Chapter 9

Transportation

Authors: Klaus Jacob,[1,2] George Deodatis,[2] John Atlas,[2] Morgan Whitcomb,[2] Madeleine Lopeman,[2] Olga Markogiannaki,[2] Zackary Kennett,[2] Aurelie Morla,[2] Robin Leichenko,[3] and Peter Vancura[3]

[1] Sector Lead
[2] Columbia University
[3] Rutgers University, Department of Geography

Contents

Introduction

The transportation sector, as defined in the context of the ClimAID report, consists of the built assets, operations, services, and institutions that serve public and private needs for moving goods and people within, to, and from the State of New York. The transportation sector and the energy and communications sectors are highly interdependent (see Chapter 8, "Energy," and Chapter 10, "Telecommunications").

Transportation occurs by different *modes*: land, air, and water. On land, it can be divided into road, rail, and pipeline systems. Transported goods are people and freight (the latter includes raw materials, supplies, finished products, and waste). In urban areas, mass transit systems serve commuting populations traveling to and from daily work, school, shopping, etc. In suburban and rural areas, largely private vehicular transportation on roads and highways dominates, but this also reaches the central business districts of cities. Long-distance and interstate traffic on roads is complemented by railway, water, and air transport.

The purposes of this chapter are 1) to provide a comprehensive overview of the vulnerabilities of the state's transportation system to changing climate, and 2) to present the adaptation options that can turn the challenges posed by the changing climate into opportunities to revitalize and modernize the state's transportation systems while at the same time improving their climate resilience. This chapter is structured based on climate hazards and risks. This means that regions with the highest concentration of transportation assets located in the most vulnerable places, and hence representing the largest risks for potential losses from climate change, will be scrutinized in much greater detail than those regions with fewer assets at risk and with lesser climate change impacts on the state's economy.

9.1 Sector Description

Transportation is a lifeline fundamental to modern developed societies. Provided in this section is an overview of the transportation sector in New York State. This section includes a description of the many transportation systems in the state and discusses the agencies that are responsible for managing them.

9.1.1 Economic Value

Nationally, transportation contributes on the order of 10 percent to the economy. Translated to New York State's annual gross state product (in excess of $1 trillion), this would correspond to a contribution of about $100 billion per year to the state's economy.[1] Without an effective transportation infrastructure, the economy of a state cannot function and grow.

9.1.2 Statewide Overview

Transportation in New York State is a complex system in which the public and private sectors interface by different transportation modes, including roads, rails, aviation, and shipping.[2] The New York State Department of Transportation (NYSDOT) is the state's transportation lead agency and has the following functions:[3]

- Developing and coordinating comprehensive transportation policy for the State; assisting in and coordinating the development and operation of transportation facilities and services for highways, railroads, mass transit systems, ports, waterways, and aviation facilities; and formulating and keeping current a long-range, comprehensive statewide master plan for the balanced development of public and private commuter and general transportation facilities.
- Administering a public safety program for railroads and motor carriers engaged in intrastate commerce;

Source: National Atlas, modified

Figure 9.1 Interstate and major state highways in New York State

directing state regulation of such carriers in matters of rates and service; and providing oversight for the safe operation of bus lines, commuter railroads, and subway systems that are publicly subsidized through the Public Transportation Safety Board.

Highways and Bridges

New York State DOT designs, operates, and maintains the majority of the Interstate and State Highway system (**Figure 9.1**). It consists of about 113,000 miles of highways and more than 16,000 bridges,[4] associated ramps, underpasses, drainage systems, other related structures, and signage and signal systems. The combined state and local highway system annually handles over 100 billion vehicle miles.

The New York State Thruway Authority operates the toll-collecting Thruway and related bridges connecting New York City via Albany and Rochester to Buffalo; it also operates the state's canals. The Thruway Authority manages 2,818 lane miles of highway and more than 800 bridges. More than 246.7 million trips were taken on the Thruway in 2009, representing more than 8.1 billion miles traveled.

The New York State Bridge Authority is responsible for five toll bridges in the Mid-Hudson Valley:[5] Bear Mountain Bridge; I-84 Bridge near Newburgh/Beacon; Franklin Delano Roosevelt Mid-Hudson Bridge near Poughkeepsie; George Clinton Kingston-Rhinecliff Bridge; and Rip van Winkle Bridge at Catskill, Hudson. Not included is the Thruway Berkshire Spur Bridge (about 10 miles south of Albany), which is overseen by the New York State Thruway Authority.

County and Local Roads

County and local roads and bridges are a vital and indispensable part of the state's transportation infrastructure. Local roads and bridges account for 87 percent of the roads, 52 percent of the bridges, and 48 percent of the vehicle mileage logged in New York State.[6]

Railways

The state is home to a 4,600-mile rail network over which 42 million tons of freight are shipped each year,

consisting of equipment, raw materials, manufactured goods, and produce (for details see Section 9.1.6). Long-distance intercity passenger rail is provided by Amtrak. Commuter rail mass transit is provided by several agencies largely in the New York City metropolitan region, further discussed below.

Aviation

The state has over 500 public and private aviation facilities through which more than 31 million people travel each year.

Shipping

The state is home to 12 major public and private ports, which handle more than 110 million tons of freight annually. Of these, five major ports handle 50 million tons of freight annually.

Mass Transit

Over 130 public transit operators serve over 5.2 million passengers each day. They include the Capital District Transportation Authority (CTDA), serving the region in and around Albany; the Central New York Regional Transportation Authority (CNYRTA), serving the region centered on Syracuse; the Rochester Genesee Regional Transportation Authority (RGRTA); the Niagara Frontier Transportation Authority (NFTA), serving the greater Buffalo region; and many county-based transit systems, plus private bus operators. In the most transportation-intensive New York City metropolitan area, several major authorities are charged with operating multiple modes of travel. (For a schematic plan of the combined passenger rail systems, visit http://www.columbia.edu/~brennan/subway).

9.1.3 Metropolitan Transportation Authority

The Metropolitan Transportation Authority (MTA) is the largest transit operator in the nation. It provides about 8.5 million passenger trips per day at twice the energy efficiency of advanced hybrid cars (MTA, 2008a). The approved MTA operating budget for 2009 was $11 billion. The actual capital project work committed for 2009, as reported in January 2010 to the

MTA Board, was $4.688 billion. MTA includes a number of operating agencies, which are described below (MTA, 2008b):

New York City Transit

New York City Transit (NYCT) operates the subway, which has 26 lines, 468 stations, and 6,241 cars; a bus division with 4,538 buses on 208 local and 36 express routes; and the Staten Island Railway (SIR) with 22 stations and 64 cars. NYCT's subway comprises 228 route miles in Manhattan, the Bronx, Queens, and Brooklyn, of which about 62 percent is below grade in tunnels, about 28 percent on elevated tracks, and 10 percent at grade. NYCT also operates the (entirely at grade but road-crossing-free) 14 mile-long Staten Island Railway (SIR). Staten Island commuters to Manhattan may chose from three public transit options: the Staten Island Ferry, NYCT express buses, or the private Atlantic express buses. The total replacement value of the NYCT tunnel, elevated, and roadbed route structures (excluding stations) is on the order of $190 billion (all values in 2007 dollars). The length of rail tracks is 628 miles, valued at $11 billion. There are nearly 300 pump stations, 200 fan plants, and more than 200 electric substations, with a combined asset value of $22 billion. There are nearly 280 underground stations (valued at $11 billion) and about 200 elevated stations (valued at $5 billion), plus some 20 station complexes (e.g., Times Square, Grand Central Terminal) that serve multiple subway or railway lines and other connections. The rolling stock is worth nearly $11 billion. There are also rail yards and maintenance shops, many at low elevations near the waterfront.

