasing or refinancing debt, debt guarantees to improve interest rates and access to funds, insurance, and under some circumstances "principal forgiveness, negative interest rate loans, or grants." In New York State, Clean Water State Revolving funds are coadministered by the NYS Environmental Facilities Corporation (EFC) and the NYS Department of Environmental Conservation. Similarly, the Drinking Water State Revolving funds are coadministered by the NYS EFC and the NYS Department of Health.

Examples of applicable wastewater and clean water improvements eligible for funding under the NYS EFC include: "construction or restoration of sewers and wastewater treatment facilities, stormwater management, landfill closures, as well as habitat restoration and protection projects" (NYS EFC, undated web site, Clean Water State Revolving Fund).

The EFC provides low-cost financing in the form of low to no interested loans through the CWSRF and Drinking Water State Revolving Fund. Both funds compile an annual priority list to strategically issue loans as funding allows. For fiscal year 2018, of the potential New York City projects on the CWSRF priority list, two are specifically for green infrastructure: one is for a green roof and the other is for NYC DOT porous pavement (NYS EFC, 2018).

The NYC OMB (December 14, 2018) notes further that "Through its Municipal Water Finance Authority and the Department of Environmental Protection, NYC is the largest recipient of the NYS CWSRF and DWSRF funds, which are used to fund a number of environmental projects, such as the Newtown Creek Wastewater Treatment Plant upgrade."

Green Grant Programs

In addition to lending money, the EFC also provides several grant opportunities: the Water Infrastructure Improvement Act Grants for infrastructure projects at municipally owned sewage treatment or public water systems, the Inter-municipal Water Infrastructure Grants Program for projects impacting multiple municipalities, the Integrated Solutions Construction Grants for green infrastructure components of Clean Water State Revolving Fund projects, the Green Innovation Grant Program (GIGP) for green infrastructure projects not receiving revolving fund loans, and Engineering Planning Grants for planning costs associated with water infrastructure projects.

Focusing on the GIGP, the GIGP (NYS EFC, undated web site, Green Innovation Grant Program) is specifically targeted to the support of a variety of different types of green infrastructure projects. The funding provides "a minimum of 40% up to a maximum of 90% of the total eligible project costs as provided in the application. A minimum of 10% up to 60% match from state or local sources is required." (EFC undated web site, Green Innovation Grant Program.)

The EFC reported that "Through 8 Rounds, GIGP has awarded \$140.2 million to over 190 GIGP projects across New York State" (NYS EFC, 2017a). Under the GIGP from 2009 through 2016, New York City funding under the GIGP accounted for about 7% of the total statewide funding (NYS EFC 2017b).

Most of the projects funded in New York City under the GIGP occurred in 2011 and 2012, with those 2 years accounting for 60% of the total through 2016 (NYS EFC, 2017b). The last Green Innovation Grant reported for New York City was in 2015 for a Department of Transportation project valued at \$1,200,000 (NYS EFC, 2017b).

7.6 Interactions with mitigation: energy and transportation

Transformation of the five boroughs of the City of New York into a sustainable metropolis over the course of the 21st century will require all sectors of the city—public, private, and independent sectors—to reduce locally generated sources of carbon emissions as well as indirect transboundary emissions that are embedded in the imported goods and services New York City consumes.

Efforts to reduce carbon from the built environment and vehicles—important sources of locally generated CO_2—have received more policy focus than efforts to reduce indirect, transboundary emissions that are part of every New Yorker's carbon footprint. Details on how New York City is preparing to reach its commitment of reducing GHG emissions 80% by 2050 are presented in Appendix 7.C.

This section highlights the important interface between two key infrastructure systems–energy and transportation–and mitigation efforts that must accompany resiliency efforts. Within these two sectors, some conflicts or tensions between mitigation and adaptation are illustrated with examples.

7.6.1 Energy

The interface between energy and other sectors is a key to mitigation efforts given the substantial contribution of the built environment to energy-related emissions in New York City either directly or indirectly. Energy providers have an interest in the energy efficiency of their clients if they are to lower the carbon footprint of energy. The providers need to manage peak load efficiently with greater certainty about capacity and growth.

New construction and major renovation of infrastructure in the private sector and independent sectors in the five boroughs of the city offer major opportunities to reduce CO_2 emissions and transition to lower carbon, greener energy feedstocks, coupled with initiatives to reduce water and waste footprints in the built environment which includes infrastructure.

Increased use of solar energy on a building scale is growing in importance in NYC. As of July 2018, there are over 154 MW across 15,000 solar installations in NYC. This is a sixfold increase from December 2013 (since this current Administration took office). For example, Grant (2017) summarized the Stuyvesant Town complex's plans to add solar energy to many of its building. Other means of improving energy use have been cited as well. The Urban Green Council was cited as indicating that from 2010 to 2015 energy reduction in existing buildings has amounted to 10% from power plant improvements and oil to natural gas conversions (Grant, 2017).

Distributed generation and new technologies such as micro-grids to improve the resilience of the energy delivery system are underway. The development of resilience is not only occurring at the facilities level, but also at the level of the users. Energy efficient buildings are a top priority and have expanded in NYC.

As indicated by the National Academies (NAS) (2016: 59): "The government of New York City exercises direct control over a small share of the built environment through ownership or use for governmental purposes as well as regulation over other sectors. Mazria (2015) offered a guide to proposed changes in the New York City Energy Conservation Code to support energy efficiency and renewable energy in order to catalyze a reduction of GHG emissions from the built environment that is largely controlled by the private sector and nonprofit or civic sector."

Some adaptation measures are not without conflicts with mitigation. For example, air cooling is needed to adapt to increasing heat waves; however, it contributes to energy demand which in turn increases CO_2emission. The IEA (2018) has identified many interconnections between air cooling and electric power usage. In particular, the IEA (2018) report notes that air cooling is growing faster than any other sector for energy use, is currently 10% of the use of energy globally, and by 2050 is expected to account for 37% of electricity demand, and energy demand from AC use could be reduced with better performing units that potentially can reduce CO_2 emissions from that source.

7.6.2 Transportation

A number of components for transportation mitigation are critical in NYC. First is the conversion of public transit diesel to combined electric diesel or entirely electric facilities to reduce diesel-related emissions, which is one type of fuel option. The second pertains to privately owned vehicles associated with surface transportation, for example, the switch to electric vehicles to reduce or avoid transportation emissions.

Connected with both of these is the feedstock issue, that is, where energy for transportation is coming from and to what extent these energy feedstocks can become greener. These issues pertain to decisions at much broader geographic levels and across many economic sectors, that is, transboundary issues, and these problems are beyond New York City and NYS MTA control.

A third component of transportation-related mitigation is the promotion of nonmotorized-based modes of travel such as biking and walking. New York City has promoted these modes through expanded numbers of bike lanes and pedestrian walkways and the availability of bike-share facilities.

A fourth component is an important transportation and urban planning and land use connection in mitigating energy use by transportation. Finally, other options are overall reduction of vehicle-miles of travel through demand management, increased use of transit, and new "shared mobility" concepts.

7.7 Conclusions and recommendations

The introduction of relatively new elements pertaining to infrastructure in NPCC3 provides lessons learned and new directions for future New York City resiliency efforts to parallel climate change projections.

Underlying or prior condition of infrastructure systems, usage versus capacity, and their ability to cope with environmental stresses are key factors in existing and future infrastructure vulnerabilities. An important element is locational lock-in that is, addressing long-standing traditions of the location of infrastructure facilities as well as the users of the services in areas vulnerable to damaging consequences of extreme events and climate change. An equity dimension exists in that not all sectors of society experience these infrastructure system conditions equally.

Interconnections among different infrastructures in the form of dependencies and interdependencies are becoming recognized as important factors in the escalation of adverse consequences resulting from extreme events and climate change. The next step will be to identify where the vital interconnection points are that produce cascading effects, the process by which those cascades occur, and how to reduce their effects through management and in some cases decentralization of infrastructure services to reduce intersection points. Data collection and metrics development are crucial to understanding and enhancing resilience, particularly toward emerging risks like climate change and cyber security.

New York State and New York City have experimented with the design, development, and deployment of DERs and battery storage. As the initiatives in Red Hook and Chelsea illustrate, these energy projects have created an opportunity to rigorously rethink and redefine the optimal balance between the share of energy that should be produced by utility sources, and the share of power that can be generated locally and close to the source of energy use under normal operating conditions.

Insurance and finance policies continually evolve to provide opportunities to reduce the cost of the consequences of climate change that can further expand to support adaptation and mitigation. Stafford Act funding following a disaster can serve as a disincentive to investment in resilience improvements, but modifications to the Stafford Act could help address this issue. Potential modifications could include availability of funding to implement resilience improvements in conjunction with repairs, and mechanisms to encourage predisaster resilience improvements and insurance purchase.

In this regard, public–private partnerships are essential for facilitating infrastructure resilience, particularly for publicly owned infrastructure systems which often lack budget for resilience improvements. These partnerships can involve insurance or financing mechanisms. Many of the mechanisms reflect a patchwork of applicability, and a coordination of these two areas is an important future direction to achieve consistent infrastructure goals to reduce climate change consequences.

Mitigation and adaptation tensions arise with respect to infrastructure choices, and some examples were presented for energy and transportation above. According to Grafakos *et al.* (2018: 105), these tensions are multidimensional and differ with respect to "spatial, temporal, institutional, and administrative scales." Attention to this will involve moving toward resolving conflicts and moving toward mechanisms that are more synergistic through processes to identify and resolve such conflicts.

The overall key findings and recommendations for critical infrastructure in the face of climate change are summarized below.

7.7.1 Key findings

1. Key infrastructure vulnerabilities exist for individual and interdependent infrastructure that are:
   - Not directly related to climate change, yet affect infrastructure resilience or the ability to withstand climate change stresses; examples include (1) low physical and functional condition and (2) usage potentially exceeding capacity; both indicate potential vulnerabilities for NYC
   - Directly related to climate change factors, such as heat, extreme precipitation, sea-level rise, and storms, for example, many vulnerabilities are locationally based: inventories indicate low-lying infrastructures
   - Creating the potential for vulnerabilities where interdependencies are involved, in the form of cascading impacts and these are not comprehensively understood
2. Community and infrastructure resilience case studies presented real-world instances of the

interface between critical infrastructure systems and climate change:

- Hospitals: New York City's 62 hospitals are dependent on transportation, power, and water, especially in emergencies; many hospitals and these infrastructures are at risk from flooding from location.
- NYCHA: In Hurricane Sandy, infrastructure service outages affected hundreds of buildings and thousands of residents; distributed energy and other service strategies are benefits.
- New York City's and New York State's transition to low-carbon and zero-carbon feedstocks for energy by 2050, as exemplified by NYCHA's exploration of distributed energy, will transform energy generation, transmission, and delivery.

3. Insurance mechanisms and federal disaster relief can be improved for better coverage in disasters; numerous and diverse financing mechanisms exist potentially applicable to climate risks; studies show that investments before disasters can lower postdisaster costs.

7.7.2 Key recommendations

NPCC3 makes the following recommendations for continued work in research and policy to address critical infrastructure risks in the New York metropolitan region:

Recommendations for Research:

- Improve knowledge of interactions between infrastructures and climate risks to understand vulnerability, requiring new science and data.

Recommendations for the City:

- Continue to work with the energy sector to develop improved resiliency to power outages.
- Increase financial strength, invest in infrastructure maintenance and upgrades, and work with insurance companies to encourage incentives with attention to the risks that infrastructure systems and their users experience.
- Integrate equity dimensions into planning for infrastructure adaptations to climate change in light of the four visions of OneNYC.
- Identify where the vital interconnection points are among different infrastructures (i.e., dependencies and interdependencies) to reduce cascading effects resulting from extreme events and climate change through management and in some cases decentralization.
- Provide access to infrastructure data and resources to explore infrastructure risks associated with climate change.

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References

Adalja, A.A., M. Watson, N. Bouri, *et al.* 2014. Absorbing citywide patient surge during Hurricane Sandy: a case study in accommodating multiple hospital evacuations. *Ann. Emerg. Med.* **64:** 66–73.

Adger, W.N. 2006. Vulnerability. *Glob. Environ. Change* **16:** 268–281.

The Advisory Committee for Environmental Research & Education. 2018. Sustainable urban systems: articulating a long-term convergence research agenda. Accessed February 2, 2019. https://www.nsf.gov/ere/ereweb/ac-ere/sustainable-urban-systems.pdf.

Alperovitz, G. & the Democracy Collaborative. 2017. Principles of a pluralist commonwealth.

American Public Transportation Association (APTA). 2015. *Public Transportation Fact Book.* Washington, DC: APTA.

