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Chapter 4: Infrastructure impacts and adaptation challenges

Rae Zimmerman[1] and Craig Faris[2]

[1]Institute for Civil Infrastructure Systems, New York University, New York, New York. [2]Executive Partner, Risk Management, Accenture, Reston, Virginia

Address for correspondence: Rae Zimmerman, Professor of Planning and Public Administration/Director, ICIS, New York University-Wagner Graduate School of Public Service, Puck Building, 295 Lafayette St., 3094, New York, NY 10012. Voice: 212-998-7432. rae.zimmerman@nyu.edu

Introduction

Creating an overall climate change adaptation strategy for urban infrastructure poses considerable conceptual and operational challenges. An understanding of the characteristics of a city's infrastructure that make it particularly vulnerable to the impacts of climate change is a critical foundation for understanding the severity of the impacts and the means for adaptation. Historical events that have compromised a city's infrastructure under conditions similar to those associated with climate change also provide information about what a city might expect in the way of consequences from a future of increased temperatures, precipitation, and sea level rise. This chapter explores the challenges to climate change adaptation in major urban infrastructure sectors with a focus on New York City, draws lessons from adaptation efforts under way in other large metropolitan regions, and discusses the role of the private sector in urban adaptation.

4.1 Adapting in an urban environment

The particular dimensions of infrastructure that are relevant to climate change primarily depend on location, exposure, and vulnerability, as well as the degree of protection against climatic forces. This section highlights some of the infrastructure most vulnerable to climate change in New York City as a means of illustrating the complexity of adapting in a dense, urban environment.

Impacts

As discussed in Chapter 3, New York City faces the following climate change hazards:

(1) **Temperature:** long-term changes in mean annual temperature and increases in the frequency, intensity, and duration of heat waves;
(2) **Precipitation:** long-term changes in mean annual precipitation and more frequent and intense precipitation events and drought; and
(3) **Sea level rise** and associated storm surge.

New York City houses one of the densest infrastructures in the world. Because of its age and composition, some of this infrastructure and materials may not be able to withstand the projected strains and stresses from a changing climate. Rising temperatures may result in increased degradation of materials. Precipitation events of increased frequency, intensity, and duration may result in inland flooding that tests current drainage capacities. Rising sea levels may result in increased flooding that could degrade infrastructure materials from more frequent saltwater inundation and river flooding that can flood infrastructure not designed to withstand those conditions. Table 4.1 gives examples of infrastructure and assets that are likely to be affected by climate change.

Table 4.1. **Examples of potential infrastructure impacts from climate risk factors by sector and component**

Infrastructure sector and component	Climate risk factor[a]	Potential infrastructure impacts[b]
Energy		
Production	Temperature	-Increased user demand for and consumption of energy -Increase in peak load days -Potential for more frequent power outages -Overuse and strain on equipment and materials, increasing maintenance -Equipment damage
	Precipitation	-Equipment damage from flooding
	Sea level rise	-Equipment damage from flooding and corrosive effects of seawater
Transmission and distribution overhead and underground	Temperature	-Increased sag of overhead lines -Increase in number of underground fires, manhole explosions -Increase in outage frequency, extent (customers lost), and duration
	Precipitation	-Increase in number and duration of local outages from flooded and corroded equipment
	Sea level rise	-Increase in number and duration of local outages from flooded and corroded equipment
Transportation		
Roadways	Temperature	-Increased road material degradation, resulting in increased road maintenance
	Precipitation	-Declining level of service from flooded roadways[c] -Increased hours of delay from increased congestion during street flooding -Insufficient pumping capacity and associated increased energy use for additional pumping to remove excess water to prevent flooding
	Sea level rise	-Declining "level of service" from flooded roadways -Increased hours of delay from increased congestion during street flooding episodes -Insufficient pumping capacity and associated increased energy use for additional pumping to remove excess water to prevent flooding
Transit	Temperature	-Increased use of cooling equipment -Increased rail degradation and equipment deterioration, resulting in increased maintenance -For commuter rail, increase in transit accidents from train collisions with overhead lines sagging

Continued.

Table 4.1. *Continued*

Infrastructure sector and component	Climate risk factor[a]	Potential infrastructure impacts[b]
	Precipitation	-Insufficient pumping capacity and associated increased energy use to remove excess water for the prevention of flooding -Mean Distance Between Failure (MDBF) decreases producing delays -Increase in number of stops due to emergencies -Increase in number of emergency evacuations
	Sea level rise	-Increased rail degradation and equipment deterioration from saltwater inundation, resulting in increased maintenance
Water supply[d]		
Quantity	Temperature	-Safe yield rate can decline for groundwater and surface water supplies due to increased evaporation -Reservoir levels decline
	Precipitation	-Uncertain changes in precipitation producing variable and unpredictable water supplies
	Sea level rise	-Impact on emergency supply from salt front movement
Distribution of water supply	Temperature	-Changes in characteristics of water flow through pipes
	Precipitation	-Pressure changes in water distribution system -Increased corrosion -Increased water loss
	Sea level rise	-Increased flooding (infiltration and inflow) from flooded distribution lines
Quality	Temperature	-Increased evaporation in surface water supplies contributes to deteriorating water quality due to concentration of contaminants
	Precipitation	-Impact on water quality from increased turbidity -Increased concentration of pollutants
	Sea level rise	-Impact on emergency supply from salt front movement -Potential increase in infiltration into distribution systems
Waste (wastewater)		
Quality	Temperature	-Treatment capability of wastewater treatment plants improved up to a point due to increased heat affecting biological processes but then declines if temperatures exceed tolerance limits

Continued.

Table 4.1. *Continued*

Infrastructure sector and component	Climate risk factor[a]	Potential infrastructure impacts[b]
		-If substantial evaporation or drought occurs, quantity of wastewater becomes insufficient to sustain treatment processes
	Precipitation	-Hydraulic capacity of sewers and wastewater treatment plants exceeded owing to increased flows
		-Treatment capacity of treatment plants exceeded from dilution from increased flows
		-Decline in water quality reflected in Clean Water Act standard variances
	Sea level rise	-Reduced function of wastewater treatment plants if sea level overwhelms plant facilities
		-Sewer backups from excess and accumulated water
Waste (solid waste)		
Closed landfills	Temperature	-Alteration of chemical composition of contaminants below the surface, changing evaporation rates
	Precipitation	-Unexpected leaching of contaminants where precipitation penetrates the surface of closed landfills
	Sea level rise	-Release of contaminants from unexpected inundation of landfills increasing public health concerns
Marine transfer stations	Temperature	-Increased evaporation of contaminants from refuse
	Precipitation	-Marine transportation impeded
	Sea level rise	-Alignment of marine transfer station docking facilities with landside facilities affected
Curbside refuse	Temperature	-Increased evaporation of contaminants and decay of refuse, thereby increasing public health concerns from vermin
	Precipitation	-Increased damages to curbside refuse containment and releasing refuse, increasing public health concerns
	Sea level rise	-Inundation of refuse from water releases contaminants to streets and waterways, increasing public health concerns
Communications		
Supplies: electric power	Temperature	-Power disruption/outage frequency and severity affects communication equipment
	Precipitation	-Equipment flooded and stored materials damaged
	Sea level rise	-Increased flooding of equipment and corrosion from salt water

Continued.