MTA Metro-North Railroad

The MTA Metro-North Railroad has total assets worth on the order of $10 billion. They include 800 miles of track and roadbed, terminals, stations, yards, bridges, movable bridges, tunnels, stone and steel viaducts, rolling stock, third rail and catenary power systems, communications and signals, and other facilities. Metro-North operates three passenger rail lines in New York State, each of which originates at Grand Central Terminal in New York City. The Hudson, Harlem, and New Haven Lines are co-located underground from Grand Central Terminal at 42nd Street to 98th Street, where they continue northward aboveground until they split in Mott Haven Yard, Bronx. The Hudson Line

continues north along the Hudson River to Poughkeepsie. From Spuyten Duyvil to Poughkeepsie, Metro-North maintains its track structure to support the speed required for the Amtrak service, as well as the loads imposed by the CSX freight traffic. The Harlem Line continues northward to Wassaic. The Beacon Line operates for freight and equipment traffic only, from Beacon east to Danbury, Connecticut. The New Haven Line splits off the Harlem Line in Woodlawn and continues eastward to New Haven, Connecticut, along the Long Island Sound. Along the New Haven Main Line, Amtrak trains travel the northeast corridor. The New Haven Line also supports loads imposed by local freight traffic. Off the New Haven Main Line there are three branch lines: the Danbury, the Waterbury, and the New Canaan Lines. Metro-North owns a portion of the Northeast Corridor (NEC) from New Rochelle to the New York/Connecticut state line. The Connecticut Department of Transportation owns the NEC from the state line to New Haven. Each owner is responsible for maintenance and operations of their respective segments. For the West of Hudson Line, Metro-North has contracted NJ TRANSIT to operate the New York portions of the two commuter lines, the Pascack Valley and the Main & Bergen Lines (the Port Jervis Line). Although Metro-North leases the West of Hudson Line, Metro-North is also responsible for maintaining the track, bridges, and stations for the Port Jervis Line. The track and bridges are maintained for passenger cars as well as the Norfolk Southern freight traffic. Metro-North is also responsible for a number of unique structures, such as historic Grand Central Terminal. The Terminal's train shed continues north to become the Park Avenue Tunnel, which runs under Park Avenue from 57th Street to 98th Street. The Park Avenue Viaduct is a stone structure from 98th Street to 110th Street and a steel structure from 110th Street to 138th Street. Metro-North has six movable bridges in its territory, including the Harlem River Lift Bridge in New York City. There are four tunnels along the Hudson Line. The Otisville Tunnel is one-mile long and is located on the Port Jervis Line. Also unique to the Port Jervis Line is the Moodna Viaduct. At 3,200 feet long and 200 feet high, it is the highest and longest railroad trestle east of the Mississippi River.

Long Island Rail Road

MTA's Long Island Rail Road (LIRR) owns and operates structures, shops, and yards with an asset value on the

Source: MTA B&T

Figure 9.2 Major bridges and tunnels in New York City

order of $19 billion, and almost 600 miles of track, stations, and power facilities whose value exceeds $20 billion. Rolling stock is valued in excess of $3 billion. LIRR uses Penn Station in Manhattan as its western anchor with transfers to/from Amtrak, NJ TRANSIT, NYCT subways, and the nearby Port Authority Trans-Hudson (PATH) system (see below). LIRR trains leave Manhattan heading eastward via the East River Tunnels, owned and co-used by Amtrak for its Washington-Boston NE Corridor. The East Side Access project, currently under construction, will use a tunnel below the East River from Queens to Manhattan into Grand Central Terminal. It will directly connect commuting locations on Long Island with Manhattan's mid-town East Side. Beyond Queens, the LIRR operates, along the North Shore of Long Island, the Port Washington, Oyster Bay, and Port Jefferson Lines; beyond the Jamaica Station, Queens, the central spine of Long Island is served by lines that terminate easterly in the island's North Fork; Long Island's southern shores are served by the Long Beach Branch and the Babylon and Montauk Lines that straddle the Great South Bay.

MTA *Bridges and Tunnels*

MTA Bridges and Tunnels (MTA B&T) owns nine large toll-collecting facilities (two tunnels and seven bridges, **Figure 9.2**). The value of total built assets approaches $25 billion. Annual toll revenues from all B&T facilities amount to about $1.2 billion (URS, 2008). The nine key assets are: Queens Midtown Tunnel, Brooklyn Battery Tunnel, Verrazano Narrows Bridge, Throgs Neck Bridge, Bronx-Whitestone Bridge, the Robert F. Kennedy (formerly Triboro) Bridge, the Marine Parkway and Cross Bay Bridges in Queens, and the Henry Hudson Bridge across the Harlem River in northern Manhattan.

MTA *Long Island Bus Service*

The MTA Long Island Bus Service operates North America's largest compressed-natural-gas bus fleet with 316 buses on 56 routes, and several fixed structures, such as depots and shops. It provides more than 100,000 trips per day among nearly 100 Long Island communities, including Nassau County, western Suffolk County, and into eastern Queens with 53 routes, and serves 48 Long Island Rail Road stations plus colleges, museums, parks, theaters, and beaches throughout the service area.

MTA *Bus Company*

The MTA Bus Company was formed in 2006 by merging seven private lines. It operates extensive bus routes in New York City (except Staten Island), and has eight fixed facilities in Brooklyn, Queens, the Bronx, and Westchester County. Of the MTA bus routes, 46 are local routes in Brooklyn, Queens, and the Bronx, and 35 are express bus routes between Manhattan and the Bronx, Brooklyn, and Queens. It has a fleet of 1,336 buses serving a ridership of approximately 394,000 on an average weekday (2009).

MTA *Capital Construction*

MTA Capital Construction was formed in 2003 to centrally manage the largest capital construction projects for the entire MTA family of agencies. Current projects in planning or under construction are: the first phase of the 2nd Avenue subway, the East Side Access project bringing LIRR into Grand Central Terminal, extension of the Number 7 (Flushing Line) subway to the West Side of Manhattan, and the Fulton Street Transit Center serving 12 lines in downtown Manhattan.

9.1.4 Port Authority of New York and New Jersey

The Port Authority of New York and New Jersey (Port Authority) fulfills multiple bi-state functions. It owns and operates international and domestic airports and marine ports, as well as interstate ground transportation facilities serving New York and New Jersey. With the exception of Stewart Airport, all the facilities the Port Authority operates are located within its originally assigned 25-mile radius from the Statue of Liberty. According to its 2008 annual report (PANYNJ, 2008):

> On a day-to-day basis, the Port Authority operates one of the most complex sets of transportation services in the nation. The agency's airports, bridges, tunnels, bus terminals, its Port Authority Trans-Hudson (PATH) rail system, AirTrain services, and seaports help move people and cargo at a pace and on a scale that life in the New York-New Jersey region demands....Nearly 1 million people each day rely on Port Authority transportation facilities to help them get to where they are going.

The Port Authority has four operating divisions: 1) Aviation; 2) Tunnels, Bridges, and Terminals; 3) Rail Transit; and 4) Port Commerce.