Anel, J.A., M. Fernandez-Gonzalez, X. Labadeira, *et al.* 2017. Impact of cold waves and heat waves on the energy production sector. *Atmosphere* **8:** 1–13.

American Public Transportation Association (APTA). 2016. *2016 Public Transportation Fact Book Appendix A, Historic Tables.* Washington, DC: APTA.

American Society of Civil Engineers (ASCE). 2015. 2015 Report card for New York's infrastructure. Accessed December 16, 2018. content/uploads/2017/01/NY_ReportCard_FullReport_9.29.15_FINAL.pdf.

American Water Works Association. 2012. Buried no longer. Confronting America's water infrastructure challenge. http://www.climateneeds.umd.edu/reports/American-Water-Works.pdf.

ASCE. 2017. 2017 Report card for America's infrastructure. *Executive summary*. Washington, DC: ASCE. https://www.infrastructurereportcard.org/wp-content/uploads/2017/04/2017-IRC-Executive-Summary-FINAL-FINAL.pdf.

Barker, R. 2017. The Boise Greenbelt and parks like Marianne Williams are protecting homes by absorbing flood flows. Accessed December 16, 2018. http://www.idahostatesman.com/news/local/news-columns-blogs/letters-from-the-west/article145539009.html.

Bartos, M., M. Chester, N. Johnson, *et al.* 2016. Impacts of rising air temperatures on electric transmission ampacity and peak electricity load in the United States, Environ. *Res. Lett.* **11:** 114008.

Bell, S.A., M. Abir, H. Choi, *et al.* 2018. All-cause hospital admissions among older adults after a natural disaster. *Ann. Emerg. Med.* **71:** 746–754.e2.

Brown, L.M., D.M. Dosa, K. Thomas, *et al.* 2012. The effects of evacuation on nursing home residents with dementia. *Am. J. Alzheimer's Dis. Other Dement.* **27:** 406–412.

Bruch, M., V. Munch, M. Alchinger, *et al.* 2011. Power blackout risks. CRO Forum: Emerging Risk Initiative – Position Paper.

Chang, S.E., T. McDaniels, J. Fox, *et al.* 2014. Toward disaster-resilient cities: characterizing resilience of infrastructure systems with expert judgments. *Risk Anal.* **34:** 416–434.

Christiansen, N., M. Kaltschmitt, F. Dzukowski & F. Isensee. 2015. Electricity consumption of medical plug loads in hospital laboratories: identification, evaluation, prediction and verification. *Energy Build.* **107:** 392–406.

City of New York. 2013. Strategic initiative for rebuilding and resiliency (SIRR). A stronger, more resilient New York. Accessed December 16, 2018. https://media.nyc.gov/agencies/sirr/SIRR_singles_Lo_res.pdf.

City of New York. 2014. News release. Mayor de Blasio, Senator Schumer announce FEMA commitment of at least $1.6 billion to repair and protect Sandy-damaged public hospitals. Accessed December 16, 2018. https://www1.nyc.gov/office-of-the-mayor/news/507-14/mayor-de-blasio-senator-schumer-fema-commitment-at-least-1-6-billion-repair-and#/0.

City of New York. 2015. OneNYC: the plan for a strong and just City. New York, NY. Accessed December 16, 2018. http://www.nyc.gov/onenyc; http://www.nyc.gov/html/onenyc/downloads/pdf/publications/OneNYC.pdf.

City of New York. 2017. Inventory of New York City's greenhouse gas emissions, by Cventure LLC, Cathy Pasion, Christianah Oyenuga, and Kate Gouin. New York, NY: Mayor's Office of Sustainability. Accessed December 16, 2018. http://www.dec.ny.gov/docs/administration_pdf/nycghg.pdf.

City of New York. September, 2017. OneNYC 1.5 Celsius Aligning NYC with the Paris Climate Agreement. http://www1.nyc.gov/assets/sustainability/downloads/pdf/publications/1point5-AligningNYCwithParisAgrmtFORWEB.pdf.

City of New York. 2018. OneNYC Progress Report 2018.

Commission on Health Care Facilities in the 21st Century. 2006. A plan to stabilize and strengthen New York's health care system final report of the Commission. New York, NY: The Commission. Accessed December 16, 2018. https://nyhealthcarecommission.health.ny.gov/docs/final/commissionfinalreport.pdf.

Con Edison. May 26, 2016. Con Edison forecasts summer savings; $1.6 Billion invested for reliability. New York: Con Edison Media Relations. Accessed February 2, 2019. https://www.coned.com/en/about-con-edison/media/news/20160526/summer-savings.

Con Edison. July 27, 2017. Statement from Con Edison Media Relations Re: MTA project plan. Accessed February 2, 2019. https://www.coned.com/en/about-con-edison/media/news/20170727/statement-from-con-edison-mta-project-plan.

Con Edison. 2017. Our storm-hardening protection plan. https://www.coned.com/en/our-energy-future/our-energy-projects/storm-hardening-enhancement-plan.

Con Edison. October 19, 2017. *Con Edison's post-Sandy fortifications prove wise $1 billion investment for customers*, New York, NY: Con Edison. Accessed February 2, 2019. https://www.coned.com/en/about-con-edison/media/news/20171019/post-sandy-fortifications-prove-wise-1-billion-investment-customers.

Con Edison Company. Undated web page. Company history and statistical information. https://www.coned.com/en/about-us/corporate-facts.

Consolidated Edison Co. of New York and Orange and Rockland Utilities. 2013. Post-Sandy Enhancement Plan. Accessed February 2, 2019. https://www.coned.com/-/media/files/coned/documents/services-outages/post_sandy_enhancement_plan.pdf.

Cummings, B. 2017. Metro-North takes heat over Rye derailment. CTPost. https://www.ctpost.com/local/article/Metro-North-takes-heat-over-Rye-derailment-11164963.php.

Czajkowski, J., H. Kunreuther & G. Tonn. 2017. Identifying and reducing barriers to catastrophic risk insurance – transportation infrastructure systems. Wharton Management and Decision Processes Center White Paper, July 31. Accessed December 16, 2018. http://opim.wharton.upenn.edu/risk/library/WP2017July_CIRI-Phase-II.pdf.

Environmental Finance Center Network. 2017. New York water and wastewater funding sources. Accessed December 16, 2018. http://efcnetwork.org/wp-content/uploads/2017/09/NY-Water-Wastewater-Funds-2017.pdf.

Farmani, R. & D. Butler. 2013. Towards more resilient and adaptable water distribution systems under future demand uncertainty. *Water Sci. Technol. Water Supp.* **13:** v1495–v1506.

Federal Transit Administration (FTA). 2018. Funding allocations for hurricane sandy recovery and resiliency. Accessed December 16, 2018. https://www.transit.dot.gov/funding/grant-programs/emergency-relief-program/fta-funding-allocations-hurricane-sandy-recovery-and.

Fitzsimmons, E.G. 2017. Subway's slide in performance leaves straphangers fuming. New York Times. Accessed December 16, 2018. https://www.nytimes.com/2017/02/12/nyregion/subway-complaints-straphangers-fuming.html.

Flegenheimer, M. 2013. Power failure disrupts Metro North's New Haven Line; May last days. New York Times.

Accessed December 16, 2018. http://www.nytimes.com/2013/09/26/nyregion/metro-norths-new-haven-line-suspended-after-power-loss.html.

Folkman, S. 2018. Water main break rates in the USA and Canada: a comprehensive study. Mechanical and Aerospace Engineering Faculty Publications. Paper 174. Accessed December 16, 2018. https://digitalcommons.usu.edu/mae_facpub/174.

Friedman, N. 2018. FEMA seeks to shift risk. *Wall Street Journal*. Accessed December 16, 2018. https://www.wsj.com/articles/fema-wants-investors-to-provide-shelter-in-the-next-storm-1522880186.

Gallopín, G.C. 2006. Linkages between vulnerability, resilience, and adaptive capacity. *Glob. Environ. Change* **16:** 293–303.

Garfield, L. 2017. China is building 30 'sponge cities' that aim to soak up floodwater and prevent disaster. Accessed December 16, 2018. http://www.businessinsider.com/china-is-building-sponge-cities-that-absorb-water-2017-11.

Georgeson, L., M. Maslin, M. Poessinouw & S. Howard. 2016. Adaptation responses to climate change differ between global megacities. *Nat. Clim. Change* **6:** 584–588.

Goodson, M., M. Moore, M. Parikh & S. Platt. 2016. Recovery to resiliency: how NYCHA is reinventing itself through Sandy recovery. ACEEE Summer Study on Energy Efficiency in Buildings.

Grafakos, S., C. Pacteau, M. Delgado, *et al.* 2018. Integrating mitigation and adaptation: opportunities and challenges. In *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. C. Rosenzweig, W. Solecki, P. Romero-Lankao, *et al.* Eds.: 101–140. New York, NY: Cambridge University Press.

Grant, P. 2017. Stuytown owners make solar-panel investment. *Wall Street Journal*. Accessed December 16, 2018. https://www.wsj.com/articles/stuytown-owners-make-solar-panel-investment-1510098039.

Guenther, R. & J. Balbus. 2014. Primary protection: enhancing health care resilience for a changing climate. US Department of Health and Human Services. https://kresge.org/sites/default/files/Healthcare-Climate-Resilience-Guidance-HHS.pdf.

Honan, K. 2016. Manhole explosion near MTA substation causes major subway delays. *DNAInfo*. Accessed December 16, 2018. https://www.dnainfo.com/new-york/20161226/midtown/mta-seventh-avenue-trains-electrical-fire-no-service/.

Honan, K. 2017. Sandy-damaged NYCHA developments may not be fixed until 2021, official says. DNAInfo. Accessed December 16, 2018. https://www.dnainfo.com/new-york/20170301/far-rockaway/nycha-hurricane-sandy-repairs-resiliency-projects-delays.

Horton, R. & C. Rosenzweig, lead authors. 2010. Appendix A. Climate risk information in NYC: building a risk management response. In *NYC Panel on Climate Change 2010 Report*. C. Rosenzweig & W. Solecki, Eds.: 147–228, Vol. 1196. Prepared for use by the NYC Climate Change Adaptation Task Force. Annals of the New York Academy of Sciences. New York, NY: NY Academy of Sciences.

Horton, R., D. Bader, Y. Kushnir, *et al.* 2015. Chapter 1: climate observations and projections. In *NYC Panel on Climate Change 2015 Report*. C. Rosenzweig & W. Solecki, Eds.: 18–35, Vol. 1336. Annals of the New York Academy of Sciences.

I95 Corridor Coalition. 2013. Significant weather-related events bridge-highway closure policies survey summary of results. Accessed December 16, 2018. http://i95coalition.org/wp-content/uploads/2015/02/Bridge-HwyCloseSurveySummary-Report-10-2013FINALREV.pdf.

INRIX. 2017. U.S. traffic hotspot study 2017. Accessed December 16, 2018. http://www2.inrix.com/us-traffic-hotspot-study-2017.

Institute for Local Self-Reliance (ILSR). 2016. Beyond sharing — how to take ownership of renewable power. Accessed December 16, 2018. https://ilsr.org/wp-content/uploads/2016/04/Beyond-Sharing-Report-Executive-Summary.pdf.

Intergovernmental Panel on Climate Change (IPCC). 2007. IPCC fourth assessment report: climate change 2007. Accessed December 16, 2018. https://www.ipcc.ch/publications_and_data/ar4/wg2/en/annexessglossary-a-d.html.

International Energy Agency (IEA). 2018. The future of cooling (IEA 2018website). Accessed December 16, 2018. https://www.iea.org/cooling/.

Jacob, K. *et al.* 2009. MTA adaptations to climate change. A categorical imperative. Accessed December 16, 2018. http://web.mta.info/sustainability/pdf/Jacob_et%20al_MTA_Adaptation_Final_0309.pdf.

Jacob, K., R. Blake, *et al.* 2010. Indicators and monitoring, Chapter 7 in climate change adaptation in New York City: building a risk management response. In *New York City Panel on Climate Change 2010 Report*. C. Rosenzweig & W. Solecki, Eds.: 127–141, Vol. 1196. Prepared for use by the New York City Climate Change Adaptation Task Force. Annals of the New York Academy of Sciences. New York, NY: NY Academy of Sciences.

Jacobs, J.M., M. Culp, L. Cattaneo, *et al.* 2018. Transportation. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. D.R., Reidmiller, C.W. Avery, D.R. Easterling, *et al.*, Eds.: 479–511. Washington, DC: U.S. Global Change Research Program.

King, D., J. Ginger, S. Williams, *et al.* 2013. Planning, building and insuring: adaptation of built environment to climate change induced increased intensity of natural hazards. *National Climate Change Adaptation Research Facility, Gold Coast*.