Table 4.1. *Continued*

Infrastructure sector and component	Climate risk factor[a]	Potential infrastructure impacts[b]
Equipment: fiber optic cable; cell towers; internet	Temperature	-Destruction of equipment and increased maintenance
	Precipitation	-Excessive precipitation flooding equipment -Line congestion, tower destruction, or loss of function -Call carrying capacity reduced, lost, or blocked -Internet traffic increases and accessibility declines
	Sea level rise	-Increased flooding of equipment and corrosion from salt water from increased sea level rise

Sources: Infrastructure impact measures are drawn from New York City, Mayor's Management Report (2008) and various regulatory and professional practices within each infrastructure sector. New York State Department of Public Service Office of Communications, Network Reliability After 9/11, Nov. 2, 2002. http://www.dps.state.ny.us/DPS-NetworkReliabilityRpt.pdf

[a]Terminology used in the NPCC, Climate Risk Information Appendix A, and also referred to as climate risk factors.

[b]Terminology used in the NPCC, Climate Risk Information Appendix A. Note: The list in this table includes impacts related to both supply and demand for system services, but does not organize the impacts in that way.

[c] Level of Service (LOS) is measured as the ratio of road volume to capacity from 0–1 in increasing order of deterioration, and is a commonly used roadway transportation indicator.

[d]New York City DEP Climate Change Program, Assessment and Action Plan, New York, NY: NYCDEP May 2008.

Energy

The provision of electricity can be roughly divided into production and distribution facilities, though many intermediate processes and facilities exist between these two services, such as transformers, area substations, switching stations, generators, and transmission towers. New York City is required to produce 80% of its electric power needs (in terms of forecasted peak events), though some pre-existing transmission systems providing external electricity that are dedicated to providing electricity for New York City can be included as part of the 80%.[1] This condition presents a challenge to adaptation since on the one hand it promotes security and on the other hand it poses constraints on alternative ways of obtaining power from outside the city.

Production facilities for electric power are concentrated in a relatively few locations relative to the customer base they serve. Presently, about two dozen power plants of varying sizes are operating in New York City (Fig. 4.1), and over a dozen more were proposed as of 2005. These facilities are owned and/or operated by a half-dozen entities. Traditionally power plants have required shoreline or close to shoreline locations for water intake structures and cooling water discharges; thus a number of the city's existing production facilities are located at lower elevations and potentially sensitive to flooding due to sea level rise.

Transmission lines that service the city are also relatively concentrated, entering the city from relatively few directions and providing little flexibility should any one of these lines be compromised. The lines enter New York City primarily from Westchester to the north and secondarily from Long Island to the east and New Jersey to the west. Thus, any given disruption in one of these locations will have relatively widespread impacts. The distribution system serving New York City, distinct from transmission, is one of the densest in the world, consisting of approximately 90,000 miles (145,000 kilometers) of underground distribution lines and 55 distribution

Figure 4.1. Locations of New York City power plants relative to 10-foot elevation contour.
Sources: Compiled from power plant web sites and NOAA MESA NY Bight Atlas Monograph for historical records, K. Ascher, *The Works* (Penguin Press 2005), p. 98, and NYS DEC South Pier Improvement Project Gowanus Power Plan, April 3, 2008, http://www.dec.ny.gov/docs/permits_ej_operations_pdf/gpublic2.pdf. http://www.uspowergen.com/projects/south-pier/. Dots indicate very approximate locations of 22 existing power plants. The base map indicating 10 foot sea level contours is from V. Gornitz of GISS.

networks within the city, each of which can operate independently of the other.[2]

Energy infrastructure poses a number of challenges to adaptation. Most infrastructure in the city relies on the city's power grid for energy, thus if it fails the other infrastructures that are dependent on it fail. The facilities that produce and distribute energy have traditionally been located in low-lying areas and are difficult and expensive to relocate. In addition, many power plants need to be located near the water to accommodate fuel deliveries, the use of water for cooling and steam generation, and water discharges, making relocation to areas not susceptible to flooding virtually impossible. These facilities are also concentrated in a relatively few locations within the city increasing the impacts of a climate hazard occurring at one location. The electric power industry is subject to a variety of regulations which presents a challenge to incorporating any new demands, such as climate change information, into its portfolio. Limited resources and multiple demands on those resources present another challenge to meeting energy needs. This situation is not only specific to New York City but is also common to the energy sector in general, occurring in many other urban areas as well.

Transportation

The transportation sector comprises the facilities and services to move people and materials over and through land, water, and air. It encompasses many modes of transport, including personal vehicles traveling on surface roads and public and

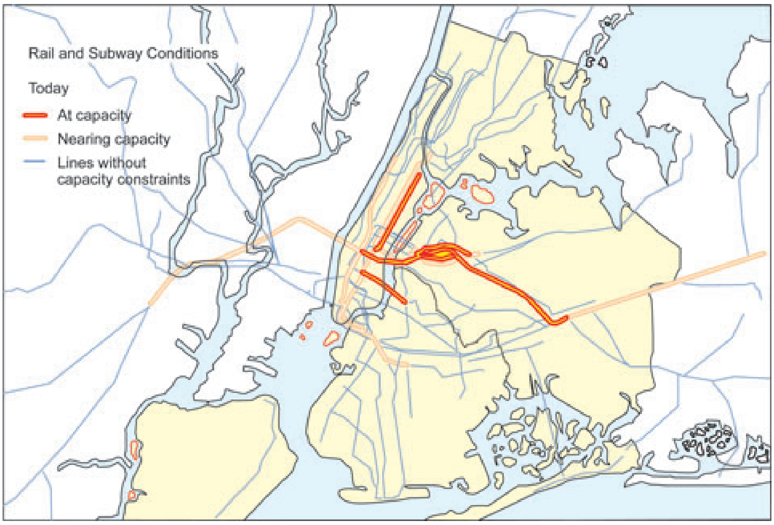

Figure 4.2. **Location and capacity constraints of New York City rail and subways.**
Source: City of New York, *PlaNYC: A Greener, Greater NY*, New York, NY: City of NY, April 2007, p. 96. http://www.nyc.gov/html/planyc2030/downloads/pdf/report_transportation.pdf.

private transport via bus, rail, ferries, and airplanes. Given the extent of use of rail transit within New York City, this section focuses on rail transit for passengers to illustrate the complexities and challenges that the transportation sector in general will encounter in adapting to climate change.

The rail transit system serving New York City is the largest in the United States. Seven local and regional transit systems serve the city; however, the city has little jurisdictional control over these systems (see Fig. 4.2 for major rail lines). First, the Metropolitan Transportation Authority (MTA) manages three of the city's transit agencies: New York City Transit, Metro North and the Long Island Railroad. New York City Transit has 660 passenger miles of track (840 in total) and serves 1.5 billion passengers annually within the five boroughs (see Fig. 4.3 for station locations). Metro-North has 775 miles of track and services more than 80 million passengers annually running mainly to and from locations north of the city. The Long Island Railroad that runs to and from Long Island east of the city and has 594 miles of track and services 82 million passengers per year (MTA, 2008).

Second, the Port Authority of NY and NJ manages the Port Authority Trans Hudson system (PATH), which has 43 miles of track and services 66.9 million passengers per year between locations within relatively close proximity to the Hudson River (PANYNJ, 2008). Third, NJ Transit, a system managed by a different agency, runs further into New Jersey and enters New York City, has 643 miles of track and services 241.1 million passengers per year (NJ Transit, 2007). Fourth, Amtrak is also another provider of rail services, providing regional service through New York City. Other providers exist as well for freight transport via rail. Many of these systems share passengers and facilities that would require extensive coordination in the event of changes for adaptation.