Major ground transportation facilities include the following Hudson River and other water crossings **(Figure 9.3)**:

- PATH commuter rail (ridership about a quarter-million people per day)
- George Washington Bridge (GWB)
- Lincoln and Holland Tunnels
- Bayonne Bridge, Goethals Bridge, and Outerbridge-Crossing

Total eastbound vehicle volume on these tunnels and bridges in 2008 was about 124 million per year, with GWB alone accounting for 53 million vehicles per year.

The Port Authority owns three regional bus terminals:

- George Washington Bridge Bus Station
- Mid-town Manhattan Port Authority Bus Terminal
- Journal Square Transportation Center Bus Terminal in Jersey City

These are used by private and public bus operators. Total combined passenger volume (in 2008) was nearly 72 million passengers per year. The total interstate (NY/NJ) ground transportation network produced gross operational revenues (largely tolls and fares) of about $1.1 billion, of which the George Washington Bridge (GWB) contributed about 40 percent.

The Port Authority operates three major international / national airports (JFK, Newark, and LaGuardia), and two smaller airports (Teterboro and Stewart). Combined total passenger volume at these airports fluctuates between 100 and 110 million passengers per year. Of these, JFK (47 million passengers in 2008) and Newark airport (35.4 million passengers in 2008) are important

Source: The Port Authority of New York and New Jersey, 2001; Bureau of Transportation Statistics, Transportation Atlas of the United States

Figure 9.3 Facilities operated by the Port Authority of New York and New Jersey (PANYNJ)

gateways for international flights to and from the U.S. The combined air cargo for 2008 was 2.4 million tons.

Combined airport gross operating revenues in 2008 were about $2 billion (with JFK accounting for $0.951 billion, Newark about $0.718 billion, and LaGuardia about $0.307 billion).

The Port Authority operates major marine port facilities and container terminals in the NY/NJ harbor. In 2008 the port facilities handled 5.27 million TEU (20-foot Trailer Container Equivalent Units), or 33.6 million metric tons, with a value of about $190 billion (about $51 billion in exports and $139 billion in imports). The ports' gross operating revenues in 2008 were about $0.21 billion.

The Port Authority owns the World Trade Center (WTC) site in downtown Manhattan, and owns and operates many other facilities (**Figure 9.3**).

The Port Authority had a $6.7 billion budget for 2009, which provided for $3.3 billion in capital projects; this was set at $3.1 billion for 2010.

9.1.5 Other Transportation Operators Serving the New York Metropolitan Area

NJ TRANSIT brings commuters by rail from New Jersey into Penn Station on Manhattan's midtown West Side via tunnels under the Hudson that are also used by Amtrak for its Washington, D.C.–New York–Boston rail passenger service. NJ TRANSIT, with funding participation by the Port Authority, is in the process of increasing trans-Hudson transportation capacity by constructing a new rail tunnel under the river between New Jersey and Manhattan. This Access to the Region's Core (ARC) project also includes a new underground station that will have a pedestrian connection to Penn Station, New York, where there will be no interconnection at track level.

The ARC project will more than double commuter rail capacity between New Jersey and New York. The availability of more and improved train service is expected to remove 22,000 cars from the region's highways. Additionally, NJ TRANSIT and the private bus carriers it supports transport 127,000 people every weekday for a total of 254,000 passenger trips each weekday into and out of New York City. The ARC project was put temporarily on halt in 2010; alternatives

to increase trans-Hudson commuter rail capacity at reduced capital spending are being explored.

The City of New York operates the Staten Island Ferry and all toll-free bridges between four of the five boroughs of New York City, including the Brooklyn, Manhattan, Williamsburg, and Queensboro bridges, and several smaller bridges crossing the Harlem River between Manhattan and the Bronx.

New York Waterway and other private ferry and water taxi services provide growing passenger service between points in and to the central business districts of New York City and on routes connecting them to communities along the lower Hudson River, Long Island Sound, Great South Bay within New York State, and to nearby Connecticut and New Jersey shore points.

9.1.6 Freight Railway Services in New York State

Freight services by railroads are in resurgence (see NYSDOT, 2009).[7] According to Railroads of New York (RONY), a trade association of New York State freight railroads, and data collected by NYSDOT, approximately 45 railroads operate in the state, although only four are Class-1 freight railroads (CSX, CN, CP, NS), in addition to the four commuter/intercity railroads (Amtrak, LIRR, Metro-North, NJ TRANSIT).

According to the American Association of Railroads (AAR),[8] in 2005, total miles of track operated in New York were about 3,600 miles, of which 65 percent is Class-1[9] railroad mileage. Amtrak owns about 150 miles of track in New York. In comparison, Metro-North and LIRR operate nearly 800 and 600 miles of track, respectively. According to the AAR, in 2005 carload tons originating in New York totaled almost 10.5 million, transporting major products including chemicals, waste and scrap, and nonmetallic minerals. Tons terminated in New York totaled over 25.3 million, including coal, chemicals, and food products.

Actual rail carloads originating and terminating within the state totaled 196,000 and 375,000, respectively. A map of all rail lines currently operating in the state is depicted in **Figure 9.4**. Major freight rail facilities and yards are located in Buffalo, Rochester, Albany, Binghamton, and New York City. Smaller yards and facilities are distributed throughout the rest of the state.

Figure 9.4 Operating rail lines in New York State in 2008

9.2 Climate Hazards

The impacts of climate change (see Chapter 1, "Climate Risks") have significant consequences for the transportation sector. Sea level rise, the intensity and frequency of some extreme weather events, mean precipitation, flooding, and coastal erosion are all projected to increase, putting transportation infrastructure and operations at risk. (For an assessment by transportation mode, see Section 9.3.)

9.2.1 Temperature and Heat Waves

Increases in both the annual average temperature (see Chapter 1, "Climate Risks," Section 1.3) and the number of days per year with extreme high temperatures will affect transportation systems in

several ways. Materials such as asphalt pavements; other road, bridge, and runway surfaces; and railroad tracks, electrified third rail, and catenary wires will need new performance specifications to cope with higher extremes and more frequent high temperatures. Air conditioning requirements for rolling stock and stations and ventilation requirements for tunnels will increase. Some runways of airports may need to be lengthened, since hotter air provides less lift and hence requires higher speeds for safe takeoff and landing.

A good example of the impact of heat waves on transportation systems is given by the European heat wave of 2003:[10]

- Britain's transport system suffered during the heat wave, particularly the railways. Widespread speed restrictions were imposed because of rail buckling,

which becomes a problem when rail temperatures reach 36ºC (97ºF). Official figures show 137 cases of rail buckling in 2003/4, compared with 36 the year before and 42 the year after. However, the authors caution that confounding factors such as maintenance cannot be discounted.

- The resulting delays are estimated to have cost passengers £2.2 million ($3.6 million) in lost time, while the National Network Rail had to pay £6.5 million ($10.7 million) to the train companies in compensation. The researchers also found that disruptive fires at the side of the tracks jumped 42 percent in 2003 compared to the following year, which also might be due to the hot weather.
- Britain's road network bore the brunt of the searing heat. Sections of the M25 highway melted, and the total costs of repairs across the country are estimated at £40 million ($66 million), of which the government contributed £23 million ($38 million). The rest of the burden fell on local authorities.
- Temperatures on the London Underground passed 41ºC (106ºF) and passenger numbers dropped 1–1.5 percent during the hottest two weeks, reducing revenue by £500,000 ($0.8 million).