King, M.A., M.V. Dorfman, S. Einav, *et al.* 2016. Evacuation of intensive care units during disaster: learning from the Hurricane Sandy experience. *Disaster Med. Public Health Prep.* **10:** 20–27.

Kinney, P.L., T. Matte, K. Knowlton, *et al.* 2015. NYC panel on climate change 2015 report, chapter 5: public health impacts and resiliency. *Ann. N.Y. Acad. Sci.* **1336:** 67–88.

Kunreuther, H. & E. Michel-Kerjan. 2013. Managing the risk of catastrophes: protecting critical infrastructure in urban areas. Presented to Federal Reserve Bank of New York. November 1.

Kunreuther, H., E. Michel-Kerjan & G. Tonn. 2016. Insurance and economic incentives for strengthening critical infrastructure resilience: 20 proposals for action. Wharton Risk Center White Paper. December. Accessed December 16, 2018. http://opim.wharton.upenn.edu/risk/library/WhartonRiskCenterReport.CIRI.Year1.Dec2016.pdf.

Leonhardt, D., T. Bourgeois, B. Bradford, *et al.* 2015. Microgrids & district energy: pathways to sustainable urban development. Pace University Law School, Pace Energy and Climate Center, White Plains, NY. Accessed December 16, 2018. https://digitalcommons.pace.edu/environmental/1/.

Lloyd, E. & A. Licata. Undated circa 2015. One New York City: one water sustainable water management for New York City's people and environment. http://www.nyc.gov/html/dep/pdf/climate/one-nyc-one-water.pdf.

Magill, B. 2014. In railways join the list of climate change's toll. Sci. Am. Accessed December 16, 2018. https://www.scientificamerican.com/article/sun-kinks-in-railways-join-the-list-of-climate-change-s-toll/.

Mazria, E. 2015. Achieving 80X50: reducing energy use, creating jobs and phasing out carbon emissions in New York City's buildings. Accessed December 16, 2018. http://www.alignny.org/wp-content/uploads/2015/07/Achieving-80X50_Final.pdf.

McGinty, M.D. 2015. Evacuate or shelter-in-place? Decision-making for hospitals during hurricane sandy. Accessed December 16, 2018. https://jscholarship.library.jhu.edu/handle/1774.2/39659?show=full.

McQuade, L., B. Merriman, M. Lyford, *et al.* 2018. Emergency department and inpatient health care services utilization by the elderly population: Hurricane Sandy in the state of New Jersey. *Disaster Med. Public Health Prep.* **12:** 730–738.

Mensah, G.A., A.H. Mokdad, S.F. Posner, *et al.* 2005. When chronic conditions become acute: prevention and control of chronic diseases and adverse health outcomes during natural disasters. *Prevent. Chronic Dis.* **2:** A04.

Metropolitan Transportation Authority (MTA). 2007. August 8, 2007 Storm report. New York, NY: MTA.

Moody's Investor Service. 2017. Environmental risks: evaluating the impact of climate change on US state and local issuers. New York, NY: Moody's. Accessed December 16, 2018. http://www.southeastfloridaclimatecompact.org/wp-content/uploads/2017/12/Evaluating-the-impact-of-climate-change-on-US-state-and-local-issuers-11-28-17.pdf.

Movement Strategy Center. 2015. Pathways to resilience: transforming cities in a changing climate. Accessed December 16, 2018. https://kresge.org/sites/default/files/Pathways-to-resilience-2015.pdf.

MTA. 2008. Blue Ribbon Commission on sustainability water sustainability report. Accessed December 16, 2018. http://web.mta.info/sustainability/pdf/MTA%20Water%20Sustainability%20Report%20Final.pdf.

MTA. 2009. Greening mass transit and metro regions, final report of the Blue Ribbon Commission on sustainability and the MTA. Accessed December 16, 2018. http://web.mta.info/sustainability/pdf/SustRptFinal.pdf.

MTA. 2013. Twenty-year capital needs assessment 2015—2034. Accessed December 16, 2018. http://web.mta.info/mta/capital/pdf/TYN2015-2034.pdf.

MTA. 2016. MTA to issue its first 'green bonds'. Accessed December 16, 2018. http://www.mta.info/news-bonds-green-bonds-mta/2016/02/10/mta-issue-its-first-%E2%80%98green-bonds%E2%80%99.

MTA. 2017. MTA Climate Adaptation Task Force Resiliency Report. Accessed February 21, 2019. http://web.mta.info/sustainability/pdf/ResiliencyReport.pdf.

MTA. 2018. Introduction to subway ridership. Accessed December 16, 2018. http://web.mta.info/nyct/facts/ridership/

MTA, undated website. Performance Data Sets. Accessed February 21, 2019. http://web.mta.info/developers/performance.hmtl.

National Academies of Sciences, Engineering, and Medicine. 2016. *Pathways to urban sustainability: challenges and opportunities for the United States.* Washington, DC: The National Academies Press. Accessed December 16, 2018. http://nap.edu/23551.

National Center for Transit Research. 2016. *State of good repair performance measures: assessing asset condition, age, and performance data final report.* Tampa, FL: University of South Florida. Accessed December 16, 2018. https://www.nctr.usf.edu/wp-content/uploads/2016/06/79060-2-B-State-of-Good-Repair-Performance-Measures.pdf.

National Grid. undated. National grid gas and electric service areas. Accessed December 16, 2018. https://www9.nationalgridus.com/non_html/a2_map_usa.pdf.

National Infrastructure Advisory Council (NIAC). 2013. Strengthening regional resilience through national, regional, and sector partnerships DRAFT report and recommendations. Accessed December 16, 2018. https://www.dhs.gov/sites/default/files/publications/niac-rrwg-report-final-review-draft-for-qbm.pdf.

National Science Foundation, Advisory Committee for Environmental Research & Education. 2018. Sustainable urban systems: articulating a long-term convergence research agenda (sustainable urban systems subcommittee). Accessed December 16, 2018. https://www.nsf.gov/ere/ereweb/ac-ere/sustainable-urban-systems.pdf.

Neuman, W. 2017. De Blasio vows to cut emissions in New York's larger buildings. New York Times. Accessed December 16, 2018. https://www.nytimes.com/2017/09/14/nyregion/de-blasio-mayor-environment-buildings-emissions.html?_r=0.

New York City. 2013. CDBG-DR. Housing, needs assessment, action plan: 39.

New York City Panel on Climate Change (NPCC). 2009. Climate risk information. Accessed February 6, 2019. http://www.nyc.gov/html/om/pdf/2009/NPCC_CRI.pdf.

New York City Panel on Climate Change (NPCC). 2010. Climate Change Adaptation in New York City. *New York City Panel on Climate Change 2010 Report.* Annals of the New York Academy of Sciences. 1196. New York, NY. Accessed February 2, 2019. https://nyaspubs.onlinelibrary.wiley.com/toc/17496632/1196/1.

New York City Panel on Climate Change (NPCC). 2015. Building the knowledge base for climate resiliency. Annals of the New York Academy of Sciences. 1336. New York, NY. Accessed February 2, 2019. https://nyaspubs.onlinelibrary.wiley.com/toc/17496632/1336/1.

New York City Panel on Climate Change (NPCC). 2010. NYC Panel on climate change. In *Appendix B: Adaptation Assessment Guidebook.* D.C. Major & M. O' Grady, Eds.: 229–292, Vol. 1196. Annals of the New York Academy of Sciences. Accessed December 16, 2018. http://onlinelibrary.wiley.com/doi/10.1111/nyas.2010.1196.issue-1/issuetoc.

New York University Langone Medical Center Web site. 2012. Accessed December 16, 2018. http://nyulangone.org/.

NPCC. 2015. NYC Panel on climate change. Building the knowledge base for climate resiliency. Annals of the New

York Academy of Sciences. Vol. 1336. http://onlinelibrary.wiley.com/doi/10.1111/nyas.2015.1336.issue-1/issuetoc.

NYC. 2018a. Lower Manhattan coastal resiliency. Accessed December 16, 2018. https://www1.nyc.gov/site/lmcr/index.page.

NYC Department of City Planning (DCP). 2011. Vision 2020 NYC comprehensive waterfront plan. Accessed December 16, 2018. http://www1.nyc.gov/assets/planning/download/pdf/plans-studies/vision-2020-cwp/vision2020/vision2020_nyc_cwp.pdf.

NYC DCP. 2013a. Flood resilience zoning text amendment. Accessed December 16, 2018. http://www1.nyc.gov/assets/planning/download/pdf/plans/flood-resiliency/flood_resiliency.pdf.

NYC DCP. 2013b. Coastal climate resilience urban waterfront adaptive strategies. Accessed December 16, 2018. http://www1.nyc.gov/assets/planning/download/pdf/plans-studies/sustainable-communities/climate-resilience/urban_waterfront_print.pdf; http://www1.nyc.gov/assets/planning/download/pdf/plans-studies/sustainable-communities/climate-resilience/urban_waterfront_print.pdf.

NYC DCP. 2016. *The New York City waterfront revitalization program*. New York, NY: DCP.

NYC Emergency Response Task Force. 2003. Enhancing New York City's emergency preparedness. Accessed December 16, 2018. www.nyc.gov/html/om/pdf/em_task_force_final_10_28_03.pdf.

NYC Department of Environmental Protection (NYCDEP). 2008. Climate change program assessment and action plan. Accessed December 16, 2018. http://www.nyc.gov/html/dep/pdf/climate/climate_complete.pdf.

NYCDEP. 2013a. *NYC wastewater resiliency plan. Climate risk assessment and adaptation study*. New York, NY: NYC DEP. Accessed December 16, 2018. http://www.nyc.gov/html/dep/pdf/climate/climate-plan-single-page.pdf.

NYCDEP. 2013b. The Staten Island Bluebelt: a natural solution to stormwater management. Accessed December 16, 2018. http://www.nyc.gov/html/dep/html/dep_projects/bluebelt.shtml.

NYCDEP. 2017a. NYC open data water consumption in NYC. Accessed December 16, 2018. https://data.cityofnewyork.us/Environment/Water-Consumption-In-The-New-York-City/ia2d-e54m.

NYCDEP. 2017b. Land acquisition. Accessed December 16, 2018. http://www.nyc.gov/html/dep/html/watershed_protection/land_acquisition.shtml.

NYCDEP. 2017c. NYC green infrastructure 2016 annual report. Accessed December 16, 2018. http://www.nyc.gov/html/dep/pdf/green_infrastructure/gi_annual_report_2017.pdf.

NYCDEP. 2017d. New York City 2017 drinking water supply and quality report. Accessed December 16, 2018. http://www.nyc.gov/html/dep/pdf/wsstate17.pdf.

NYCDEP. 2018a. Stormwater management program. Accessed December 16, 2018. http://www.nyc.gov/html/dep/html/stormwater/ms4.shtml; http://www.nyc.gov/html/dep/pdf/water_sewer/NYC_SWMP_Report_2018_DRAFT_04032018-Spreads.pdf.

NYCDEP. 2018b. 14 Wastewater treatment plants' SPDES permits combined sewer overflows best management practices. Annual report for the period January 1, 2017–December 31, 2017. Accessed December 16, 2018. http://www.nyc.gov/html/dep/pdf/harbor/spdes_bmp_report_2017.pdf.

NYCDEP. undated web site. NYC green infrastructure program. Accessed December 16, 2018. http://www.nyc.gov/html/dep/html/stormwater/using_green_infra_to_manage_stormwater.shtml.

NYC Health + Hospitals. Undated web site. Healthcare locations. Accessed June 17, 2017. http://www.nychealthandhospitals.org/health_care/.

NYC Housing Authority (NYCHA). 2017. Recovery to resiliency NYCHA's Superstorm Sandy recovery program fact sheet. Accessed December 16, 2018. https://www1.nyc.gov/assets/nycha/downloads/pdf/nycha-sandy-factsheet.pdf.

NYC IBO. 2016. Three years after hurricane Sandy: more federal aid for storm resiliency and sandy related repair work added in executive budget. Accessed December 16, 2018. http://www.ibo.nyc.ny.us/iboreports/three-years-after-hurricane-sandy-more-federal-aid-for-storm-resiliency-and-sandy-related-repair-work-added-in-executive-budget.pdf.

NYC Independent Budget Office (IBO). 2012. How many of the city's hospitals, and hospital beds, were at risk during hurricane Sandy? Accessed December 16, 2018. http://www.ibo.nyc.ny.us/iboreports/printnycbtn5.pdf.

NYC Mayor's Office of Recovery & Resiliency. 2018. *Climate resiliency design guidelines. Version 2.0*. New York, NY: NYC ORR. Accessed December 16, 2018. https://www1.nyc.gov/assets/orr/pdf/NYC_Climate_Resiliency_Design_Guidelines_v2-0.pdf.