The sheer size and density of the city's transit sector, the fact that many of the facilities are located underground and/or either in coastal or river floodplains, the difficulty and considerable expense that would be incurred to retrofit or to relocate vulnerable portions of the system, and the need to keep the system operational are important considerations for climate change adaptation. The system has condition and capacity issues, which add to the climate change problem (Figs. 4.2 and 4.3). The transit sector and roadways have multiple owners and complex sharing arrangements that pose challenges to introducing adaptation.

The city's rail systems are vulnerable to climate change by virtue of their low elevations which are

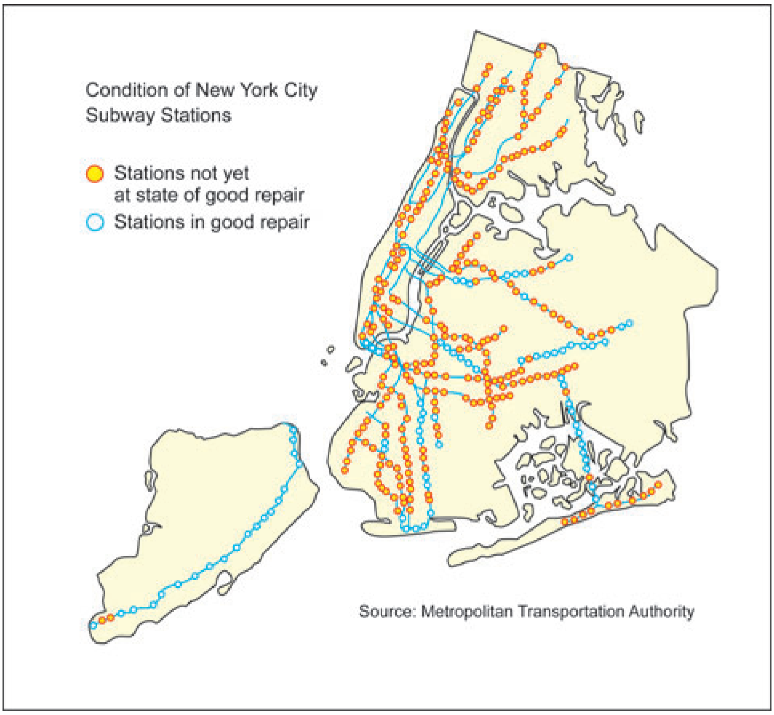

Figure 4.3. Location and condition of New York City subway stations.
Source: City of New York, *PlaNYC: A Greener, Greater NY*, New York, NY: City of NY, April 2007, p. 93. http://www.nyc.gov/html/planyc2030/downloads/pdf/report_transportation.pdf.

susceptible to flooding from increased precipitation and sea level rise. Although many rail components in New York City are at low elevations, there is a dramatic variation in height above sea level. These locations are well known for the New York area, which will help in identifying particularly vulnerable areas (U.S. Army Corps of Engineers, 1995; and summarized in Jacob *et al.*, 2001; Jacob *et al.*, 2007; Zimmerman, 2003a; and Zimmerman and Cusker, 2001). For example, New York City Transit subway stations are as high as 91 feet,[4] and as low as 180 feet below sea level in upper Manhattan. In addition to the stations themselves, the location and design of public entrances and exits, ventilation facilities, and manholes can play a role in determining vulnerability. Many stations are also very old, and the difficulty of relocating or elevating them to avoid flooding necessitates additional adaptation strategies.

A recent incident of heavy precipitation of short duration gives an example of how extensive flooding of the rail system can be. Massive area-wide flooding from the August 8, 2007 storm discussed in Chapter 1 resulted in a near system-wide outage of the MTA subways during the morning rush hour. The event also required the removal of 16,000 pounds of debris from tracks and the repair or replacement of induction stop motors, track relays, resistors, track transformers, and electric switch motors.[5] Such phenomena have periodically halted transit in New York City over the years (MTA, 2007) necessitating the use of large and numerous pumps throughout the system. Storms such as these lend themselves to analogies to flooding from climate change in the future (Rosenzweig *et al.*, 2007).

The flexibility of transit users to shift from one system to another is an important adaptation mechanism. An important factor influencing adaptation for rail transit facilities is the extent to which the configuration of transit networks consist of single extended rail lines that are not frequently interconnected with other lines, resulting in relatively little flexibility for shifting to another rail line if any one area of the line is disabled. Shifting to bus lines is often an option under such conditions. Portions of the New York City Transit and PATH systems are able to bypass bottlenecks depending on location, which was the case in both systems immediately following the September 11, 2001 attacks on the World Trade Center (Zimmerman and Simonoff, 2009).

Water and waste

Challenges to climate change adaptation related to the water and waste sectors include aging infrastructure, a complicated regulatory environment, and lack of redundancy.

Water resources

The water supply sector comprises an interconnected system of natural water bodies and manmade structures, consisting of raw water sources (e.g., groundwater and surface water supplies) and facilities for water extraction (e.g., wells, where applicable, and pumps), storage, transmission, treatment, and distribution that bring water from sources to consumers. Water infrastructure components vary according to the type of water usage, such as the provision of potable water, wastewater transport and treatment, recreation, power generation, and supporting aquatic and terrestrial ecosystems. Used water that is not fully consumed is connected to wastewater systems. The nature of water supply infrastructure varies depending on the size, configuration, and nature of the sources and the distance water has to be conveyed.

The New York City water supply system supplies about 1.1 billion gallons a day from a 1972 square mile watershed that extends to 125 miles from City Hall. The Catskill and Delaware watersheds provide 90% of this water, with the older Croton System supplying 10%.[6] This flow to the city travels through an extensive network consisting of aqueducts, dams, reservoirs, and distribution lines along with pumping and other support facilities. To capture the supply, for example, there are four reservoirs and an aqueduct in the Delaware system; two impounding reservoirs, an aqueduct, and a tunnel in the Catskill System; and 12 reservoirs, the Jerome Park Reservoir, three controlled lakes, and an aqueduct in the Croton System (NYC MWFA, 2009, p. 46–47). Water from the impounding reservoirs in the Catskill and Delaware Systems flows to two balancing reservoirs, Kensico and Hillview. The construction of a treatment plant for the Croton System is under way in the Bronx.

Within the city's water distribution system as shown in Figure 4.4 there are two water tunnels and over 6000 miles of water distribution pipe.[7] The city is planning to introduce redundancy into its in-city water supply distribution system and also improve the ability for system maintenance through a variety of measures such as the construction of a 60 mile-long water tunnel, Water Tunnel No. 3, which is occurring in four stages.[8]

Wastewater treatment

Wastewater treatment plants pose a challenge for adaptation, since they are characterized by older facilities located on the coastal estuary with limited ability to accommodate excess water, either from rising sea levels or intense precipitation. However, newer more decentralized ways of capturing and treating stormwater (NYC DEP, 2008) provide an important supplement for the stormwater wastewater component. These need careful coordination and integration into the city's system, and have multiple owners including private ownership. The wastewater collection and distribution system consists of "6600 miles of sewers, 130,000 catch basins, almost 100 pumping stations, and 14 water pollution control plants (WPCPs)."[9] The wastewater treatment plants, by virtue of the way they are intended to operate with discharges to waterways, are primarily located along the city's shorelines, where the lowest elevations above sea level occur. During dry weather, the wastewater treatment plants are designed to fully treat one and a half times their design capacity and can partially treat about two times their design capacity. Where flows exceed that amount, for example, during wet weather conditions, water is discharged through the city's wastewater collection system—through combined sewer overflows (CSOs). CSOs and wastewater treatment plants are shown in Figure 4.5.