9.2.2 Precipitation

The central and northern regions of New York (with elevations that exceed 5,000 feet) currently are prone to more frequent and severe ice and snowstorms than near-coastal regions of the state. Air- and land-based transportation systems and operations are susceptible to freezing rain (icing) and snow. In fact, New York State is the most vulnerable to icing of all of the lower 48 states (**Figure 9.5**) (NOAA, 2004).

Icing can affect transportation systems in many different ways. It is a direct, serious hazard for aviation and for vehicular traffic on the ground. Indirectly, icing can also affect transportation by loss of electric power and/or, to a lesser degree, communication systems.

Freezing rain, black-ice conditions, and severe snow pose hazards to highway transportation and increase accident rates under current climate conditions. Climate change is likely to bring changes to these hazards. For instance, increasing winter temperatures are likely to shorten the duration of ice cover of the Great Lakes and, therefore, potentially allow more moisture to be drawn from the ice-free lakes, which
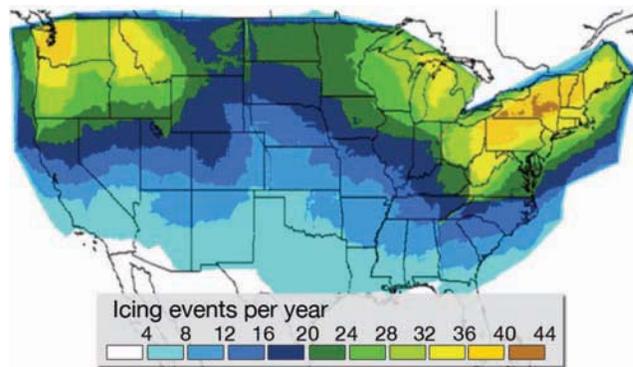
Note: Icing hazards are particularly severe in New York State, with the highest icing hazard in the central and western regions of the state. Note that warmer colors in this map indicate a greater icing hazard. Source: NOAA 2004

Figure 9.5 Estimated rendering of the likelihood of icing events across the United States

would then fall as snow in western New York during the cold season (see Chapter 1, "Climate Risks").

While the severity of such extreme snowfalls is likely to increase, the number of days per year with snow on the ground is likely to decrease. In the estuary and coastal regions, nor'easter storms, which in the past caused blizzards, may more often turn into severe rainstorms rather than severe snowstorms. On the benefit side, it is more likely than not that the need for snow removal and salting of highways will gradually decrease for low-elevation, southern, and coastal areas of the state. The need for snow removal and salting under future climate conditions may change little in northern New York, though it may increase in western New York in the next couple of decades in areas that are subject to episodes of extreme winter lake effects (see Chapter 1, "Climate Risks").

9.2.3 Sea Level Rise and Storm-Surge Hazards in Coastal Regions, Tidal Estuaries, and Rivers

All transportation systems—roads, tunnels, railways, subways, airports, and seaports—are at risk from coastal storms and related coastal storm-surge flooding hazards. In New York, a number of these systems are located along the water at low elevations, and some subways, railroads, and highways are located in tunnels below sea level.

Storm-surge hazards along New York's shores (and the tidal Hudson River from New York Harbor to the Federal Dam at Troy) arise from tropical cyclones—

hurricanes, tropical storms, tropical depressions—during the summer and fall, and from nor'easter storms during winter and early spring. Coastal storm surges have caused damage in the past, and based on their historic frequency and severity of occurrence, these hazards have been quantified for the historic record.[11]

Climate change, especially its effect on sea level rise, will significantly raise coastal storm-surge hazard levels, as described in Chapter 1, "Climate Risks." Many near-shore transportation systems are at risk already (e.g., to coastal storm surges that reach the 100-year base flood elevations in coastal zones as currently mapped by FEMA). Sea level rise will increase the probability of flooding dramatically. Projections show[12] that the storm elevations now reached by the 100-year flood (i.e., a 1-percent annual probability of occurrence) will be reached before the end of the century by a flood with an approximately 3 to 10 percent annual probability of occurrence—about a three- to ten-fold increase. These changes will require the flood maps in near-shore areas to be updated to reflect new flood elevations that account for sea level rise. The flood-risk zones will need to be extended farther inland accordingly. These updates will place many transportation facilities that are currently safely located above and/or outside designated flood zones and related flood elevations within the newly assessed coastal flood zones. Additional details are discussed in Case Study A.

Sea level rise will eventually inundate low-lying areas permanently if no mitigation or adaptation measures are taken, and it may also accelerate saltwater intrusion in some areas. For most transportation facilities, the increased coastal storm surge hazard, however, will dominate over these permanent inundation hazards for most of this century.

9.2.4 Other Climate Factors

Additional climate hazards that impact the transportation sector are extreme storms events and droughts. These hazards and how they are projected to change in the future are described here.

Increased Storm Intensities

While it is unclear whether the total number of storms (hurricanes, nor'easters, thunderstorms, tornados,

wind storms) will significantly change, it is more likely than not that the most extreme hurricanes and nor'easters will become more frequent. (see Chapter 1, "Climate Risks," and Chapter 5, "Coastal Zones"). The increase in intensity will affect air transportation: More storms (of any kind) may increase the number of delayed or cancelled flights, cause the temporary shutdown of airports, and/or result in flight detours to alternate airports. High winds may result in more frequent temporary closures or restricted use of larger bridges.

Intense storms redistribute existing sediments in the periodically dredged New York Harbor and Hudson River shipping lanes and bring increased sediment loads into them. These processes may increase the frequency of needed dredging operations. On the other hand, sea level rise tends to increase the available water depth. However, sediment transport in the Hudson and New York/New Jersey harbor is not sufficiently understood, and the understanding of sediment transport for these waterways under future climate conditions is even less well understood. Thus, it is not known whether sediment clogging or sea level rise will dominate over time or over which spatial distribution.

Urban Flash Flooding and Inland River Flooding

ClimAID projections show that the number of days per year with extreme precipitation (e.g., more than 2 inches per day) is likely to increase.[13] Projections for annual average precipitation rates (inches per year), however, show no clear trends in New York State for some time. An increase in extreme precipitation events will increase the hazards for urban and river flooding, with associated risks for transportation in cities and in rural areas along many rivers. This will necessitate increases in street stormwater drainage and processing peak capacity and/or result in environmentally undesirable combined sewer overflow events in those communities (including New York City) where street runoff is channeled into the public sewage system. The scouring potential for bridge foundations in some rivers is also likely to increase.

Droughts and Great-Lakes Climate Effects

Droughts can affect New York State's transportation systems in several ways. Extended droughts may lower

the water levels of the Great Lakes and canals, and reduce the shipping capacity to the Atlantic coast via the St. Lawrence River Seaway (Millerd, 2007). For the Great Lakes, climate change is expected to result in lower water levels, higher surface water temperatures, and shorter duration of ice cover—all of which will affect shipping.