NYC Office of the Comptroller. 2009. Off track. A review of NYC transit's service indicators and recommendations for improvement. Accessed December 16, 2018. https://comptroller.nyc.gov/wp-content/uploads/documents/sept09-OffTrack.pdf.

NYC Office of Emergency Management (OEM). 2014. 2014 New York City hazard mitigation plan. Accessed December 16, 2018. http://www1.nyc.gov/assets/em/downloads/pdf/hazard_mitigation/plan_update_2014/final_nyc_hmp.pdf.

NYC Office of Management and Budget (OMB). 2018. Information provided by NYC OMB to the NYC Office of Recovery and Resiliency.

NYC Office of the Mayor. 2016. New York City's roadmap to 80x50. New York, NY. Accessed December 16, 2018. http://www1.nyc.gov/assets/sustainability/downloads/pdf/publications/New%20York%20City's%20Roadmap%20to%2080%20x%2050_20160926_FOR%20WEB.pdf.

NYC Office of the Mayor. 2017. Mayor's management report 2017. Accessed December 16, 2018. http://www1.nyc.gov/assets/operations/downloads/pdf/mmr2017/2017_mmr.pdf.

NYC Office of the Mayor. 2018. Mayor's management report 2018. Accessed February 6, 2019. http://www1.nyc.gov/assets/operations/downloads/pdf/mmr2018/2018_mmr.pdf.

NYC Recovery Sandy Funding Tracker. 2017. Accessed December 16, 2018. http://www1.nyc.gov/sandytracker.

NYC Sandy Funding Tracker. 2018. Accessed February 2, 2019. https://www1.nyc.gov/content/sandytracker/pages/.

NYC Water Board. 2016. New York City water and wastewater rate report – FY 2017.

New York Metropolitan Transportation Council (NYMTC). undated web site. Accessed June 16, 2017. https://www.nymtc.org/ABOUT-US.

New York State (NYS) Department of Environmental Conservation. 2016. New York State Department of Environmental Conservation: Community Risk and Resiliency Act, CRRA. Accessed December 16, 2018. http://www.dec.ny.gov/energy/102559.html.

New York State (NYS) Department of Environmental Conservation. DEC undated web page. Facts about the NYC watershed. Accessed December 16, 2018. http://www.dec.ny.gov/lands/58524.html.

NYS Comptroller. 2018. Financial outlook for the metropolitan transportation authority report 8–2019. Accessed December 16, 2018 https://www.osc.state.ny.us/osdc/rpt8-2019-mta-financial-outlook.pdf.

NYS DEC. 2012. Order on consent (CSO modification to CO2-20000107-8). Accessed December 16, 2018. http://www.nyc.gov/html/dep/pdf/green_infrastructure/CO2-20110512-25.pdf.

NYS Department of Health. Undated web site. Hospital profiles. Accessed December 16, 2018. https://profiles.health.ny.gov/hospital/.

NYS Department of Public Service. 2016. Staff report and recommendations in the value of distributed energy resources. documents.dps.ny.gov/public/Common/ViewDoc.aspx? . . . E15B B6E0545E%7D Proceedings, 15-E-075.

NYS Energy Research and Development Administration (NYSERDA). 2015. Reforming the energy vision (REV).

NYSERDA. 2016. NY prize stage I feasibility study. Eight Avenue Microgrid, ERS.

NYS Environmental Facilities Corporation (EFC). undated web site. Clean water state revolving fund. Accessed December 16, 2018. https://www.efc.ny.gov/CWSRF.

NYS EFC. 2017a. Green innovation grant program. Accessed December 16, 2018. https://regionalcouncils.ny.gov/sites/default/files/2017-12/2017-efc-green-innovation-grant-program-overview.pdf.

NYS EFC. 2017b. GIGP-previous awards EFC. Accessed December 16, 2018. https://www.efc.ny.gov/gigp-previous-awards.

NYS EFC. 2018. 2018 Final CWSRF intended use plan annual CWSRF project priority list. Accessed December 16, 2018. https://www.efc.ny.gov/sites/default/files/uploads/Intended%20Use%20Plans/Clean%20Water/2018/2018%20Annual%20List.pdf.

NYS Independent System Operator (ISO). 2015. *Power trends 2015*. Rensselaer, NY: ISO.

NYS ISO. 2016. *2016 Power trends*. Rensselaer, NY: ISO. Accessed February 8, 2019. https://www.nyiso.com/documents/20142/2223020/2016-Power-Trends.pdf/1bec79c7-ffda-1476-1aaf-1bf27ef8b67b.

NYS ISO. 2017a. 2017 Load & capacity data "gold book." Accessed December 16, 2018. https://www.nyiso.com/documents/20142/2226333/2017-Load-Capacity-Data-Report-Gold-Book.pdf/8f9d56cc-dc20-0705-ca19-52e35a535b44.

NYS ISO. 2017b. Power trends report 2017. Accessed December 16, 2018. https://www.nyiso.com/documents/20142/2223020/2017-Power-Trends.pdf/7baea2ba-cdca-93a6-2e45-4d948383ccbd.

NYS Office of the Comptroller. 2017. Financial outlook for the metropolitan transportation authority report 7–2018. Accessed December 16, 2018. http://www.osc.state.ny.us/osdc/rpt7-2018-mta-financial-outlook.pdf.

NYS Office of the Governor. 2012a *Governor Cuomo directs port authority and MTA to close bridges at 7:00 PM*. Albany, NY: NYS Office of the Governor. Accessed December 16, 2018. https://www.governor.ny.gov/news/governor-cuomo-directs-port-authority-and-mta-close-bridges-700-pm.

NYS Office of the Governor. 2012b. Governor Cuomo holds meeting with New York's Congressional Delegation, Mayor Bloomberg and Regional County Executives to review damage assessment for the State in the wake of Hurricane Sandy. Press Release. Accessed December 16, 2018. https://www.governor.ny.gov/news/governor-cuomo-holds-meeting-new-yorks-congressional-delegation-mayor-bloomberg-and-regional.

NYS Office of the Governor. 2017. Governor Cuomo announces State orders Con Edison to take immediate action to guarantee power reliability across the subway system. Albany, NY: State of NY. Accessed December 16, 2018. https://www.governor.ny.gov/news/governor-cuomo-announces-state-orders-con-edison-take-immediate-action-guarantee-power.

NYS Public Service Commission (PSC). 2016. PSC approves $459M Con Edison storm-hardening plan for 2016 — NYC utility storm-hardening efforts and investments hit. Accessed December 16, 2018. https://www3.dps.ny.gov/pscweb/webfileroom.nsf/Web/3017A6317FE9B3B485257F42006A26A1/$File/pr16005.pdf?OpenElement.

O'Neil-Dunne, J. 2012. A report on the City of New York's existing and possible tree canopy. Spatial Analysis Laboratory at the University of Vermont, Burlington, VT. Accessed December 16, 2018. http://www.fs.fed.us/nrs/utc/reports/UTC_NYC_Report_2010.pdf.

Ortiz, L.E., J.E. Gonzalez, W. Wu, *et al.* 2018. NYC impacts on a regional heat wave. *J. Appl. Meteorol. Climatol.* **57:** 837–851.

Pace Energy and Climate Center. 2013. Powering through the storms. Accessed December 16, 2018. http://energy.pace.edu/sites/default/files/publications/Fact%20Sheet%20-%20CHP%20Resiliency-1.pdf.

Pidot, J.R. 2007. Coastal disaster insurance in the era of global warming: the case for relying on the private market. Georgetown Environmental Law & Policy Institute. Accessed December 16, 2018. http://gelpi.org/gelpi/current_research/documents/CoastalDisasterInsuranceReport.pdf.

Powell, T., D. Hanfling & L.O. Gostin. 2012. Emergency preparedness and public health: the lessons of Hurricane Sandy. *JAMA* **308:** 2569–2570.

Rebuild by Design. undated web site. The Big U. Accessed June 16, 2017. http://www.rebuildbydesign.org/our-work/all-proposals/winning-projects/big-u.

Redlener, I. & M.J. Reilly. 2012. Lessons from Sandy—preparing health systems for future disasters. *N. Engl. J. Med.* **367:** 2269–2271.

Red Hook NY Rising Community Reconstruction Planning Committee, Smarter Grid Solutions and IMG Rebel. 2014. Red Hook Community Microgrid: powering Red Hook with Red Hook power. Accessed December 16, 2018. https://redhookcommunitymicrogrid.wordpress.com/project-description/.

Regional Plan Association. 2016. Charting a new course a vision for a successful region. Accessed December 16, 2018. http://library.rpa.org/pdf/RPA-Charting-a-New-Course.pdf.

Rinaldi, S., J. Peerenboom & T. Kelly. 2001. Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Contr. Syst. Magazine* **21:** 11–25.

Rosenzweig, C. & W. Solecki. 2010. Chapter 1: NYC adaptation in context in NYC: building a risk management response. In *NYC Panel on Climate Change 2010 Report*. C. Rosenzweig & W. Solecki, Eds.: 19–28, Vol. 1196. Prepared for use by the NYC Climate Change Adaptation Task Force. Annals of the New York Academy of Sciences. Accessed December 16, 2018. http://onlinelibrary.wiley.com/doi/10.1111/j.1749-6632.2009.05308.x/epdf; http://onlinelibrary.wiley.com/doi/10.1111/nyas.2010.1196.issue-1/issuetoc.

Rosenzweig, C., W. Solecki, A. DeGaetano, *et al.*, Eds. 2011. Responding to climate change in New York State: the ClimAID Integrated assessment for effective climate change adaptation. Technical Report. New York State Energy Research and Development Authority, NYSERDA, Albany, NY. Accessed December 16, 2018. www.nyserda.ny.gov.

Rosenzweig, C., W.D. Solecki, R. Blake, *et al.* 2011. Developing coastal adaptation to climate change in the NYC infrastructure-shed: process, approach, tools, and strategies. *Clim. Change* **106:** 93–127.

Runkle, J.D., A. Brock-Martin, W. Karmaus & E.R. Svendsen. 2012. Secondary surge capacity: a framework for understanding long-term access to primary care for medically vulnerable populations in disaster recovery. *Am. J. Public Health* **102:** e24–e32.

Sanderson, D., J.S. Kayden & J. Leis, Eds. 2016. *Urban Disaster Resilience: New Dimensions from International Practice in the Built Environment*. Routledge.

Schaeffer, R. *et al.* 2012. Energy sector vulnerability to climate change: a review. *Energy* **38:** 1–12.

Seitzinger, S.P. *et al.* 2012. Planetary stewardship in an urbanizing world: beyond city limits. *Ambio* **41:** 787–794.

Sharp, M.J., M. Sun, T. Ledneva, *et al.* 2016. Effect of Hurricane Sandy on health care services utilization under Medicaid. *Disaster Med. Public Health Prep.* **10:** 472–484.

Solecki, W., C. Rosenzweig, S. Dhakal, *et al.* 2018. City transformations in a 1.5 °C warmer world. *Nat. Clim. Change* **8:** 174–185.

Sterpi, D. 2015. Effect of freeze–thaw cycles on the hydraulic conductivity of a compacted clayey silt and influence of the compaction energy. *Soils Found.* **55:** 1326–1332.

Stormwater Management and Road Tunnel (SMART). undated website. Accessed December 16, 2018. http://www.smarttunnel.com.my/.

Tekin, E., A. Bayramoglu, M. Uzkeser & Z. Cakir. 2017. Evacuation of hospitals during disaster, establishment of a field hospital, and communication. *Eurasian J. Med.* **49:** 137.

Teperman, S. 2013. Hurricane Sandy and the greater New York health care system. *J. Trauma Acute Care Surg.* **74:** 1401–1410.

The Climate Bonds Initiative. 2018. Climate bonds standard and certification scheme NY MTA. https://www.climatebonds.net/standards/certification/metropolitan-transport-authority.

TRIP. 2016. Bumpy roads ahead: America's roughest rides and strategies to make our roads smoother. Washington, DC: TRIP. Accessed December 16, 2018. http://www.tripnet.org/docs/Urban_Roads_TRIP_Report_November_2016.pdf.

The Trust for Public Land (TPL). 2016. City Park Facts, San Francisco, CA. December 16, 2018. https://www.tpl.org/sites/default/files/2016%20City%20Park%20Facts_0.pdf.

U.S. Army Corps of Engineers (USACE), FEMA, National Weather Service, NY/NJ/CT State Emergency Management. 1995. Metro New York Hurricane transportation study. Interim technical data report. New York, NY: USACE.