Municipal solid wastes

Waste collection is under the responsibility of numerous public and private entities in the City of New York, posing the challenges to the development of coordinated climate change adaptation plans. The New York City Department of Sanitation "recycled or disposed of 15,500 tons of waste per day (tpd) from curbside and containerized collections in

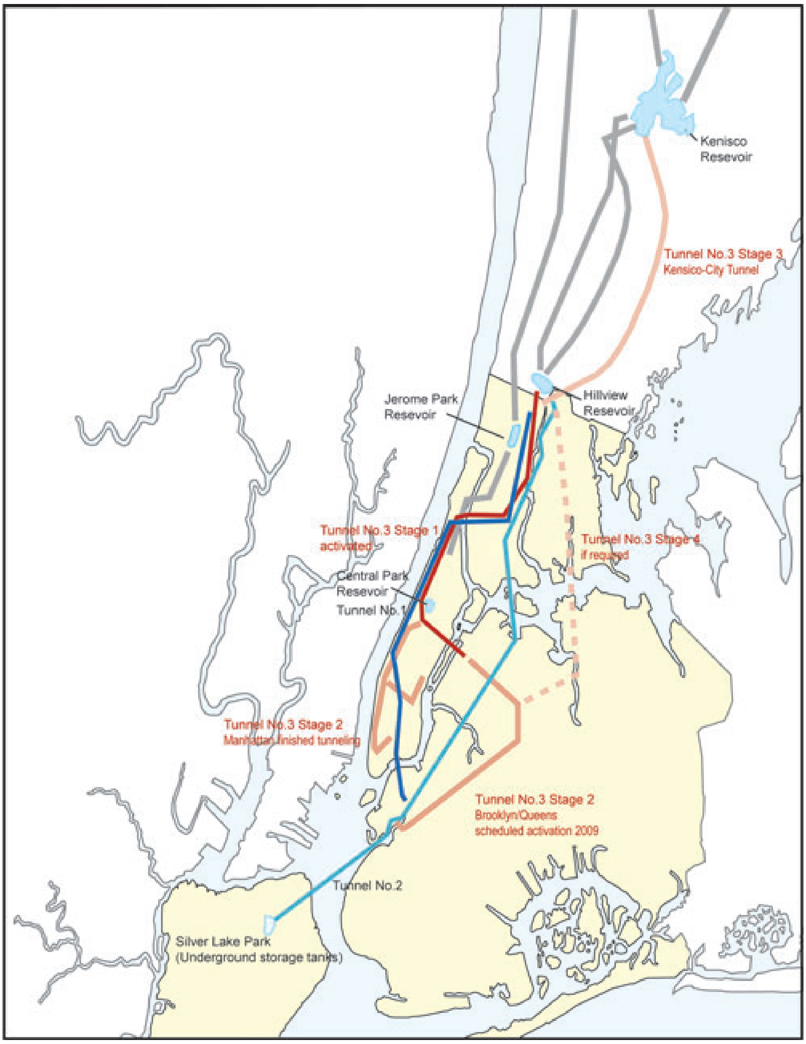

Figure 4.4. **New York City water supply distribution system and third water tunnel planned locations. Source: City of New York, *PlaNYC: A Greener, Greater NY*, New York, NY: City of NY, April 2007, p. 69. http://www.nyc.gov/html/planyc2030/downloads/pdf/report_water_network.pdf.**

FY2006."[10] Most of the solid wastes that are not recycled are transported outside of the city for treatment and/or ultimate disposal rather than relying on disposal sites within the city. In the past, New York City has used in-city landfills for this purpose, but these have now been closed. Private sector entities play a large role in commercial waste management.

Waste facilities sited in low-lying areas including closed landfills are also subject to flooding that could result in increased contamination of water bodies. If inundated by sea level rise, these facilities could create water quality problems, since many of them are located near shorelines and relied on closure technologies that did not take into account the current knowledge around climate changes. Solid waste facilities at risk include the marine transfer stations (shown in Fig. 4.6), garages and collection routes. As indicated in Table 4.1, marine transfer station operations can be interrupted and refuse along collection routes can be flooded during storm episodes.

Communications

The widely dispersed nature of the city's infrastructure and the wide variety and extensiveness of networks and facilities is well illustrated by the

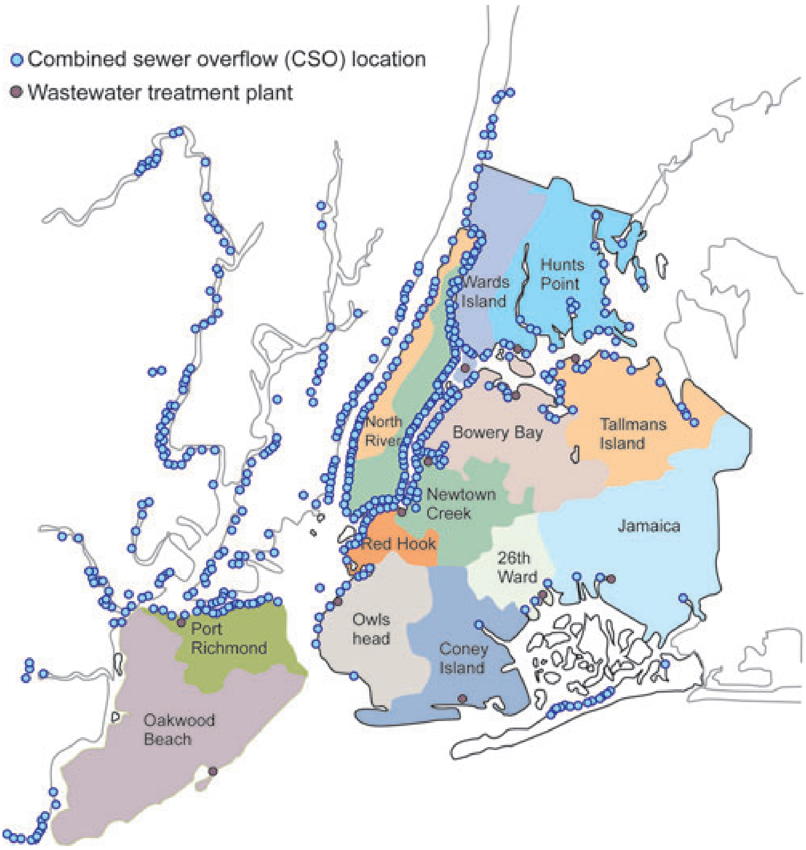

Figure 4.5. Locations of Water Pollution Control Plants, CSO Outfalls, and Drainage Areas in the NYC area, 2008. Source: City of New York, *PlaNYC: A Greener, Greater NY,* New York, NY: City of NY, April 2007, p. 55. http://www.nyc.gov/html/planyc2030/downloads/pdf/report_water_quality.pdf.

communications sector. This sector is also heavily dependent on other sectors, particularly electric power as discussed in the section on interdependencies below, in order to function. The communications sector covers a wide range of services and facilities, including telecommunications, Internet service, and cable television. According to the Telecommunications Act of 1996, telecommunications, its equipment, and services are defined as follows:

> "(43) The term "telecommunications" means the transmission, between or among points specified by the user, of information of the user's choosing, without change in the form or content of the information as sent and received. . .
> (45) . . . The term "telecommunications equipment" means equipment, other than customer premises equipment, used by a carrier to provide telecommunications services, and includes software integral to such equipment (including upgrades).
> (46) . . . The term "telecommunications service" means the offering of telecommunications for a fee directly to the public, or to such classes of users as to be effectively available directly to the public, regardless of the facilities used."[11]

Communication systems encompass networks, such as fiber optic cable and copper wire, and include many different kinds of facilities for the intermediate and final receipt, transmission, and processing of signals (e.g., cell towers, satellites, computers, and phones). Each of these is potentially vulnerable to the impacts of climate change.