To maintain sufficient water depth along shipping routes (i.e., keel clearances), vessels may need to reduce the total weight of cargo carried on each voyage to mitigate the effects of reduced water levels. On average, shipping between Lake Ontario and Montreal (passing through the Welland Canal that connects Lake Ontario and Lake Erie) amounts to about 2,700 transits, carrying about 31 million tons per year. Transporting a given weight of a commodity with reduced under-keel clearance will require additional trips, thus increasing total shipping costs. Lake Erie's water level has been projected to decrease by 1.97 feet by 2030 and 2.62 feet by 2050, using the Canadian Centre for Climate Modelling and Analysis (CCCMA) climate model, and by 4.59 feet assuming stabilization of atmospheric carbon dioxide concentration after it doubles (Millerd, 2007). The water level of Lake Ontario has been projected to drop by 1.15 feet by 2030 and by 1.64 feet by 2050, and by 4.27 feet under the same stabilization conditions (these lake level changes are relative to the International Great Lakes Datum of 1985.) The decrease in load capacity from these reduced water levels in the navigable channels may require an increase in the number of trips needed to ship the same tonnage, resulting in increased shipping costs. For example, the cost to ship grain under these lower-water conditions is projected to increase by 5 to 10 percent per ton of grain.

On the other hand, a warming climate may increase the shipping season since the duration of ice cover in the winter will be shortened. Ice breaking is currently shared between two Canadian and one U.S. Coast Guard ice breaker. Due to warmer temperatures, the time at which winter ice is cleared at the beginning of the shipping season may occur earlier, but no quantitative estimates are currently available. The closure of shipping in the winter has been used in past decades for lock maintenance of the Welland Canal. If year-round shipping becomes possible, then consistent twinning (doubling up the number of locks in each direction) may be needed to allow maintenance without impeding shipping.

Droughts can also affect land transportation by leading to fires along railroad tracks and interstate and state highways. They can cause temporary closures, traffic delays, and slowdowns, and can increase highway traffic accidents because of reduced visibility (apart from undesirable pulmonary health effects; see Chapter 11, "Public Health").

Extended droughts may affect the availability of water for washing buses and mass transit rolling stock fleets— a water-intensive operation. These activities may be curtailed during extended droughts that lead to water shortages. Measures to mitigate this consequence may include recycling gray water.

9.3 Vulnerabilities and Opportunities

Earlier reports have addressed the vulnerabilities of transportation systems to climate change on national,[14] regional,[15] and some New York City[16] scales. The national and regional reports provide an excellent background to major vulnerabilities, but need to be modified for statewide climate projections and transportation systems across New York State. Lessons learned from extreme weather events at other locations across the United States (e.g., Hurricane Katrina and other major storms along the Gulf Coast)[17] and Canada (e.g., the ice storm of 1998)[18] also provide useful information for New York, if modified to meet the needs of the state. This section of the ClimAID analysis addresses climate change vulnerabilities of transportation systems by mode of transportation. In Section 9.4 the risks from climate change are described from the perspective of the type of climate hazards. For each transportation mode, it is important to distinguish between the vulnerabilities of operations and those of physical assets. Information on generic vulnerabilities to climate change is largely based on the Transportation Research Board's report on the potential impacts of climate change on the transportation sector in the United States (TRB, 2008a).

9.3.1 Ground Transportation

One specific area of the transportation sector that is vulnerable to climate is ground transportation. This section discusses the vulnerabilities of ground transportation systems, which include roads, highways, and railways.

Roads and Highways (including bridges, tunnels, drainage, and signal systems)

The physical assets and structures of the transportation system are vulnerable to climate change amplified precipitation and flooding and related erosion of road embankments near inland rivers and streams. Gradually increasing severe coastal storm surge flooding (because of anticipated sea level rise) along coasts and estuaries, including the tidal portions of the Hudson River, also put transportation structures at risk. Heavy rains can also cause mud and landslide hazards. High temperatures require heat-resilient asphalt mixtures for road and highway pavements.

There are also a number of other structure-related vulnerabilities. Drainage systems may have insufficient capacity to cope with the heavier precipitation events. Bridge foundations in some streams will likely experience increased scour potential. Clearances of some bridges across waterways subject to sea level rise may be diminished below the limits set by the U.S. Coast Guard or other jurisdictions. Bridge access ramps, tunnel entrances and ventilation shafts, and highway beds may need to be raised in coastal zones to prevent frequent coastal storm-surge flooding, amplified over time by sea level rise. The same hazards may make ineffective the collision fenders protecting bridge foundations in navigable rivers from impacts of ships or barges during high-water events; the fenders may have to be vertically extended to accommodate sea level rise (e.g., for the Tappan Zee Bridge[19] main span, relying on the buoyancy of caissons vulnerable to impact by out-of-control ships or barges). Road surface materials and bridge decks will need to be resilient to virtually certain higher and more frequent peak temperatures. Roadbeds and surfaces may experience winter temperatures nearer the freeze and thaw cycle, rather than steady below-freezing conditions (TRB, 2008a).

For highway operations and construction activities, more extreme weather events will increase traffic interruptions, may increase the number of extreme-weather-related traffic accidents, and may slow down or interrupt summer construction activities at temperatures above 105°F, largely because of worker heat exhaustion. Heat-resistant pavements will need to be used where they were not needed before as the number of days per year with average temperatures above certain thresholds increases substantially (Chapter 1, "Climate Risks"). Power outages during summer heat waves may affect signals, and hence slow traffic, especially in urban areas.

Freezing rains at higher elevations are more likely than not to become more frequent, and so may snow hazards, mostly in western New York. Both snow and freezing rains, however, may diminish in the southern portions of the state and along the coast, thereby reducing snow removal and salting costs. Closures of roads due to wildfires and related diminished visibility from smoke during extreme and extended droughts are likely to increase in frequency and geographic extent. High winds are likely to require more frequent temporary closures of major bridges, may cause more damage to traffic signs, and may call for increased fallen-tree and debris removal from roads and highways.

Coastal evacuation routes may have to be prepared to accommodate reverse traffic flow to speed up evacuations out of coastal flood zones by using all traffic lanes to direct flow from coastal to safe inland or higher locations. Road tunnels and sub-grade underpasses in coastal areas and other flood-prone zones relying on pumped drainage will very likely need increased pump capacity and back-up power, especially if they serve as designated evacuation routes and/or need to stay open for first-responder emergency services.

Railways (subways and commuter, passenger, and freight railroads)

Rail systems in coastal zones and tidal estuaries are subject to storm surges, whether at grade or partially elevated, or running in tunnels below grade and/or below sea level when crossing bodies of coastal or estuary waters. These vulnerabilities will become ever more amplified by sea level rise. To reduce or remove these vulnerabilities in the coastal and estuary zones will require large long-term investments and, in some instances, either vertical or even horizontal relocation. For the latter option, this may require new rights-of-way and related land-use decisions for communities served by rail services.

Vulnerabilities to flooding, washouts and erosion, mud- and landslides in steep terrain of some railroads running along inland rivers and streams, and insufficient or marginal drainage capacity of culverts and catch basins will need attention. Increased river flooding is not always due to more extreme climate events, but can be

caused by changed land use, i.e., developments that increase rapid runoff and reduce infiltration of rain into natural ground cover and soils.

Extreme heat events also increase the vulnerability of railroads. Extreme heat can cause rail buckling. Routes along wooded areas may see increased wildfire hazards during extended droughts and heat waves. Power and related signal and/or communication failures during heat waves, floods, or windstorms can contribute to interruptions in rail and commuter services, with related economic effects.

In the New York City metropolitan area, coastal emergency evacuation plans partly rely on mass transit to provide evacuation capacity in the hours before severe coastal storms make landfall.