U.S. Code of Federal Regulations. 2011. Accessed December 16, 2018. https://www.gpo.gov/fdsys/pkg/CFR-2011-title40-vol1/pdf/CFR-2011-title40-vol1-part35-subpartK.pdf.

U.S. Department of Energy (DOE), Energy Efficiency and Renewable Energy (EERE). 2011. Hospitals pulling the plug on energy wasting electric equipment and procedures. Accessed December 16, 2018. https://www1.eere.energy.gov/buildings/publications/pdfs/alliances/hea_plugloads.pdf.

U.S. DOE. 2013a. Comparing the impacts of Northeast Hurricanes on energy infrastructure. Accessed December 16, 2018. http://energy.gov/sites/prod/files/2013/04/f0/Northeast%20Storm%20Comparison_FINAL_041513c.pdf.

U.S. DOE. 2013b. U.S. Energy sector vulnerabilities to climate change and extreme weather. Accessed December 16, 2018. https://www.energy.gov/sites/prod/files/2013/07/f2/20130710-Energy-Sector-Vulnerabilities-Report.pdf.

U.S. Department of Homeland Security (DHS). 2013. National infrastructure protection plan. Accessed December 16, 2018. https://www.dhs.gov/sites/default/files/publications/national-infrastructure-protection-plan-2013-508.pdf.

U.S. DHS. 2015. Sector specific plan for energy. Accessed December 16, 2018. https://www.dhs.gov/sites/default/files/publications/nipp-ssp-energy-2015-508.pdf.U.S.

U.S. DHS, FEMA. Programmatic environmental assessment public housing resiliency New York City Housing Authority (NYCHA) New York, NY 4085-DR-NY. Accessed December 16, 2018. https://www1.nyc.gov/assets/nycha/downloads/pdf/nycha-pea-2015-12.pdf.

U.S. DHS, FEMA. 2016. 44 CFR Part 206 Docket ID FEMA-2016-0003 RIN 1660-AA84 Establishing a Deductible for FEMA's Public Assistance Program. Accessed December 16, 2018. https://www.fema.gov/media-library-data/1489005227353-55712e7eb2c87a85308df4f59e043015/FEMADeductibleSANPRM.pdf.

U.S. DHS, FEMA. 2017a. FEMA hazard mitigation grants: 404 and 406. Accessed December 16, 2018. https://www.fema.gov/news-release/2017/05/03/4309/fema-hazard-mitigation-grants-404-and-406.

U.S. DHS, FEMA. 2017b. NYU Langone Medical Center. Accessed December 16, 2018. https://www.fema.gov/nyu-langone-medical-center.

U.S. DHS, FEMA. 2017c. Additional assistance available to repair disaster-damaged infrastructure release number: DR-4344-CA NR 019. Accessed December 16, 2018. https://www.fema.gov/news-release/2017/11/28/4344/additional-assistance-available-repair-disaster-damaged-infrastructure.

U.S. DOT, FHWA. 2017. Post-Sandy transportation resilience study in New York, New Jersey and Connecticut. Accessed December 16, 2018. https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/hurricane_sandy/fhwahep17097.pdf.

U.S. DOT, Federal Transit Administration (FTA). 2011. Flooded bus barns and buckled rails: public transportation and climate change adaptation. Accessed December 16, 2018. http://www.fta.dot.gov/documents/FTA_0001_-Flooded_Bus_Barns_and_Buckled_Rails.pdf.

U.S. DOT, FTA. 2018a. Funding allocations for Hurricane Sandy recovery and resiliency. Accessed December 16, 2018. https://www.transit.dot.gov/funding/grant-programs/emergency-relief-program/fta-funding-allocations-hurricane-sandy-recovery-and.

U.S. DOT, FTA. 2018b. Emergency relief program. Accessed December 16, 2018. https://www.transit.dot.gov/funding/grant-programs/emergency-relief-program/emergency-relief-program.

U.S. Environmental Protection Agency (EPA). 2014. What is green infrastructure? Accessed December 16, 2018. https://www.epa.gov/green-infrastructure/what-green-infrastructure.

U.S. EPA. 2016. Overview of clean water state revolving fund eligibilities. Accessed December 16, 2018. https://www.epa.gov/sites/production/files/2016-07/documents/overview_of_cwsrf_eligibilities_may_2016.pdf.

U.S. EPA. 2017a. News releases from headquarters Water (OW) EPA launches new program with $1 billion in loans available for water infrastructure projects. Washington, DC: U.S. EPA.

U.S. EPA. 2017b. Combined sewer overflows (CSOs). Accessed https://www.epa.gov/npdes/combined-sewer-overflows-csos.

U.S. EPA. 2018a. Laws and regulations. Accessed December 16, 2018. https://www.epa.gov/cwsrf/clean-water-state-revolving-fund-cwsrf-resources#lawsreg.

U.S. EPA. 2018b. Drinking water state revolving fund (DWSRF). Accessed December 16, 2018. https://www.epa.gov/drinkingwatersrf.

U.S. House of Representatives Committee on Transportation and Infrastructure. 2015. Memorandum on Committee Hearing on rebuilding after the storm: lessening impacts and speeding recovery.

Vale, L.J. 2014. The politics of resilient cities: whose resilience and whose city? *Build. Res. Inform.* **42:** 191–201.

Water Environment Federation. 2017. Trinity River floodplain set to become one of nation's largest and greenest urban parks. Stormwater report. Accessed December 16, 2018. http://stormwater.wef.org/2017/03/trinity-river-floodplain-set-become-one-nations-largest-greenest-urban-parks/.

Waterfront Alliance. 2018. Waterfront edge design guidelines. Accessed February 2, 2019. http://wedg.waterfrontalliance.org/wp-content/uploads/delightful-downloads/2018/07/WEDG-Manual-FULL-EXTENDED_2018_small.pdf.

Wikipedia. 2017. Accessed May 15, 2017, cell site. https://en.wikipedia.org/wiki/Cell_site.

Zhu, Q. and R. Zimmerman. September 20, 2018. Dynamic resiliency modeling and planning for interdependent critical infrastructures. Champaign-Urbana, IL: Critical Infrastructure Resilience Institute, U. of Illinois webinar. Accessed February 2, 2019. https://go.illinois.edu/CIRIWebinarNYU.

Zimmerman, R. 2003. Global climate change and transportation infrastructure: lessons from the New York area. In *The Potential Impacts of Climate Change on Transportation: Workshop Summary and Proceedings*, Washington, DC: U.S. DOT (Center for Climate Change and Environmental Forecasting) with the U.S. EPA, U.S. DOE, U.S.GCRP, pp. 91–101. Accessed December 16, 2018. http://climate.dot.gov/documents/workshop1002/workshop.pdf.

Zimmerman, R. 2012. *Transport, the Environment and Security. Making the Connection.* Cheltenham, UK and Northampton, MA: Edward Elgar Publishing, Ltd.

Zimmerman, R. 2016. Chapter 32, resilient urban infrastructure for adapting to extreme environmental disruptions. In *The Routledge Handbook of Urbanization and Global Environmental Change.* K.C. Seto, W.D. Solecki & C.A. Griffith, Eds: 488–512. New York, NY: Routledge.

Zimmerman, R. 2018–2019. Ongoing research on infrastructure interdependencies and extreme events. Wagner Graduate School of Public Service, New York University.

Zimmerman, R. & C. Faris. 2010. Infrastructure impacts and adaptation challenges, Chapter 4. In *Climate Change Adaptation in NYC: Building a Risk Management Response, NYC Panel on Climate Change 2010 Report.* C. Rosenzweig & W. Solecki, Eds.: 63–85, Vol. 1196. Prepared for use by the NYC Climate Change Adaptation Task Force. Annals of the New York Academy of Sciences. New York, NY, NY Academy of Sciences.

Zimmerman, R. & C.E. Restrepo. 2006. The next step: quantifying infrastructure interdependencies to improve security. *Int. J. Crit. Infrastruct.* **2:** 215–230.

Zimmerman, R. & C.E. Restrepo. 2009. Analyzing cascading effects within infrastructure sectors for consequence reduction. In *Proceedings of the HST 2009 IEEE Conference on Technologies for Homeland Security*, Waltham, MA, pp. 165–170. Accessed December 16, 2018. https://doi.org/10.1109/THS.2009.5168029.

Zimmerman, R., C.E. Restrepo & H.B. Kates. 2015. Flooding impacts on drinking water systems. (Work Unit 2.4) New York State Resiliency Institute for Storms & Emergencies (draft final report), New York University, New York.

Zimmerman, R. & M. Cusker. 2001. Institutional decision-making. Chapter 9. In *Climate Change and a Global City: The Potential Consequences of Climate Variability and Change. Metro East Coast.* C. Rosenzweig & W.D. Solecki, Eds.: 149–173. New York, NY: Columbia Earth Institute.

Zimmerman, R., Q. Zhu & C. Dimitri. 2016. Promoting resilience for food, energy and water interdependencies. *J. Environ. Stud. Sci.* **6:** 50–61.

Zimmerman, R., Q. Zhu & C. Dimitri. 2018. A network framework for dynamic models of urban food, energy and water systems (FEWS). *J. Environ. Progr. Sustain. Energy*. **37:** 122–131.

Zimmerman, R., Q. Zhu, F. de Leon & Z. Guo. 2017. Conceptual modeling framework to integrate resilient and interdependent infrastructure in extreme weather. *J. Infrastruct. Syst.* **23**. Accessed December 16, 2018. http://ascelibrary.org/doi/pdf/10.1061/(ASCE)IS.1943-555X.0000394.

Appendix 7.A. The "infrastructure-shed" and critical infrastructure systems in the New York metropolitan region

The "infrastructure-shed." The Regional Plan Association (2016: 5, 6, 8, 24) has specifically emphasized the central place of infrastructure among other elements in its plan for the New York region's future. A few components of the infrastructure-shed are described briefly below, but each sector is presented in more detail in the infrastructure lifelines section that follows.

Energy. According to Con Edison, one of the major distributors of NYC's electric power, the Con Edison service area, is cited as 604 square miles including service areas that extend beyond New York City boundaries (Con Edison Company undated web page accessed June 16, 2017). National Grid (National Grid, undated) also serves certain portions of the city, namely, Staten Island, Brooklyn, and part of Queens for gas (National Grid). According to the New York State Independent System Operator 2016 power trends report, the energy usage in the downstate area is about 1.5 times greater than what it generates, indicating that energy has to be obtained from outside of the city (NYS Independent System Operator (ISO) 2016).

Transportation. New York City encompasses transportation infrastructure managed by numerous transit, road, and bridge agencies. The road system consists of Federal, state, and local owned and/or operated roadways, bridges, and tunnels. The agencies involved in the management of this infrastructure include the NYC DOT, the Port Authority of NY and NJ, NYS DOT, and the NYS Metropolitan Transportation Authority (MTA). For transit, the NYS Metropolitan Transportation Authority (MTA) is the largest provider of transit for the city extending to portions of its region as well. The Port Authority of NY and NJ, NJ Transit and Amtrak also manage bus and rail transit. According to the MTA's description of its network, the MTA service area extends over 5000 square miles (MTA, 2016, 2017), more than 16 times the area of the city reflecting its reach well beyond the city's borders. Both passenger and freight rail transit are affected by conditions outside of the city given the flow of goods in and out of the city that is carried by rail and the commuters in and out of the city as well for jobs, recreational, educational, and other activities. For example, extreme weather, accidents, or other sources of disruption occurring in areas outside of the city inevitably affect the ability of people, goods, and services to move in the region. The U.S. Census Bureau definition of its term "Metropolitan Statistical Area" is generally based on travel in terms of economic connectivity. The effects of transportation infrastructure often act through intermediaries in the form of other infrastructures that transportation is dependent on in particular electric power. When a massive electric cable outage occurred to the north of the city, Metro-North lines were disabled for over a week. The extent of the total impact area is referred to as the New York metropolitan region; however, the reach of each infrastructure is different.

Water. As noted in Chapter 2, the water supply systems draw from a watershed that is almost seven times the area of the City (NYC DEP), and New York city residents and businesses are affected when the infrastructure in areas outside of the city experiences disruptions.

Infrastructure lifeline sectors——new elements of risk and resilience. Definitions of critical infrastructure identify almost a dozen and a half different categories that include Chemical, Commercial Facilities, Communications, Critical Manufacturing, Dams, Defense Industrial Base, Emergency Services, Energy, Financial Services, Food and Agriculture, Government Facilities, Healthcare and Public Health, Information Technology, Nuclear Reactors, Materials, Transportation Systems, and Water and Wastewater Systems (U.S. DHS, 2013).