The New York City communications infrastructure consists of a vast network of fixed structures to support communication and computing, consisting of voice lines, data circuits, fiber optic cable, switching stations, backbone structures, domain

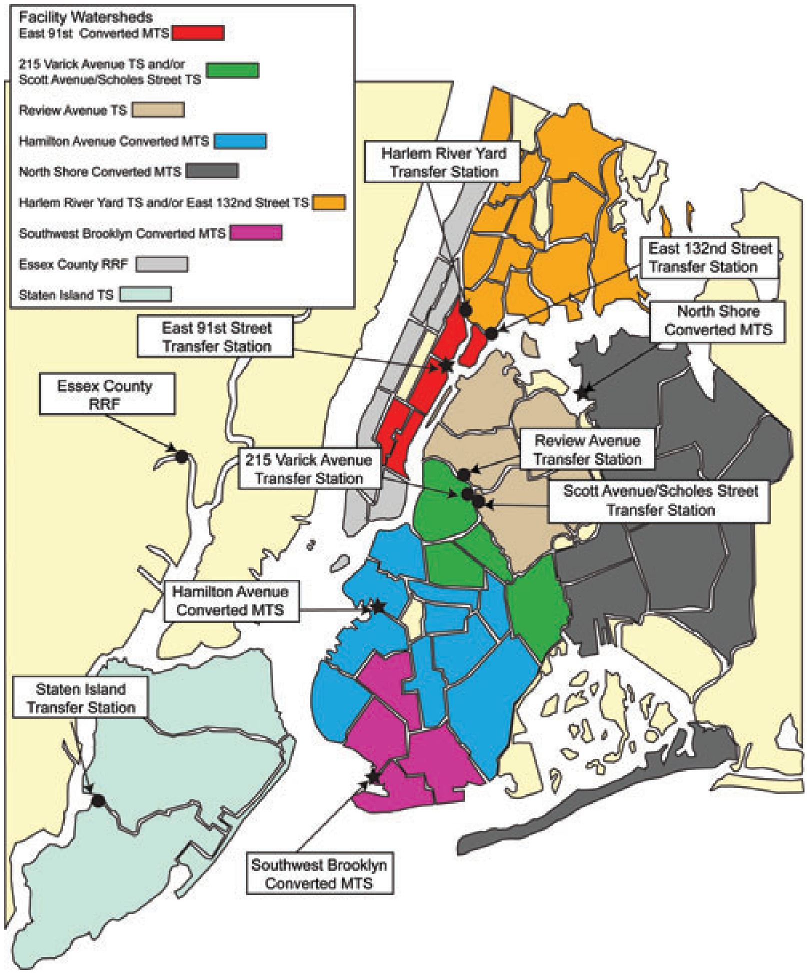

Figure 4.6. Long-Term Export Facilities and Watersheds. Location of solid waste marine transfer stations. Source: Modified from NYC Department of Sanitation, *Comprehensive SWMP September 2006*, Executive Summary, p. ES-17. http://www.nyc.gov/html/dsny/downloads/pdf/ swmp/swmp/swmp-4oct/ex-summary.pdf.

name servers, cell towers, satellites, computers, telephones (landlines), televisions, radios, and many more (Zimmerman, 2003b). Numerous communications providers serve New York City including AT&T, Verizon, T-Mobile, and many others.

Communication equipment is vulnerable to climate impacts, for example, electrical support facilities such as relays, wiring, and switches associated with fiber optic cable can become flooded; cell towers can topple in strong winds and become corroded from unexpected exposure to seawater if sea level rises; and as seen in numerous disasters, an indirect impact is the dropping of calls due to saturated capacity from impacts that are more sudden. These vulnerabilities suggest relocating sensitive electrical equipment to avoid flooding and strengthening cell tower construction.

Sensitivity analysis for alternative climatic conditions

Given the high degree of variability of the extent and ownership of the city's infrastructure, studies are needed to determine how such changes, variability, and differences affect any given climate change adaptation strategy. Sensitivity analysis is one method for accomplishing this evaluation. Sensitivity analysis is both a qualitative and quantitative technique to identify how results of an analysis change if the types and/or values of any variables change. For example, in the case of energy systems, such an analysis could identify how much electricity demand deficit would occur and hence how much backup power would be needed given an incremental change in electricity capacity due to excessive heat. Infrastructure designers, managers, and operators can use such analyses in considering climate change impacts and developing adaptation strategies. Sensitivity analysis is an important way of evaluating uncertainties. Uncertainties are associated with climatic conditions, impacts, and the success of adaptation. Impacts will not only change with variations in climatic conditions, but the estimates will also vary according to the degree of uncertainty in the climate risk factors. Therefore, even qualitatively performed sensitivity analyses are useful on scenarios or alternative conditions to determine the degree to which changes in the likelihood of climatic conditions will change impacts on infrastructure.

Interdependency

All of the infrastructure sectors described above are dependent on and interdependent within one another in often complicated ways. Interdependency in the form of interconnectedness of infrastructure services is a critical factor in assessing climate change impacts and developing adaptation strategies, since they can magnify the consequences of a failure of a given type of infrastructure. Rinaldi, Peerenboom, and Kelly (2001) define infrastructure interdependency as, "a bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other. More generally, two infrastructures are interdependent when each is dependent on the other."[12] A dependency in contrast would be a situation where one infrastructure depends on another, but the opposite is not true.

Interdependencies and dependencies can be geographic or spatial (as created by spatially colocated infrastructure), or functional (including information technologies or cyber connections). In identifying these relationships, it is important to include all system components. Interdependence or interconnectivity occurs not only between infrastructures but within them as well. The importance of identifying these relationships is to enhance the ability to correct for cascading effects that might occur when one infrastructure failure inadvertently affects others.

Examples of interdependencies *among* infrastructure sectors in New York City

Numerous and often unspecified relationships among infrastructures exist that will make an outage in any one create an outage in another and vice versa. Examples for New York City are numerous given the complexity and density of the city.

Transportation facilities depend on electric power to operate electric rail lines, traffic signals and lights for both road and rail transportation. Transit signals, electrified rail, and traffic lights shutdown when there is an electricity blackout. The subways and commuter rails and roadways have been temporarily disabled when a water main breaks in the vicinity of these facilities, and many of these episodes have been documented.[13] The flooding resulting from water main breaks is analogous to what might be expected during flooding episodes brought about by increased storms and sea level rise associated with climate change. Train signaling systems and electric power plant and distribution controls that depend on telecommunications can and have failed when communication systems fail, and communications can fail in turn where the electric power, upon which they rely to function, fails. Electric power and emergency repair vehicles, in turn, rely on transportation for the delivery of goods and services.

Water supply treatment or purification plants rely heavily on electric power and consume a large amount of water in their processes. A notable example in connection with climate change impacts is the increase in power needed by wastewater treatment plants in hot weather.[14] Electric power facilities in turn are heavy users of water for cooling and steam generation.