9.3.2 Aviation

Another area of the transportation sector that is vulnerable to climate is aviation. Vulnerabilities to aviation structures and facilities and operations are discussed in this section.

Structures and Facilities

Airports and related technical aviation facilities located in coastal areas at low elevations (e.g., La Guardia, Newark, JFK) and serving the greater New York City metropolitan region are all to some degree vulnerable to coastal storm-surge flooding amplified over time by sea level rise. Existing flood-protection levees (e.g., for LaGuardia) may have to be raised or new ones installed, to the extent that raised levee elevations are compatible with the clearance height required for takeoffs and landings. Over time, some runways and other airport facilities located at low elevations above sea level, such as fuel-storage farms, terminals, sewage treatment plants, and maintenance sheds, may have to be raised or protected in place to keep up with sea level rise and increased coastal storm-surge hazards. Drainage of runways is generally designed such that it is likely to keep up with increased intense precipitation events.

More frequent weather-related power failures might require improved back-up capacity at airports. Runway materials will need to resist higher and more frequent peak temperatures. Indoor airport facilities may need additional air conditioning capacity to deal with more extreme hot days. To determine effective adaptation strategies, each facility will need to conduct its own evaluation to assess its respective vulnerabilities (see TRB, 2008a).

Operations

Aviation operations will more likely than not have to cope with more severe weather conditions (high winds, thunderstorms, extreme precipitation, high temperatures) that generally lead to flight delays, cancellations, or detours to unscheduled landing destinations. These outcomes have economic implications for airlines, airports, and travelers alike. Loaded planes waiting excessive times for takeoff under extreme heat conditions can cause passenger discomfort and health emergencies. Extreme high air temperatures reduce the lift capacity of planes during takeoff and landing (TRB, 2008a), thus requiring, in some locations, longer runways, lower passenger or freight loads, or lower fuel loads that reduce distance range and reserve safety margins. In-flight icing conditions or deicing needs before takeoff could become more acute for airports and flight routes, especially in western and central New York.

9.3.3 Marine Transportation, Hudson River, and Great Lakes/St. Lawrence River Seaway Shipping

In coastal and estuary ports, including along the tidal portions of the Hudson River, vulnerabilities to coastal storm surges, amplified over time by sea level rise, will need to be assessed and addressed. Sea level rise, tides, and coastal storm surges propagate up the Hudson River estuary to Albany and the Federal Dam in Troy. The magnitude of the inland effects of sea level rise on the estuary is the same as for the coast; the inland effects of storm surge and tides decrease very little in force and amplitude.[20] This virtually certain increase in hazard related to sea level rise may affect pier heights, base elevation of loading cranes, power supply substations, access roads and rail tracks, open air storage (for containers or automobiles), and warehouse facilities located at low elevations along all shores subject to tides. In particular, the frequency of the 1-in-10-year coastal flood may triple over the next century, depending on sea level rise (see Chapter 1, "Climate Risks", and Chapter 5, "Coastal Zones").

On the other hand, for Great Lake ports (and related St. Lawrence River Seaway shipping lanes), increased lake evaporation under severe and prolonged drought conditions and extended heat waves are likely to lower the lake levels to such a degree that it may impede shipping capacity to the Atlantic Ocean and, via out-of-state routes, to the upper Great Lake states and Canada.[21] During extended droughts, the canal and lock systems in central, western, and northern New York, which currently serve largely recreational purposes (Erie-Mohawk and St. Lawrence-Lake Champlain-Hudson systems), may also not be able to accommodate as much traffic in the future as a result of periodic water scarcity needed to operate the locks. On the benefit side, the expected climate warming is likely to prolong the ice-free shipping season on the Great Lakes and St. Lawrence Seaway and make the navigable portions of the Hudson River less prone to the ice floes or shore-to-shore freezes that occurred more commonly in past centuries and on occasion interrupted the transport of fuel and other supplies to Albany and mid-Hudson terminals.

9.4 Adaptation Strategies

Adaptation to climate change involves a complex multi-dimensional array of options (See Chapter 2, "Vulnerability and Adaptation"). Typically adaptation is specific to a particular mode of transportation and to the specific climate hazards that pose the threats. Options may differ across the geographical, land use, and climatic zones within the state. They can differ in scale and granularity, from statewide to regional to local and site-specific solutions. Short-, medium-, and long-term solutions must be balanced against each other. Adaptation should be risk-based and consider benefits versus costs. In this context, the questions of who pays the costs and who gets the benefits raises social and environmental (and intergenerational) justice issues with fiscal, economic, and ecological consequences (see Chapter 3, "Equity and Economics"). How and where current investments in infrastructure are planned, engineered, and constructed affects their future vulnerabilities. If existing infrastructure is not upgraded and adapted to the new demands posed by climate change (just as infrastructure needs periodic upgrades to demographic and economic demands) it will put the neglected regions, their economies, and, in the worst cases, lives in jeopardy.

Transportation adaptation strategies are intertwined with land-use issues. The question of whether land use leads to transportation demands or transportation capacities lead to land use must be approached holistically (TRB, 2008a). Land use has implications for both climate change mitigation (i.e., limiting greenhouse gas emissions) and for climate change adaptation (e.g., of transportation corridors along flood-prone coasts and inland rivers). There exists a vast literature that has detailed the relationship between land use and natural disaster risk management (see e.g., Mileti, 1999; Godschalk et al., 1999). Climate change add an additional dimension to managing natural hazard risks in the context of land use over the long term.

The connection of climate change adaptation to land use is clearest in the coastal zones that are at an increasing risk from sea level rise and related coastal storm surge inundations. This connection is discussed in the coastal storm surge case study. The issue of "home rule"[22] is embedded in the culture and legal foundations of the nation, states, counties, cities, and villages and puts local communities in the critical position of primary decision-maker. As a tool to guide states and, in some cases, local communities toward an environmentally sustainable path, the federal government can attach conditions to transportation financing. The actual authority for designs and planning generally lies, however, with the state or local community. Hence, states and local communities are key partners for sustainability. Federal guidance via the financing option is limited, and the project-by-project approval process, including how environmental impact statements are prepared, reviewed, and approved, is not yet well suited to sustainable adaptation to climate change and sea level rise.

In this context, transportation agencies having active roles in the state's coastal zones (including New York State Department of Transportation, MTA, the Port Authority, and many others in the public and private transportation sector) will need to balance their adaptation efforts to cope with sea level rise on a project-by-project basis with a more regional approach. Such balancing will include difficult decisions for communities and, consequently, transportation agencies. Such decisions include determining whether engineered defensive levees, pumping stations, and estuary-wide protective storm surge barriers are sustainable adaptation solutions, or if such defensive structures are only temporary solutions. Such structures

could be combined with long-term exit strategies involving carefully staged and equitable retreats from, and relocation of assets in, communities that are at risk. FEMA's National Flood Insurance Program includes an option to buy out properties; a potential strategy would be to extend such buyout programs beyond the National Flood Insurance Program to include critical infrastructure systems exposed to repetitive risks. This may require new federal initiatives, but states could help to bring about such changes.

Transportation agencies will be at the center of a systematic river and coastal flood-risk assessment, land-use planning, and ultimately a consensus-forming decision process. Without such an overarching process—and with challenges to the *status quo* on home rule and other land-use practices—it will be difficult to shape a sustainable future for communities and for the transportation systems that serve them, and to build resilience to river flooding and sea level rise. At-risk communities may be given some assurance that government will assist in creating a safer future, if the communities recognize and act upon managing responsibly their exposure to the risks from sea level rise and increased coastal, estuary, and river flooding.