Energy. The energy system serving New York City consists of an extensive array of facilities from production through end usage. A list of the existing electric power production facilities was compiled by the NYS ISO (2017a: Table III-2). Con Edison, for example, indicates that it manages 95,720 miles of underground cable and 34,215 miles of overhead cable each with transformers and other support systems (Con Edison undated web page, accessed June 16, 2017). Each of the components requires a unique set of protection measures against destruction associated with extreme weather events and climate changes ranging from elevation, submersion, sealing, and operational controls (Con Edison and Orange and Rockland Utilities, 2015).

The main energy service providers for New York City are Consolidated Edison (Con Ed), the New York Power Authority, and National Grid, with the latter providing natural gas. In addition, the Long Island Power Authority (LIPA) provides electric service to the Rockaways in Queens. According to NYS Independent System Operator (ISO), New York City annual energy use has been declining: Over the 2010–2014 period, NYS ISO power trends data indicated a drop of 4.7% in annual usage of electric energy in New York City (from 55,114 to 52,541 GWh) with a decline occurring each year (NYS ISO, 2015: 10), which NYS ISO primarily attributes to recent cooler summers, that may not be likely to continue (see Chapter 2) and also increased use of more energy efficient appliances. From 2014to 2015, however, usage increased by 1.8% though still indicating an overall drop in the 2010–2015 of 3% (NYS ISO, 2016: 10), and NYS ISO generally attributed these changes in energy use to changes in weather and economic activity (NYS ISO, 2016: 7). In the 2015–2016 period, New York City was the only one of the ISO-defined regions that increased in annual electric energy usage by 0.31% from 53,485 to 53,653 GWh (NYS ISO 2017a: 13). The NYS ISO (2017a: 12, 16) forecasts both with and without weather taken into account generally anticipated declines in annual energy usage over a 10 year period from 2017 to 2027 along with an increase in summer peak demand and a decrease in winter peak demand.

Transportation. The transportation system serving the City of New York is comprised of over thousands of miles of surface transportation via various conduits such as roadways, bridges, tunnels, rail, waterways, air, and pipelines. In addition, there are related infrastructures such as terminals and stations and for water-based transportation, ports, and docks. These in turn are owned and/or managed by many organizations. For transit exclusive of pipelines, these include the New York State Metropolitan Transportation Authority (MTA), the Port Authority of NY and NJ facilities such as PATH and the region's airports, NJ Transit, AMTRAK, freight rail companies, and Federal, State, and local highway authorities or transportation departments.

The NYS MTA network consists of almost 9000 rail and subway cars, over 5700 buses across 2080 rail track miles, and 2952 bus route miles (MTA, The MTA Network, undated web site). According to MTA, its network of facilities supports about 2.7 billion trips per year and accounts for about half of the total transit ridership in the U.S. (APTA, 2015). Numerous other support facilities for equipment and operations are a part of MTA's network. One way its robustness is measured is in terms of service disruptions in the form of mean distance between failures (MTA Performance Data Sets undated web site), which is defined for subways, for example, as "Average number of miles a subway car travels in service before a mechanical failure that makes the train arrive at its final destination later than 5 minutes." The lower the number, the worse the performance is with respect to this particular characteristic (MTA undated web site). Fitzsimmons (2017) cited a decline to 120,000 miles in November 2016 compared with 200,000 in November 2010. Fitzsimmons (2017) cited other performance indicators such as number of subway delays, and the NYC Office of the Comptroller (2009) identified a number of different indicators, some of which would be relevant for potential climate change impacts. Delays due to signal and switch failures have received considerable attention.

The viability of the bus and rail transit system reflects Metropolitan Transportation Authority's post-Hurricane Sandy capital projects as well as other MTA plans and programs. Examples of these capital projects include extensive repairs to the subway tunnels, switches, and signals (MTA, 2017; MTA web site Fix&Fortify program). The time period over which these improvements occur could be aligned with NPCC forecasts for heat and precipitation. This is also true of the network of other transportation facilities and services in New York City and probably other infrastructures as well.

Some adaptations since Sandy have been undertaken ranging from short-term (episode-specific, often operational measures) to medium-term measures including flood protection, water removal, and green infrastructure (U.S. Environmental Protection Agency (EPA) July 3, 2018). Transportation projects after Hurricane Sandy have initially focused on repair of damage but have since employed flood protection and other adaptation measures, some of which are discussed in the adaptation section.

Two communities that are being studied by the NPCC3 Community WG that have been identified as having transportation and flooding issues are Hunts Point in the Bronx and Sunset Park in Queens (see Chapter 6: Community-Based Assessments of Adaptation and Equity). At Hunts Point, transportation circulation is relatively restricted, and some of the areas within Hunts Point are susceptible to flooding though these areas barely missed flooding during Hurricane Sandy. The Sunset Park area encompasses portions of the proposed Brooklyn Queens Light Rail whose route partially traverses floodplain areas. Sunset Park is currently served by three subway lines around its periphery: The northern and eastern portions of Sunset Park are served by the D line, the western portion by the R line, and the western and southern portion by the N line. It is also served by bus transit lines.

Water/wastewater. According to NYCDEP, the New York City water supply system encompasses a nearly 2000 square mile watershed north and west of NYC (NYCDEP 2017d: 2). The water supply system is managed by New York City and portions of the counties directly to its north: Westchester, Putnam, Orange, and Ulster. The facilities consist of three water systems–Croton, Catskill, and Delaware, three water tunnels, 19 reservoirs, and thousands of miles of conveyance systems consisting of transmission and distribution networks.

Extensive work is underway to complete the third water tunnel that will provide part of the system within the city's borders with a redundant water distribution system, and that redundancy will support resilience (NYC Special Initiative for Rebuilding and Resilience (SIRR), 2013: 63; NYCDEP 2017d Drinking Water Supply and Quality Report).

The New York City wastewater treatment system consists of 14 wastewater treatment plants, numerous pumping stations that support them, about a half-dozen sludge treatment plants, most of which are located near the wastewater treatment plants, and about 6000 miles of collection lines with a few pumps to convey the wastewater where gravity is not sufficient (NYCDEP, 2013). In addition, there are combined sewer overflow facilities that handle stormwater flows. In many parts of New York City, the wastewater collection system does not separate sanitary sewage and storm sewage, and combined sewers are estimated at 60% of the city's sewer system (NYCDEPa, 2018: 4) The City of New York has embarked on ambitious green infrastructure programs aimed at water management through nonstructural controls (NYCDEPa, 2018: 37–38) such as the Staten Island Bluebelt project (NYCDEP, undated web site accessed June 16, 2017).

The city tracks the viability of its distribution infrastructure for both water and sewer in terms of breakage rates and service interruption and has reported declines in those rates recently as well as declines in restoration time summarized earlier in this chapter (NYC Office of the Mayor Management Report (MMR), 2017: 262–263; 2018: 261) (see Chapter 8: Indicators and Monitoring).

Telecommunications. The telecommunications structure within New York City provides telephone, wireless, Internet, and cable services. Verizon is the incumbent telecom franchise in NYC. Telecommunications infrastructure consists broadly of buildings that house communication equipment, exchanges, switches, and computers; cabling for signal transmission and conduits; intermediary locations such as cell towers that house telecommunication equipment (Wikipedia, 2017), and equipment at user locations (City of New York, 2013: 163). The expanse of the system and its network is comprised of: "... over 50 thousand miles of cabling, thousands of cell sites [or cell towers where telecommunication facilities are located], and nearly 100 critical facilities." "New York City accounts for approximately 3% of the world's web traffic—even though the city is home to only 0.1% of the world's population" (City of New York, 2013: 163). Telecommunication infrastructure is not only vulnerable to power outages and damages also to backup power facilities which was experienced during and after Hurricane Sandy (City of New York, 2013: 168), but also to the stresses created by direct impingement by floodwaters and wind and water-driven debris. The intensely complex and interconnected networks and rapidly changing technologies that characterize the telecommunications sector create challenges to addressing its climate vulnerabilities.

Appendix 7.B. Compendium of selected adaptations[b]

A wide range of strategies specific to infrastructure are under consideration and in many cases are underway throughout the United States and the world to strengthen the resilience of the infrastructure against the consequences of climate change across numerous infrastructure sectors. These are aimed at increasing the resilience of the built environment overall and the social systems it serves. These generally fall under the heading of adaptation. These have tended to occur separately for each type of infrastructure though some protective measures afford simultaneous and coordinated protection.

Many of these strategies and approaches were introduced in the main section of the report. A few additional approaches are introduced here for illustrative purposes and generally pertain to introducing flexibility into the design and operation of infrastructure. Adaptation measures encompass design strategies for new and retrofitted infrastructure. A number of different design guidelines have been summarized for adaptation measures depending on the type of construction and the location of a facility (NYC Mayor's ORR, 2018: 27, Climate Resiliency Design Guidelines). Examples of design and construction measures suggested in the guidelines and elsewhere include relocation, elevation, hardening, barriers, reconfigurations (e.g., elevating structures for flooding and sea level rise), providing flexible routing (e.g., among transportation modes), altering materials, etc., and the relevance very much depends upon the nature of the hazard. Operational measures in addition to design have also been put forth to support flexibility, for example, by using alternative resources, configurations for infrastructure facilities, and usage or consumption. In many cases, these adaptation measures have been known for some time. The NYC Department of City Planning's waterfront plan that predated Hurricane Sandy set forth a number of strategies aimed at resilience pertaining to flooding in the areas of "retreat," "accommodation," and "protection," many applicable to infrastructure (NYC DCP, 2011: 109–110) and they also identified a number of adaptation measures within the city after Hurricane Sandy (NYC DCP, 2013b). Protective mechanisms, for example, include many structural approaches involving gates, seawalls, and others. These mechanisms were expanded considerably in the New York area following Hurricane Sandy (City of New York, 2013; New York State 2100 Commission, 2013; NYS Department of Environmental Conservation, 2016), and have been listed by the NYC Mayor's Office of Recovery & Resiliency (2017: 24) as design interventions in connection with sea level rise. Green infrastructure is an expanding area of interest for adaptation primarily for water management (U.S. EPA, undated web site accessed June 16, 2017), but other approaches exist as well such as urban tree canopies (O'Neil-Dunne, 2012). New York City has been pursuing a project originally developed as the "Big-U" (Rebuild by Design, 2017) and currently referred to as the East Side Coastal Resiliency (ESCR) project, the Lower Manhattan Coastal Resiliency (LMCR) project, and Two Bridges (NYC, 2018a, b), that combines structural and green infrastructure approaches and numerous strategies targeted specifically to improve transportation resilience after Hurricane Sandy (U.S. DOT, FHWA 2017).

[b]The NYC ORR (2018: 36) Climate Resiliency Design Guidelines defines adaptation as: "Adjustment in natural or human systems to a new or changing environment that seeks to maximize beneficial opportunities or moderate negative effects." Adaptation was defined by the IPCC (2007) early in the climate change assessment process in the following ways: "Adaptation Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory, autonomous and planned adaptation: Anticipatory adaptation – Adaptation that takes place before impacts of climate change are observed. Also referred to as proactive adaptation. Autonomous adaptation – Adaptation that does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems. Also referred to as spontaneous adaptation. Planned adaptation – Adaptation that is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state." "Adaptive capacity (in relation to climate change impacts) The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences."

A number of efforts are underway for managing water, for example, stormwater management (NYCDEP, 2018), measures specific to wastewater treatment plants and related facilities such as pumps (NYCDEP, 2013: 9–10) and tailored by NYCDEP to specific plants, and land management through flood zoning (NYCDCP, 2013a). One relatively newer land management mechanism primarily for controlling and managing water is green infrastructure. The NYC Department of Environmental Protection has embarked upon a green infrastructure program to comply with the NYS DEC consent orders for combined sewer overflows (NYC EP, 2017). NYCDEP manages an extensive program to install green infrastructures, and indicates thousands of these have been installed throughout the city using a variety of technologies between 2011 and 2016 (NYC EP, 2017). The U.S. EPA defines green infrastructure as: "Green infrastructure uses vegetation, soils, and natural processes to manage water and create healthier urban environments. At the scale of a city or county, green infrastructure refers to the patchwork of natural areas that provides habitat, flood protection, cleaner air, and cleaner water. At the scale of a neighborhood or site, green infrastructure refers to stormwater management systems that mimic nature by soaking up and storing water." (U.S.EPA, June 13, 2014).

Specific infrastructure agencies have developed extensive adaptation mechanisms. For example, the MTA (2009; 2017) has set forth numerous measures to protect its transit infrastructure and the U.S. DOT (2011) has considered a broader scale of measures applicable to the city. The city's transit system has undertaken adaptation measures in response not only to Hurricane Sandy's impacts but also to current and anticipated impacts of climate change aimed primarily at temperature and flooding associated with precipitation and sea level rise (MTA, 2017: 4). The 2016 commitment for 46 projects was $751 million with a total of $3 billion in overall resilience funds, and additional funds were indicated for 2017 and 2018 (MTA, 2017: 12). The projects consist of strengthening the condition and design of MTA facilities, relocation of equipment to higher elevations, and barriers.