While electric power used to be the sector upon which most other sectors depended, **communication information technologies** are growing in their importance given the increasing dependency on these technologies for the command and control of infrastructure (Zimmerman and Restrepo, 2009). Power plants rely on communication equipment to monitor and control operations and coordinate activities over a vast network with multiple actors. Wired connections rely on wireless for backup. Wireless systems, however, rely on electricity to function, and wireless lines can become congested as traffic increases. Dedicated lines are one answer to the congestion problem, however, they are also vulnerable in emergencies. Communication and computer systems, in turn, rely on electric power to function.

Examples of interdependencies *within* infrastructure sectors

Examples within a given infrastructure sector include the reliance of power plants and power transmission and distribution networks upon one another. When one system or set of facilities is down, others can absorb or share the required load. For example, after the September 11, 2001 attacks on the World Trade Center which destroyed two substations, Con Edison was able to extend cables to substations in areas adjacent to the World Trade Center area to restore electricity at least on a temporary basis. There are management limitations to this adaptation strategy, however, since restrictions on electric power and operating permits, including emission limitations, are placed at the plant level. For electric power in New York City, these limits are set by the New York Independent System Operator (NYISO), Federal Energy Regulatory Commission (FERC), and the New York State Department of Environmental Conservation (NYS DEC).

Similarly in the water sector, in times of drought, water sharing is common among water supply systems, or at least the facilities are in place to allow such sharing. During the drought of 1965, New York City put in a temporary pipe across the George Washington Bridge to share water with New Jersey. This is an example of geographic interdependency rather than functional interdependency.

In order to develop adaptation strategies where interdependencies exist among infrastructures, the location and functional strength of these interdependencies have to be identified first.

Challenges to developing citywide adaptation measures: a case example

The scale of large urban regions presents unique challenges to climate change adaptation. Large-scale approaches have been suggested worldwide for cities of the size and density of New York City, largely surrounded by waterways. One example of an approach to developing citywide adaptation measures to enhance coastal flooding is storm surge barriers (Box 4.1). With regard to development of such citywide adaptation plans, it is important that cities consider adaptation approaches that are robust in several dimensions. The first dimension needs to be a thorough understanding of the risks that future coastal storms pose for any given urban area. Further dimensions are cost, timing, environmental impact, and feasibility.

Box 4.1 One possible long-term infrastructure adaptation: storm surge barriers in New York

One possible long-term infrastructure adaptation measure for New York City would be barriers designed to protect against high water levels, which will increase in height as sea level rises (and possibly also through increasing intensity of storms). The risk of future casualties and damage from hurricanes and nor'easters might be reduced by barriers placed across vulnerable openings to the sea. Each barrier would require large open navigation channels for ships and a porous cross section allowing sufficient tidal exchange and river discharge from New York Harbor to maintain ship passage and water quality.

At present, conceptual designs of storm surge barriers should be considered as contributions to the discussion on how to deal with the increasing risks of storm surge in New York City and the surrounding region in the era of climate change. A key point is that those risks still need to be better characterized in regard to the efficacy of citywide measures. Such options, which would entail significant economic, environmental, and social costs, would require very extensive study before being regarded as appropriate for implementation, especially as alternative robust approaches to adaptation are available. New York could protect against some levels of surge with a combination of local measures (such as flood walls and reclaimed natural barriers), improved storm information and forecasting, and evacuation plans for at least the next several decades. Moreover, barriers would not protect against the substantial inland damages from wind and rain that often accompany hurricanes in the New York City region.

4.2 Lessons learned from other metropolitan areas

New York City and other large cities have seen a significant awakening in the last few years to the potential threats presented by climate change. Numerous cities have conducted varying levels of analysis, planning, and execution of climate change adaptation and mitigation actions. These analyses typically are grounded in some form of regionally downscaled climate projections (e.g., Hayhoe and Wuebbles).[15]

In developing climate action response plans, the focal points and nature of actions/policies recommended vary widely from city to city. Although adaptation is often not directly separated out in many of these plans, the plans still provide important lessons and insights for adaptation. In part, it is this breadth of response approaches that indicates the physical, political, and philosophical challenges that urban areas face in adapting to climate change. To this end, we see climate response plans presenting a mix of tangible actions, policies, and cultural aspirations. Following is a description of three large metropolitan area climate change response plans: Chicago, King County, Washington, and London, which were selected to provide examples of this diverse set of considerations.

Case studies

The case studies are from three major urban areas: Chicago, King County, Washington, and London. The focus of each area's plan varied as a function of timing, specific municipality priorities, mandates among city initiatives and degree of embedded efforts within higher level plans. For example, Chicago and King County's adaptation efforts are embedded in their climate action plans (hence they include GHG mitigation efforts), while London and NYC have robust climate action plans (i.e., PlaNYC) and more specific adaptation efforts (i.e., NYC Climate Change Adaptation Task Force, which is an initiative of PlaNYC). The following descriptions are not meant to be comprehensive but to illustrate the good work accomplished, and the unique considerations and range of approaches taken by the various areas:

- **Chicago's** action plan emphasized efficiency, energy sourcing, transportation, and waste-management themes. This plan highlights the ability of individuals in the city to make local changes with a large collective impact;
- **King County, Washington's** climate action plan seeks to aggressively reduce greenhouse gas (GHG) emissions while at the same time beginning to adapt to potential climate changes. This plan focuses on the need for flexibility along with constant tracking and monitoring. There is a strong policy and governmental management element in these plans; and
- **London's** adaptation plan centered on reducing vulnerability to extreme weather-related events as viewed through the lens of societal impacts. This plan focuses heavily on city-led solutions to address specific impacts to large portions of the population.

Following is a brief description of the efforts by Chicago, King County, Washington, and London to assess their climate change vulnerabilities and to plan/prepare for these potential changes. The following tables summarize some of the key plans for each of the cities.

Chicago

The City of Chicago[16] has identified its key climate-related threats as coming from (1) increased average temperatures, (2) increased number of heat waves, and (3) increased precipitation. They evaluated these potential impacts from physical and economic perspectives, as well as from the standpoint of possible mitigation contributions to arrive at an integrated strategy composed of five key elements, each linked to climate adaptation strategies (also related to mitigation):

1. Energy-efficient buildings—reduce energy use in buildings;
2. Clean and renewable energy sources—turn to cleaner and renewable energy sources;
3. Improved transportation options—use a variety of transportation modes and cleaner vehicles;
4. Reduced waste and industrial pollution—prevent, reduce, reuse, and recycle; and
5. Adaptation—minimize and prepare for the impact of climate change.

Their evaluation of physical climate change impacts was enhanced by analysis of the potential economic impacts on city departments and agencies,

Table 4.2. Adaptation planning in Chicago

	Energy-efficient buildings	Transportation	Water and waste	Outreach
Chicago	-Pursue innovative cooling options -Develop energy efficient buildings -Retrofit commercial, industrial, residential buildings -Trade-in old appliances -Conserve water -Update City energy code -Establish new renovation guidelines -Green roofs and tree planting -Increased dependence on renewable energy sources -Upgrade power plants -Improve power plant efficiency -Increase distributed generation -Promote household power generation	-Improve transportation options -Invest more in transit -Expand transit incentives -Promote transit oriented development -Improve walking and biking systems -Increase car share and pooling availability -Improve city vehicle fleet efficiency -Achieve higher fuel efficiency standards -Switch to cleaner fuels -Support intercity rail -Improve freight movement	-Reduce waste and industrial pollution -Reduce, reuse, recycle -Shift to alternate refrigerants -Improve storm water management, including capturing on-site	-Better engage the public in climate change discussions -Promote green urban designs

including both operational spending and capital investments. This analysis served to help prioritize action responses and provide forward-looking projections for future strategic planning and budgeting.