A likely outcome will be that well-organized, large transportation organizations (such as the New York State Department of Transportation, MTA, the Port Authority, several New York City agencies, and others, including some county and community governments) will initially plan for, seek financing, and implement interim adaptation measures at their existing facilities, often as part of their regular maintenance plans, capital budgets, and operations. Private operators and owners of properties will do the same, sometimes motivated by the availability (or lack) and pricing of insurance in high-risk coastal zones. This insurance effect is already starting to become operative in local development projects by the private sector. Over time, it will gradually affect future demographic and transportation patterns and related demands for infrastructure. The public sector may be supportive of these self-regulating market forces. Transportation planning agencies should collaborate with these positive developments, even if they occur only on a project-by-project basis.

With time, as climate stresses increase, more central, coordinated, regionally planned yet grassroots-supported, integrated planning will be needed to more cost-effectively and safely address coastal adaptation measures. Local decisions may eventually be replaced by a comprehensive approach that aims at flexible, adaptive solutions with sustainable outcomes.

There are precedents for such overarching efforts, some successful. The Netherlands' Delta Waterworks and the London/Thames Estuary Project (TE2100) are well-planned, flexible, and foresighted projects. Both protect land already at or below sea level.

Currently, New York State has virtually no land with built-at-grade structures at elevations below sea level. However, a large and often critical portion of its transportation (and some other) infrastructure—largely in the New York City metropolitan area—is already well below sea level and, therefore, increasingly at risk. Agencies such as MTA and others are in the initial stages of an evolving process to include climate adaptation principles in their planning, design, capital construction, and financing procedures. A similar planning process needs to include the transport infrastructure along the Hudson River below the Federal Dam in Troy and the Great Lakes and St. Lawrence River shipping routes. Any initial administrative and exploratory steps that have been undertaken (e.g., MTA, 2009a) require additional attention in the pertinent institutions. They also require endorsements from their governing boards and by society at large. This will require corporate leadership. Even then, however it may take time before climate change adaptation is firmly embedded into the normal functioning and decision making of the transportation institutions. The seeds are sown,[23] but in order to take root, sustained leadership, financing, political and public support, and implementation is required.

The rising technical awareness of changing climate conditions in the transportation community will need to be echoed by public and its representative political institutions. Their strong support for a broadly based sharing, for the common good, of the costs for safeguarding the public transportation infrastructure—especially in the coastal and estuarine risk zones—will be important to ensure effectiveness of agencies' adaptation efforts. The State of New York is in a position to provide leadership. The formation of the State's Sea Level Rise Task Force (SLRTF)[24] and the Climate Action Plan are good first steps. Near-term implementation of adaptation measures is the next step.

9.4.1 Key Adaptation Strategies

The technical and procedural tasks for climate change adaptation at hand will include the following steps:

- A full inventory of the hazards as a function of time related to climate change (e.g., NPCC, 2010; and Horton and Rosenzweig, 2010; also see Chapter 1 of this report, "Climate Risks").

- A full inventory of the transportation infrastructure at risk to these climate change hazards (and benefits where applicable) and a systematic assessment of transportation system vulnerabilities to these hazards.

- A well-planned effort of technical and fiscal evaluation of adaptation options and their local, regional, social, and environmental implications. An important part of developing these multiple options is to allow flexible implementation along multiple, time-staggered decision paths (e.g., see NPCC, 2010).

- This approach requires, in turn, institutionalization of a scientifically based monitoring and decision-support system and process that can inform decision-makers of when the climate risks reach trigger (or tipping) points where decisions cannot be any longer delayed without potentially dire consequences (NPCC, 2010).

- The above steps need to be reassessed regularly until it is clear that full consideration of short- and long-term effects of climate change are effectively embedded in infrastructure planning and decision making at all levels of government and by the operating transportation agencies.

9.4.2 Large-Scale Adaptations

The following sections provide medium- to long-term technical options for adaptation to various types of climate change, i.e., those that go beyond temporary emergency measures (such as sandbagging or pumping by mobile units). They are organized by type of climate hazard.

Adaptation for Coastal Hazards

- Constructing local flood proofing by building local levees, sea walls, floodgates, and pumping facilities. For truly low-lying areas such measures may be only temporarily effective (in some instances only for several decades). Site-specific studies for different time horizons will be needed.

- Raising structures or rights of way. For instance, commuter rail tracks could be put on elevated structures as part of a regional rejuvenation to a new generation of commuter and intercity rail systems, like those already implemented in Japan, Taiwan, and parts of Europe or as currently under widespread construction in China. Privately owned freight rail systems (e.g., along the west shore of the Hudson River) may need to consider equivalent options.

- Sealing of ventilation grates of belowground facilities (e.g., NYCT subway system) only in those locations that are in potential and future storm surge inundation zones. These sealed tunnel sections will need a newly engineered, forced ventilation system not open to the normal street grade, with consideration of fire safety.

- Designing innovative gates at subway and road/rail tunnel entrances, unless other options to extend the entrances to higher elevations exist, are practical, and can be implemented.

- Designing road and rail embankments as super-levees that could provide a double function: flood protection and transportation corridors.

- Conducting a feasibility study for a system of storm-surge barriers to assess their potential position and ability to provide protection for New York State's waterfront and transportation systems.

- Retreating and relocating critical systems out of and/or above flood zones.

- Raising bridge landings along shorelines to ensure there is sufficient clearance for the transportation systems (highways, roads, rail systems) they cross over, given the need to potentially raise these systems as a result of sea level rise and related storm surge inundation hazards. Site-specific studies are needed to develop solutions for this seemingly intractable problem. Preventive solutions (sufficient clearances) need to be planned for any new bridge structures that cross bodies of water controlled by tides and rising sea levels (e.g., the currently planned new Tappan Zee Crossing).

- Vertically extending collision fenders to higher elevations on bridge foundations in tidal waters.

Adaptation for Heat Hazards

- Confirming that currently used heat-resistant road surfacing and rail track materials are capable of

withstanding additional, more extreme heat conditions.

- Upgrading air conditioning of rolling stock (trains, subways, buses) to meet the demand on extreme hot days.
- Inspecting bridge expansion joints, since they tend to lock with age, imposing extra stresses under extreme heat. This condition needs attention during bridge inspections. Ensuring adequate bridge clearances, as very large bridges tend to sag during extreme heat. Sea levels will rise, and modern ships often stack containers to heights that use as much of the clearance available, so it must be ensured that the available clearances continue to conform to U.S. Coast Guard limits for bridges across tide-controlled waterways. New height limitations may have to be imposed.
- Modifying airport and airplane functions. The aviation industry may encounter more frequent extreme weather events, with respective travel delays for airlines and their customers, and related economic impact. Airport runway lengths, extreme high air temperatures (hot air provides less lift), and required takeoff speeds of airplanes must be in balance to provide sufficient safety margins for takeoff. New generations of planes with more powerful engines are able to overcome this issue, but older planes may have to face load limitations or be phased out.
- Preparing for power and communication failures. Transportation agencies may need to be prepared for more frequent power failures (and related potential communication failures (see Chapter 10, "Telecommunications"). This applies especially during extended summer heat waves, when peak power demands exceed what electric utilities can supply due to increased need for air conditioning, unless the utilities' adaptation plans cover these needs or plans are in place to reduce public demand during such times (see Chapter 8, "Energy").