Consolidated Edison Company of New York and Orange & Rockland Utilities (2013) developed an extensive set of primarily structural mechanisms to protect its electric power infrastructure. The portion of the city's electric power system operated by Con Edison went through an extensive adaptation review following hurricane Sandy involving various techniques such as sealing, cable removal and reconnection flexibility, submersion, strengthening of overhead electric power polls, tree trimming, and numerous other measures (Consolidated Edison Company of New York and Orange and Rockland Utilities, 2013). The 2013 plan has now, according to Con Edison, been updated and portions of it have been implemented with an estimated $1 billion investment (Con Edison, October 19, 2017). Con Edison reported a $1.6 billion investment for work begun in 2016 that included the following improvements:

- "12 network transformers;
- 70 overhead transformers;
- 16 underground feeder sections connecting manhole structures and transformer vaults;
- 37overhead sections of power lines, and reinforcement of 25 electric feeders . . .
- a new underground electric network to help meet growing energy needs on the west side of midtown Manhattan . . .
- and completing a $1 billion, 4-year storm hardening plan to protect infrastructure and customers from the impact of major storms, like hurricanes." (Con Edison, July 12, 2016).

Con Edison estimated that through October 19, 2017, 250,000 outages had been averted through "the installation of more than 1,000 'smart' switches on its overhead system, submersible equipment that can withstand flooding, redesigned underground electrical networks, and numerous other steps to avoid outages," circuit breakers to achieve more rapid recovery, flood walls and seals specified in their 2013 plan and numerous other design and operational changes (Con Edison, October 19, 2017).

Summary of shoreline programs and plans. New York City has about 520 miles of shoreline (NYC DCP, 2016: 7). Portions of it are at sea level or within margins that are potentially vulnerable to flooding from sea level rise as well as storm surge. The coastal boundary for both developed and undeveloped shoreline areas is defined relative to sea level (NYC DCP, 2016: 9). Numerous proposals for altering the coast exist some of which are protective in light of climate change and others not, but have the potential for integrating climate change. These include some of the suggestions in the NYC DCP (2011) Vision 2020 waterfront plan, the NYC (2013) designs for many of the shorefront locations in and around the city, the Waterfront Alliance's (2018) plans and manual for coastal planning, and the post-Sandy competitions that included the selection of the Big U project. Current city programs such as zoning and land use should continue to incorporate these ideas.

Parkland. An important aspect of the resiliency of NYC's shoreline is the extent to which parkland can buffer the effects of storm surge, sea level rise, and coastal flooding. Parks near coastlines can provide temporary inundation areas that can recover relatively quickly after extreme weather events involving flooding. Permanent increases in sea level are more challenging, however. Some social infrastructure overlaps with and depends upon transportation infrastructure, such as bike and pedestrian paths. Parks often provide protection of neighborhoods from severe weather by providing shade from trees; however, trees can also be vulnerable to extreme wind events.

Shoreline parks comprise the largest portion of the parks managed by the New York City Department of Parks comprising "7,300 acres or 30% of its total land area and found along 150 miles—or almost 30%—of the city's total coastline," and in addition natural areas comprise another 9900 acres under the Department's jurisdiction (NYC EM 2014: 59).

A number of concepts for using land susceptible to flooding to absorb water have been put forth. Within NYC, the Staten Island Bluebelt provides such an example. The NYCDEP (c2013) describes it as "natural drainage corridors, called Bluebelts, including streams, ponds, and other wetland areas. Preservation of these wetland systems allows them to perform their functions of conveying, storing, and filtering stormwater. In addition, the Bluebelts provide important community open spaces and diverse wildlife habitats. The Bluebelt program saves tens of millions of dollars in infrastructure costs when compared to providing conventional storm sewers for the same land area." Similar ideas have been put forth for Boise, Idaho (Barker, 2017), the Trinity River System (Water Environment Federation, 2017), and as the ideas for "Sponge Cities" particularly in China (Garfield, 2017). Other approaches include integrating transportation and water management, for example, in Kuala Lumpur where a six mile tunnel is used for traffic control in dry weather and the conveyance of stormwater in wet weather (Zimmerman, 2012: 115; Stormwater Management and Road Tunnel (SMART, undated website). Finally, the U.S. EPA and the City of New York along with a number of other cities throughout the country and the world have been leaders in developing green infrastructure concepts that serve as both mitigation and adaptation measures. Although the concept has been used for a number of different environmentally purposes, its use for water absorption or storm water management is key to confronting some of the flooding aspects of climate change.

For 2015, the Trust for Public Land (2016) listed 39,615 acres of parkland within the City, comprising about a fifth of its land area (TPL, 2016: 5). Of that, three-quarters is under the jurisdiction of the NYC Department of Parks and Recreation, and New York City ranks second in the set of high-density cities in percent parkland (TPL, 2016: 9). There were 4.7 acres per 1000 residents, and New York City ranked 13th in the high density city group (TPL, 2016: 10). Park access is very high for NYC, and is critically dependent upon transportation infrastructure. TPL indicated that 97% of NYC's population was within a half mile of a park–walking distance, unobstructed, from a road (TPL, 2016: 13). Two characteristics of parks interrelated with infrastructure and climate change are first the proximity of some parks to coasts and hence, the potential vulnerability to sea level rise and second the integration of trees in parks and elsewhere that affects urban heat levels. Given the extensive coastline of New York City and its attractiveness for recreation, a large number of parks are located along the city's shoreline (NYC Department of City Planning, 2011: 11). The city has acquired 1250 acres of waterfront parks since 1992 with Staten Island having the highest acreage, followed by Brooklyn, Queens, the Bronx, and Manhattan (NYC, 2011: 11). Many of those parks that are in flood zones are potentially prone to flooding during weather extremes.

Jamaica Bay represents an extensive program of shoreline and estuary planning and management with the participation of numerous organizations including the Science and Resilience Institute at Jamaica Bay (SRIJB) aimed in part at increasing

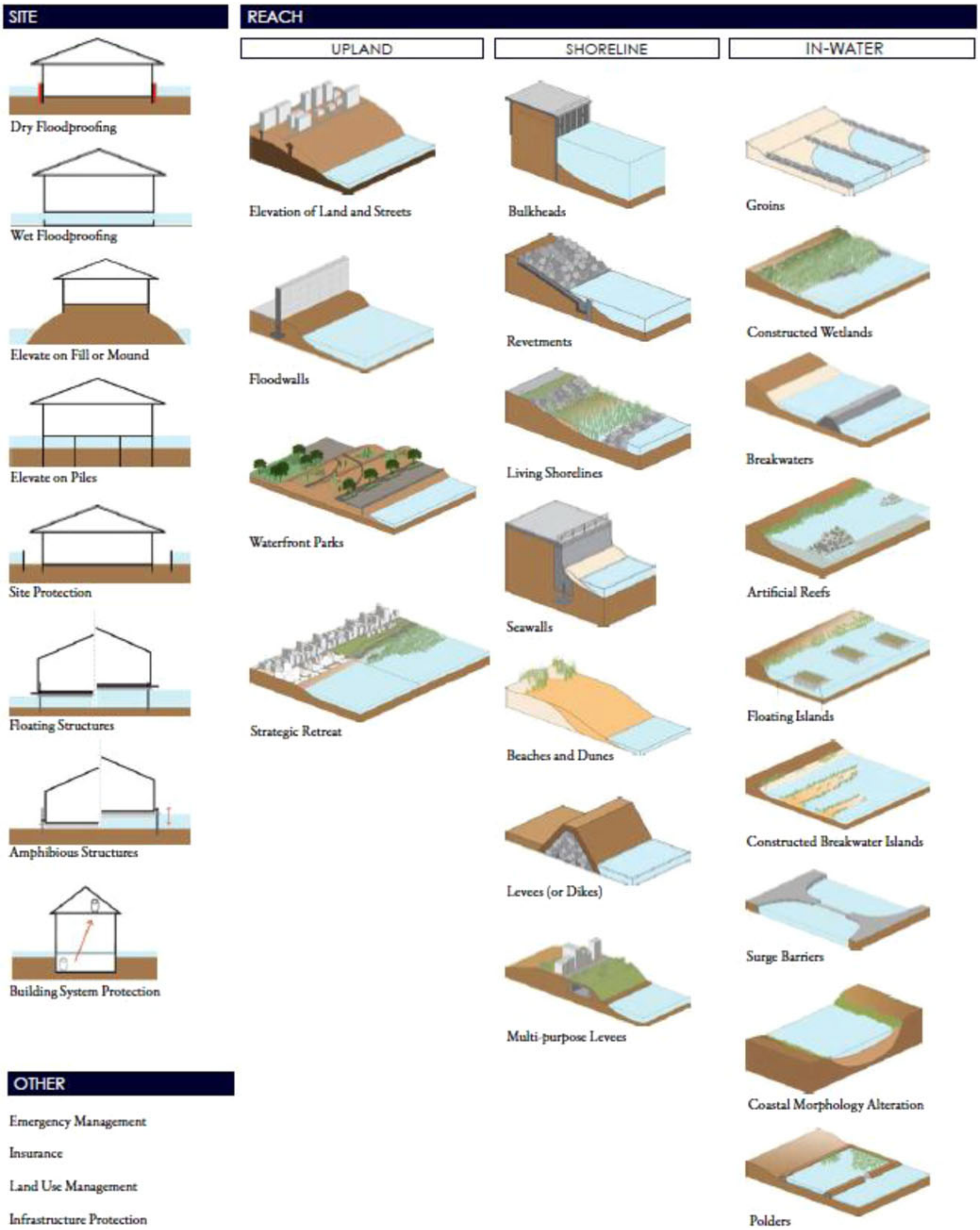

Figure 7.B.1. Strategies for coastal resilience by location. Source: New York City Department of City Planning, 2013.

the resilience of the area to future storms. The Institute has partnered with The City of New York and National Park Service and affiliates with the NYC Department of Environmental Protection on projects and events, in particular the Jamaica Bay Watershed Protection Plan (http://www.srijb.org/sotb2016/). With respect to infrastructure, a recent study identified eight different organizations for utilities and 14 involved in transportation (Sanderson *et al.*, 2016).

Shoreline planning and modifications. Numerous agencies have taken part in planning for the increased resilience of New York City's shoreline in light of Hurricane Sandy and prior to it. A

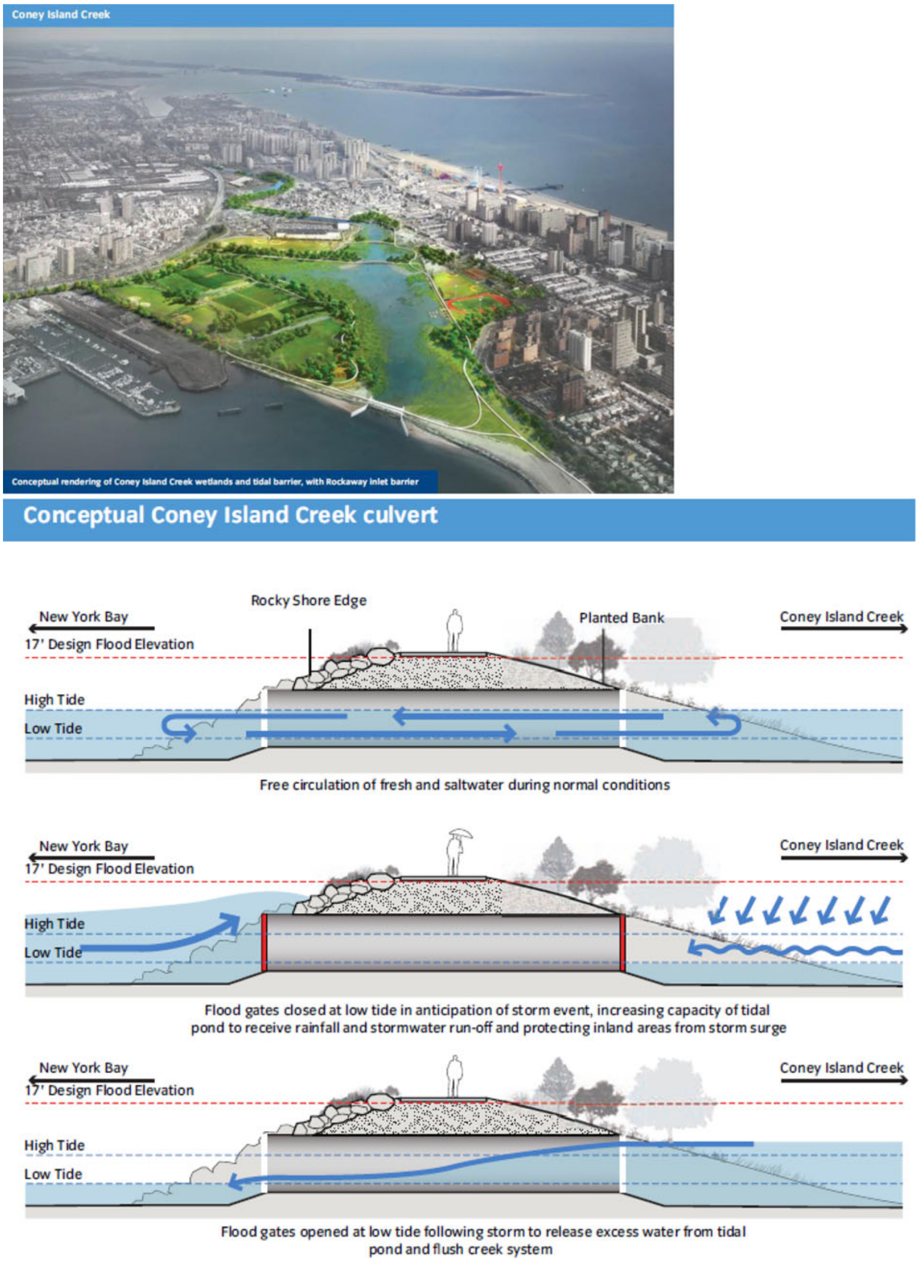

Figure 7.B.2. Example of possible shoreline modifications proposed in the NYC SIRR (2013). Source: City of New York, 2013.