Chicago's integrated plan addresses reduction of physical impact and practical adaptation to climate changes. These efforts are designed to minimize negative economic impacts (both individual and collective), increase air and water quality, improve overall quality of life, and position Chicago to be resilient to all changes. Chicago's overall approach, therefore, represents an integrated mitigation/adaptation plan with anticipated investment to achieve both of these goals. Critical elements of Chicago's plan are highlighted in Table 4.2.

King County, Washington

King County is the largest regional government in the northwest United States and is a leader in consideration and planning for climate change integration into its management practices. The 2007 Climate Plan[17] lays out the direction and mandate for an integrated approach to reducing GHG emissions and beginning to systematically adapt to changes. The plan itself builds on a 15-year history of environmental consciousness and actions.

The King County plan includes strong mitigation and adaptation steps. Due to the construct of their plan, it is helpful to note the mitigation aspects to set the context for their adaptation efforts, as these two are closely linked in their documentation. The mitigation aspect is based on a focus in the areas of:

1. GHG accountability and limits;
2. Climate-friendly transportation choices;
3. Clean fuels, clean energy, and energy efficiency; and
4. Land use, buildings, design, and materials.

While there is not consensus as to the ultimate impacts of climate change on the area, King County anticipates some amount of sea level rise in Puget

Sound as well as increased seasonal fluvial flooding. The adaptation portion of the plan therefore focuses on enhanced regional coordination relative to a number of areas, and specifically focuses on adaptation in the categories of:

1. Climate science—leading in research, monitoring, and use in public policy decisions;
2. Public health, safety, and emergency preparedness;
3. Surface water management, fresh water quality, and supply;
4. Land use, buildings, and transportation;
5. Financial and economic impacts; and
6. Biodiversity and ecosystems.

King County's 2007 plan was designed to be updated as necessary on an annual basis, and the 2008 report does indeed makes comparisons with previous-year metrics and includes recommendations for adjustments. This dynamic feedback aspect is a key element of the King County plan. Critical elements of King County's plan are highlighted in Table 4.3.

London

London is pursuing an aggressive adaptation approach, in part due to its heat wave experience in 2003 and severe flooding of 2007, though their efforts began prior to these events. London's efforts have been widely noted for the large Thames barrier installed to address tidal flooding. However, it is important to note that roughly 15 percent of London is at risk for both tidal and fluvial flooding. To address this vulnerability, London is protected by a complex and integrated system of flood walls, barriers and gates, with the Thames barrier being one element of that system.[18] Their risk-based approach underscores the dynamic aspect of climate change and highlights the need for frequent reassessment and update. The London plan is based on four basic management actions: prevention, preparation, response, and recovery.

The climate in London is anticipated to become increasingly warm and wet in winter and hotter and dryer than previously experienced in the summer. Additionally, London anticipates increased intensity and frequency of extreme weather events (heat waves, precipitation, tidal surges) leading to increased flooding and wind damage. Their plan therefore focuses on flooding, drought, and overheating, with emphasis on health, the environment, the economy, and city infrastructure. The London 2008 adaptation strategy is forward-looking from the standpoint of existing gaps and vulnerabilities. Therefore, the focus is specifically directed toward addressing the most urgent exposures.

The London plan has three key strategies at its core:

1. Flood—reduce fluvial and surface water flood risk and protect key infrastructure from flooding;
2. Drought—significantly reduce demand for water within the metro area; and
3. Heat wave—limit exposure to high temperatures by reducing urban heat island effects and reduce human heat exposures.

Impacts are given for health, the environment, the economy and city infrastructure. Examples of direct health impacts include things such as poor air quality affecting the elderly and those with respiratory problems; increased extreme weather effects on injury, disease, and mental health; and increased incidents of food poisoning (4.5% increase in incidents per 1° C rise in temperature). Indirect health impacts are also discussed, such as disproportionate impacts on residents living in poor quality and overcrowded housing, increased health risks on people working outside (especially in heavy labor) or poorly ventilated facilities, and negative effects on education in overheated schools. Finally there are also direct effects on health service delivery, such as weather or other events that prevent health workers from attending work, many primary care facilities located in high flood risk areas, and hospitals and care facilities that are not designed to accommodate increased heat events.

Critical elements of London's plan are highlighted in Table 4.4.

4.3 Corporate and business climate change action planning

The City of New York has taken a leadership role in considering the potential impacts of climate change on its residents, infrastructure, and business community. Both the NPCC and Task Force included private-sector practitioners in their work. This combined focus and understanding of

Table 4.3. Adaptation planning in King County, Washington

	Climate science	Biodiversity and ecosystems	Financial and economic impacts
King County, Washington	-Maintain an interdepartmental climate change action team -Create a climate change technical advisory group w/in the action team -Increase focus on understanding climate change impacts and environmental conditions in the Water and Land Resource Dept. -Proactively provide climate change science updates to policy makers -Create an outreach database of County experts for broad use	-Collaborate with regional climate scientists and experts to increase knowledge of current and projected impacts to salmon, wildlife, and biodiversity -Reevaluate the existing ambient monitoring program to determine if additional biodiversity monitoring is needed -Develop and conduct sensitivity and vulnerability assessments of King County's marine ecosystems relative to climate change	-Continue to evaluate potential impacts on government operations and discuss with residents, businesses, and agencies -Continue to build expertise on climate change impacts to forest health and forestry -Support biofuel development by the region's agricultural economy (to increase resilience) -Continue to develop expertise to project climate change impacts to regional energy supply

infrastructure-related issues will enable New York City to maintain practical functionality and support resident needs in the face of ongoing climate changes.

While the members of the Task Force have been active in evaluating potential climate changes, not all businesses will respond in the same fashion, in that business concerns related to climate change vary greatly depending on size, location, business model, scope of operations, and products/services. This means that what might have relevance to one company is of no material concern to another if their operations and income are not affected. Additionally, in light of the current financial crisis, many companies are primarily focused on balancing the short term (e.g., revenue, cash flow) with the medium-long term (e.g., growth) to generate viable survival/success strategies and actions. For most corporations and businesses, the topic of climate change is perceived as a long-horizon issue that does not have urgent impact on their day-to-day operations. Although extreme weather, flooding, and similar events can be of critical importance and impact, these issues are generally captured in most companies under the auspices of business continuity plans (BCP) and emergency-response plans.[19] Companies vary on the robustness and level of sophistication of BCP, but the intent is to ensure continuous business operations in the case of any natural or manmade (security) disaster. These plans are integral to companies, as cessation of operations can cause significant revenue and brand impairment. Therefore, most companies have short-term plans in place to prevent situations (if possible), manage through the crisis, and recover operations as quickly as possible.