few examples are given below in addition to the work in Jamaica Bay that cuts across park and shoreline modification efforts. Two major programs that New York City is a part of are: Rebuild by Design (http://www.rebuildbydesign.org/) funded by the U.S. Department of Housing and Urban Development (HUD) with not for profit organizations and philanthropies (http://www.rebuildbydesign.org/about) and the Rockefeller Foundation 100 Resilient Cities with which Rebuild by Design has partnered (http://www.100resilientcities.org/about-us/). These have particularly targeted shoreline areas in addition to supporting actions for a broader base of hazards related to infrastructure and other areas.

Figure 7.B.1 portrays the work of the NYC DCP (2013b) visualizing different shoreline modifications that increase resilience depending upon the characteristics of the shoreline and the adjacent water environment. These apply not only to buildings, but also to infrastructure.

Extensive efforts were made in the New York City Special Initiative for Rebuilding and Resilience (SIRR) to identify ways in which selected shorelines could be adapted to create greater resilience. Figure 7.B.2 gives just one example of the many potential modifications to NYC's shoreline to improve its resilience provided by the NYC SIRR by taking into account the dynamics of the water environment. The area below is identified as Coney Island Creek in the SIRR.

Appendix 7.C. New York City greenhouse gas goals

Like other C40 cities in North America (C40 is a network of cities committed to addressing issues related to climate change (https://www.c40.org/about)), New York City under the mayoral administrations of Michael Bloomberg (2002 through 2014) and Bill de Blasio (2014–present) has maintained city government's commitment to reducing citywide human-generated greenhouse gases (GHG) 80% by 2050. Achieving that 80 × 50 goal of cutting city-generated emissions requires a major focus on New York City's built environment. The building stock of the city's five borough (counties) generates nearly 70% of the emissions in 2015 (Inventory of New York City Greenhouse Gas Emissions, April 2017). Progress toward the goal of reducing city-generated carbon emissions has been incremental but encouraging as the city government and the state government in Albany implement policies to alter energy-consumption practices in all sectors (public, private, and independent).

In keeping with the 80 × 50 commitment, Mayor de Blasio announced the outlines of proposed legislation to reduce emissions from fossil fuel consumed onsite in buildings primarily for heating and hot water—apartment houses, office buildings, and warehouses—with more than 25,000 square feet (Neuman, September 15, 2017). This mayoral initiative, announced in the fall of 2017 while United Nations met in New York and reaffirmed the tenets and goals of the Paris Climate Accord, promised to impose strict standards on as many as 23,000 inefficient buildings in this category by 2030. Clearly, final provisions of this mayoral legislative initiative—even its fate—will be subject to negotiations between the mayoral administration and the New York City Council as well as efforts by interested parties, from business sectors like commercial real estate to environmentalists focused on climate mitigation issues. This particular de Blasio initiative, whatever its final shape or fate, also opens up space for the policy and research infrastructure of the city and the state to pose at least two questions related to achieving the 80 × 50 goal. These efforts to reduce and cap CO_2 emissions in buildings have been supported by city legislative initiatives (The Council of the City of New York, November 20, 2018; Kaufman, November 20, 2018).

Does the current inventory of city-led and state-led 80 × 50 programs add up to a comprehensive, milestone-driven approach to reducing emissions from the built environment 80 × 50? Are the city programs and state programs designed in a way to substantially reduce GHGs across all four classes of property in the city—Class I (most residential property of up to three units and small condominiums), Class II (mostly rental, cooperatives, and condominiums), Class III (utility property), and Class IV all commercial and industrial property not in Classes I, II, and III)? Are the GHG-reduction programs of New York City and Albany equally robust across all categories of the built environment in the five boroughs? Which city-led and state-led GHG programs are comprehensive and robust? Which are pilots with limited reach and impact? Are the seven goals, next steps, and implementation timelines of One City Built to Last: Transforming New York City Buildings, Technical Working Group Report sufficient? Some of the current patterns and trends inform some of these questions.

The City of New York (September 2017) report "OneNYC 1.5 Celsius Aligning NYC with the Paris Climate Agreement" tracked emission changes in a number of sectors, two of which were directly infrastructure related: transportation and waste (including wastewater treatment). However, the other sectors for which emissions were tracked (residential, commercial, and institutional) include changes in emissions from electricity use, a key infrastructure sector tracked by NPCC. Emissions were all reported as tons of carbon dioxide equivalent, but fugitive natural gas, compostable waste, and wastewater treatment measured methane and nitrous oxide emissions.

Overall, total emissions reported from 2016 (the most recently available data) are down 15% compared to emissions from 2005: down from 61.08 to 51.91 million tCO2e. About 67% of these emissions are from stationary sources (residential, commercial, and institutional), 30% are from transportation, and 3% are from waste. In absolute terms, emissions from stationary sources decreased the most from 2005 to 2016: down 18.5% from 42.39 to 34.56 million tCO_2e. Emissions from waste decreased the most in terms of percent change from 2005 to 2016: down 21% from 2.28 to 1.80 million tCO_2e. Transportation had a much more modest decrease: down 5.2% from 16.41 to 15.55 million tCO_2e.

Under the transportation sector, subway and commuter rail emissions decreased 41.9% from 953,856 to 554,345 tCO_2e and emissions from buses decreased 14.7% from 687,896 to 586,830 tCO_2e, but emissions from passenger cars and trucks remained relatively constant (a 3.6% decrease of 12.88–12.42 million tCO_2e for passenger cars and a 3.5% increase of 1.81–1.87 million tCO_2e for all trucks) and marine navigation emissions increased 82.8% from 49,962 to 91,353 tCO_2e.

In New York City's Roadmap to 80 × 50 report, the de Blasio administration framed its decarbonization strategy, in part, as a guide "on how to grow a dynamic and inclusive economy to spur innovation, develop globally-recognized industries with the potential for high-paying jobs, and to make the city more resilient against climate change and other 21st century threats."(NYC Office of Sustainability, September 2016). This section of the 2016 report identifies equity as "an explicit guiding principle" of the city's environmental agenda. This commitment to equity as a guiding principle will need to be articulated and actualized in the city's emerging DERs strategy, policies, and projects. As New York City pursues DERs projects as part of its decarbonization strategy for achieving 40 × 30 and 80 × 50, city agencies, community-based organizations (CBOs), other nongovernmental organizations (NGOs), and businesses will need to embed equity in DERS and various forms of community energy strategies.

This commitment to equity will likely require a continuing focus on understanding and developing the economic benefits and cobenefits of DER projects in the five boroughs. The criteria for assessing the viability of a DERS project ought to rigorously evaluate issues related to the flow of economic benefits and cobenefits. These economic issues include forms of ownership of DERS, beneficiaries of the sale of excessive power capacity (via energy arbitrage, NY ISO demand response programs, etc.) Roadmaps for building equity into DERS policies and projects can be found in variety of places, including:

- PATHWAYS TO RESILIENCE (P2R): Transforming Cities in a Changing Climate | Kresge Foundation, Movement Strategy Center, The Praxis Project and the Emerald Cities Collaborative | 2015 (Movement Strategy Center, 2015);
- NYSERDA's Reforming the Energy Vision (REV) Working Group II, Subcommittee on Microgrids and Community Grids: Ownership and Control (WG 2, _ Microgrids and Community Grids _Fina Report & Appendices.pdf) (NYSERDA) (NYSERDA, 2015);
- Beyond Sharing — How to Take Ownership of Renewable Power, Institute for Local Self-Reliance, 2016;
- Principles of a Pluralist Commonwealth, Gar Alperovitz and the Democracy Collaborative, 2017, Ownership: Why Is Ownership a Key Determinant of System Structure? (Alperovitz and the Democracy Collaborative, 2017).

In light of the new set of challenges, opportunities, economic benefits, and cobenefits that will accompany New York City and New York State's transition to a low-carbon economy, City Hall could impanel a commission made up of city agencies and stakeholders in the independent and private sector to: map the emerging challenges, opportunities, economic benefits, and cobenefits; formulate recommendations about how the flow of those benefits can be leveraged to create new sources of economic opportunity in low-income, low-wealth communities in the five borough.

High on the list of issues that the commission could examine are: defining economic benefits and cobenefits to include not only green jobs and lower energy bills, but also the opportunities for people and entities in low-income, low-wealth communities to be owners, investors, and shareholders in new green energy enterprise (distributed energy resources, DERS) and other forms of climate-friendly projects that lead to mitigation, adaptation, and resilience.

Identifying any legal or regulatory obstacles at the city and state scales that would stymie the development of neighborhood-owned co-operatives, B corporations, traditionally structured green businesses, NGO-owned, CBO-owned businesses that can help people and community institutions build ownership and wealth; and cataloguing and benchmarking pathways/modalities in use in the United States and overseas for leveraging the creation of income and wealth for individuals and community-based entities that work with people in low-income, low-wealth communities.

The second mitigation issue that deserves greater and sustained focus involves accounting for and dealing in a meaningful way with the share of the New York City's carbon footprint that is generated beyond its political boundaries. New Yorkers, like all residents of megacities, suburbs, towns, and rural areas, are responsible for transboundary emissions. They consume carbon-intensive goods (from cars to clothing to food and appliances) and services that are imported from other parts of the United States and the rest of the world.

Policies and actions that appear to be sustainable locally (at the city or metropolitan-region scales) ought to account for the total planetary-level environmental and social consequences of local consumption patterns (NAS, 2016). GHG mitigation policies and programs ought to take account of and take actions that recognize the biophysical limits of the planet; all cities need to identify and pursue specific policies that reduce the city's metabolism, mostly composed of material and energy flows (NAS, 2016). Accounting for and working to reduce transboundary GHG emissions will require cities across all sectors to play a major role in managing Earth's finite resources in a sustainable way (Seitzinger *et al.*, 2012 in NAS, 2016).

World cities, New York included, could agree on a methodology for accounting for transboundary GHG emissions, estimate those emissions and report them, along with implementing long-terms strategies for reducing each city's transboundary footprint. To that end—the collection of transboundary data and the analysis of it—the National Science Foundation's Advisory Committee for Environmental Research & Education issued a 2018 report, Sustainable Urban Systems: Articulating a Long-Term Convergence Research Agenda (Sustainable Urban Systems Subcommittee (National Science Foundation, 2018). This report by the advisory committee's Sustainable Urban Systems Subcommittee offers a guide to researchers and stakeholders on how to conduct convergent science required to understand the local and transnational footprints of cities and metropolitan regions. According to the report, the key elements of the next cycle of sustainable urban systems science ought to lead to the production of in-depth knowledge of (NSF, 2018: 16):

- "Single urban/metropolitan regions where multiple sustainability outcomes are addressed for a multi scale systems perspective that connects homes, businesses and communities to regional and global scales.
- Multiple cities and communities, exploring relationships among networks of communities and identifying city/urban typologies for the study of cohort groups and comparison groups.
- Supra-aggregations of cities and urban areas, e.g., all urban areas in an electrical grid region, nation, world-region, or the world, to study the collective impact of urban transformation on people and the planet."