Climate change is usually addressed by businesses as part of their strategic planning and long-range budgeting processes, if at all. The long time horizons and uncertainty of climate changes can enter into discussion of long-term growth, capital investment, challenges/barriers, and modifications to

Table 4.3. *Continued*

Surface water management, fresh water quality, and water supply	Land use building and transportation	Public health safety and emergency preparedness
-Actively re-evaluate climate change impacts to stream flows -Promote water supply management structures that support resilience to climate change -Increase use of reclaimed water produced from wastewater systems Work with the State to increase reclaimed water usage statewide -Expand storm water management systems	-Depts. that manage capital projects will incorporate climate change information on adaptive green building into plans, policies, and codes -Dept. of Natural Resources and Parks Solid Waste will provide green outreach information and technical assistance to residents -Identify cultural resources, buildings, and archaeological sites at risk -Incorporate climate change impact information on construction, operations, and maintenance of infrastructure projects of the Road Services Division -Climate change Technical Advisory subgroup will train the road Services Division staff in understanding climate change impacts	-Increase collaboration between academics, public agencies, private sector, and nonprofits to increase understanding and visibility of climate change issues -Develop proactive strategies to reduce known risks -Regularly analyze climate change impacts on natural hazards and update emergency plans -Utilize the climate change adaptation team to review County plans, policies, and investments -Implement a newly revised flood risk map and institute a countywide fee to fund investments necessary to address high flood risks

operations. Companies are also concerned about issues, such as facility susceptibility to flooding and weather trends that affect operations, but generally the pace of change can be handled with ongoing adaptation. Projected climate changes may become a larger issue when considering new investments or long-range planning. However, because of the increasing prominence of these issues, we are beginning to see more businesses considering GHG/carbon footprint and climate adaptability in

Table 4.4. **Adaptation planning in London**

	Flooding	Heat
London	-Improve risk management of London's rivers -Increase emergency fluvial flood storage capacity -Increase urban absorption and storage capabilities -Identify critical infrastructures at risk -Raise public awareness and ability to act in flooding situations	-Manage heat island effect through "greening" the City via green roofs and new green spaces -New building design and retrofits to minimize powered cooling needs -Increase use of low-carbon, energy efficient cooling -Focus on social adaptation to higher temperatures -Implement London "heat wave plan"

their investments and operations decision-making processes. It is anticipated that this trend will continue to increase and become more sophisticated in coming years.

4.4 Conclusions and recommendations

Adaptation strategies are needed that respond to the challenges described in this chapter. A number of similar adaptation strategies apply generally to different kinds of infrastructure and thus can produce benefits across multiple infrastructures at the same time. These adaptation strategies pertain to the redirection of water away from infrastructure, the choice of more resilient infrastructure materials to reduce the impacts, and operational strategies. Some of these adaptation measures double as mitigation strategies as well, such as the use of insulation to reduce heat loads, which also helps to reduce energy use and thus GHG emissions. Key recommendations to create and implement effective adaptation plans are outlined below, many of which are already in place in New York City:

- Create a full cycle perspective: understanding what has contributed to the situation (in the past), what is impacting it currently, and the ramifications of potential solutions;
- Conduct sensitivity analysis of climate change impacts on infrastructure;
- Identify location and functional strength of interdependencies;
- Involve the broader community, including businesses, to build buy-in and crucial partnerships;
- Enhance adaptative capacity in expandable, modifiable, and broadly diverse ways. This means that infrastructure and solution designs must include an ability to incorporate and readily adjust to changing solutions and technologies;
- Develop a full-spectrum planning scenario that includes prevention, preparation, response, and recovery; and
- Create dynamic adaptation approaches by avoiding a predominance of solutions that lock into single pathways or irreversible courses of action. While often single pathways are necessary, it is important to design flexibility into solutions.

Plans must evaluate adaptation solutions in an integrated fashion. This means that as a general rule, the business case for the proposed adaptation solutions should be supported by an analysis of the implementation costs (incremental, long and short term) along with an evaluation of the anticipated benefits, an assessment of policy implications (e.g., required changes, legal hurdles, constituencies and their responses), peripheral impacts that may be embedded in the solution (e.g., to infrastructure elements, preclusion of other alternatives, societal patterns), and required change management initiatives to make the change (e.g., individual behaviors, political, psychological). Failure to consider these dimensions in solution planning can cause a good idea or approach to lose or fail to obtain necessary support, funding, or momentum required to succeed.

Two critical considerations are sensitivity of results to changes in assumptions and uncertainties, and how interdependencies among infrastructures can influence assessment of the impact of climate changes on infrastructure. These two issues are a critical part of the decisions regarding infrastructure adaptation and should be factored into all ongoing discussions.

Adaptation solutions need to be viewed in a full-cycle context. It is this full cycle view that often highlights potential downsides to what seem to be very good solutions, or better, that brings risks and liabilities to light. Often these downsides and liabilities can be mitigated by revised solution design or modified implementation planning. Solution plans therefore, should consider: the potential for unintended consequences, creation of "one way" changes that limit downstream flexibility, requirements and prerequisites to make a plan actionable (interdependencies), and potential synergies with other adaptation/mitigation approaches. An additional benefit of a full cycle view is that this often provides a level of positive integration among solutions that would not have otherwise existed, yielding both cost and effectiveness benefits.

Other metropolitan areas have also made significant strides in climate change adaptation planning. For example, London points out that a key goal is to develop widespread adaptive capacity. This means that infrastructures of the future should be built in a way that allows and supports ongoing adaptation. The London plan also illustrates the concept of adaptation planning based on four stages: prevention (understanding and preventing exposures before they occur), preparation (being ready for an occurrence), response (real-time and/or immediate post event actions), and recovery (post-event capabilities, infrastructure, and societal rebuilding). These four stages provide a full-spectrum planning scenario, which can build buy-in and a comprehensive view of adaptation plans. Further to this point, Chicago's plan highlights the importance of building a strong dialogue between interest groups in order to ensure the success of adaptation approaches in a complex society made up of innumerable vested interests. Chicago lists some of the groups to consider: the physical adaptation engineering community, infrastructure owners and maintainers, policy makers, city planners, political interests, and, of course, the residents of the city itself. Finally, King County is a good example of plan updating and evolution. They perform an annual update of the extensive 2007 plan in order to make adjustments, incorporate new knowledge, and provide status reporting. The message is clear from this example, adaptation plans should not be static, but should be dynamic approaches drawing from the broader community of interest.

In summary, a constellation of efforts is needed that are both infrastructure and location specific as well as integrated at the citywide scale. The important message is that these efforts be developed and employed together, with coordination among many different public- and private-sector entities.

Endnotes

[1]This originates from the NYS Reliability Council. It is a regulatory rule not a law. The percentage is computed each year.

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

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

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[6]NYC, Sustainable Stormwater Management, Main Report, 2008, p. 34. New York City Municipal Water Finance Authority, Water and Sewer System Second General Resolution Revenue Bonds, 2009, pp. 44–54.

[7]NYC, PlaNYC, 2007, pp. 63–65.

[8]NYC, PlaNYC, 2007, p. 65.

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

[10]New York City Department of Sanitation, Solid Waste Management Plan. September 2006, p. 1–2.

[11]Telecommunications Act of 1996 47 U.S.C. §§ 153, 255.

[12]S.M. Rinaldi, J.P. Peerenboom, and T.K. Kelly, Identifying, understanding and analyzing critical infrastructure interdependencies, IEEE Control Systems Magazine, December 2001. p. 14.

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[14]NYC DEP, Assessment and Action Plan, 2008, p. 41.

[15]K. Hayhoe and D. Wuebbles, Climate Change and Chicago, Projections and Potential Impacts, Chicago Climate Action Plan, Chapter 2, 2007.

[16]Chicago Climate Action Plan, 2008.

[17]2007 King County Climate Plan, February 2007.

[18]Greater London Authority, The London climate change adaptation strategy, 2008.

[19]Emergency-response plans cover the same type of issues as BCP plans and are integrated with them, but also focus attention on non-revenue issues, such as employee safety and welfare. In many cases these plans are synonymous, but are not always.

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