Adaptation for Precipitation Hazards

- Increasing the carrying capacities of culverts, retention basins, and other drainage systems in accordance with future precipitation normals (i.e., new averages and extremes, to be issued on a regional basis by NOAA's National Climatic Data Center). It may also require changes in American Association of State Highway and Transportation Officials (AASHTO) drainage guidelines and other applicable engineering standards.
- Raising road and rail embankments and/or strengthening their slopes to be resilient to flow dynamics and bank erosion in river flood zones prone to high flow velocities.
- Relocating rights of way out of new and future flood zones.
- Monitoring and remediating scour action at bridge foundations in rivers as flood and related flow conditions become more severe and frequent as a consequence of more extreme precipitation events (often further amplified by inappropriate upstream land use and development).
- Working with local agencies to reduce runoff from nearby properties and other rights of way onto transportation systems. This may involve creation of permeable surfaces and retention basins, restoring marshlands, increasing sewer or pumping capacities, and regrading slopes to direct runoff away from critical transportation infrastructure.

Adaptation for Winter Storms (Snow and Ice)

Overall snowfall and days per year with snow cover, especially in the more southern portions of New York, are expected to decrease gradually as snow will be more frequently replaced by rain. On the other hand, individual snowstorms and ice storms (with freezing rain) may become more intense, especially in higher elevations, in more northern regions, and those in areas prone to the lake effect, which may be amplified by a shorter duration of ice cover on the Great Lakes. These geographically diverse trends across the state may require potential reallocation of operational resources for snow clearing and sanding/salting. One alternative includes increasing the amount of intelligent signage that warns drivers about high-hazard road conditions. On average, across the state, a net reduction in snow hazard is more likely than not, but no clear trend is yet forecast for future freezing rain and icing conditions (see Chapter 1, "Climate Risks").

Other Adaptation Options

Other climate-related risks that require adaptation measures may originate from more frequent extreme winds (characterized as hard to quantify, see Chapter 1, "Climate Risks"). Transportation agencies may want to

keep track of whether the design wind speeds need to be adjusted with time on a regional basis. A practical adaptation measure to cope with higher wind speeds is operational. Anemometers measuring wind conditions may be installed on bridges of a certain length and height above ground or water, and wind velocity limits may need to be set, above which bridge traffic will be allowed only at reduced speeds or, for higher wind speeds, will need to be suspended entirely to avoid excessive accident rates. Such limitations are already in place on some bridges in New York State and are, for instance, included as constraints in the New York City Office of Emergency Management hurricane evacuation plan.[25] MTA Bridges and Tunnels, and operators of other large bridges in the region, also have protocols in place for traffic restrictions during high winds.

Adaptation Options Related to Federal/State/Agency Policies and Cooperation

Intrastate Cooperation
At this time the major transportation agencies, authorities, owners, or operators in New York State do not yet have publicly accessible, internally approved master plans for how to adapt to those aspects of climate change that are currently known. The New York City Climate Change Adaptation Task Force (City of New York, 2011) in conjunction with the NPCC (2010) assessments come close to producing a roadmap and a technical/scientific foundation on which such a master plan can be based. This ClimAID project contributes to fulfilling a similar goal statewide. The MTA's *Greening Mass Transit & Metro Regions* report (MTA, 2009) provides the recommendations for such a plan. Actionable and internally approved plans can become an integral part of a long-term capital-spending budget to which the respective entity is committed.

For the private sector, and for the first time, the Securities and Exchange Commission (SEC) issued in January 2010 a statement[26] that "public companies should warn investors of any serious risks that global warming might pose to their businesses." An equivalent rule (or even law) may be developed by the State to go one step further and request that each transportation operator doing business in New York State produce every few years an updated actionable plan on how it intends to manage the emerging risks from climate change over short to medium time horizons. A less detailed but mandatory long-term outlook for up to a century should also be included.

The federal and state governments could use such agency plans as a precondition for financing climate change adaptation assistance. There are many precedents for such conditional financial assistance, ranging from the multi billion dollar federal sponsorship to reform state and local education systems, to DHS/FEMA's disaster mitigation assistance grants given to states (and in earlier times, directly to communities), conditional on their having developed a FEMA-approved disaster mitigation plan.

Given this situation, the State could consider establishing a ruling that each Transportation Agency operating in the State of New York should develop by a certain deadline (say, 2015) a climate change adaptation master plan with an institutional management, operational, engineering, and capital spending project component, for short (years), medium (a few decades), and long-term (50–100 years) time horizons laid out in various degrees of detail, respectively. The basis of the report should be a science-based hazard assessment pertinent to the transport agency's assets and operations, an engineering-based vulnerability (fragility) and risk assessment, and a ranking of options to manage these risks, with estimates of costs for adaptation measures and of potential costs (risks) for incurring gradual and/or potential catastrophic losses if no action is taken. Such plans should be updated on a regular basis, perhaps on the order of, say, 5 years, or commensurate with agency-specific planning cycles.

In many of the major urban or metropolitan centers across New York State, multiple agencies are responsible for operating various modes of transport systems, whether they are public or private entities. Since transportation is a networked system, delays, failures, or (at worst) catastrophic failures in one system can affect the other systems, and in such cases the customer may not be able to get from point A to point B within a reasonable time at reasonable cost.

Especially in the case of floods in connected underground structures, system vulnerability is often determined by hydraulic connectivity between tunnels, stations, and other structures. Any effort by one agency to adapt to a certain climate change performance standard can be made ineffective by others adhering to a lower standard. The weakest link in the system may critically control the system's overall performance, even if it is a very diverse and redundant system.

There are examples of how transportation agencies have worked together to coordinate joint planning, set performance standards, or solve other coordination issues for the benefit of the public at large. The EZ-Pass is one such example of an interagency practical, successful solution.

Another example of interagency coordination occurred in the post-9/11 cleanup and recovery phase. Due to the urgency of rebuilding several high-priority projects in Lower Manhattan, the Federal Transit Administration (FTA) set up an FTA Lower Manhattan Recovery Office[27] that worked with project sponsors on innovative, streamlined project delivery processes in the areas of development, oversight, and environmental management. This approach was developed early, with a consensus among federal and local partners. In the arena of environmental oversight it led to a memorandum of understanding between EPA and other federal agencies defining roles and response times. It also developed agreement among project sponsors to a common Environmental Analysis Framework and Environmental Performance Commitments as well as to coordinated cumulative effects analysis.

An organization potentially suited to take on this regional coordination for climate change adaptation standard and performance goals in the state's coastal region could be the New York Metropolitan Transportation Council, an association of governments, transportation providers, and environmental agencies that is the Metropolitan Planning Organization for New York City, Long Island, and the lower Hudson Valley.

In regions of the state with dense and diverse transport systems operated by multiple agencies and owners, an alliance of operators should be formed to coordinate climate change adaptation measures to ensure a coherent systematic approach with mutually agreed-upon performance goals and standards. In addition, the alliance may coordinate policy, oversight, and other issues with federal and state agencies to streamline a regional approach and to put the region in a better competitive position when applying for federal technical and financial support for climate change adaptation.

A particular task for coordination could be delegated to an "adaptation moles" technical working group. This group should be charged to ensure that the underground connectivity between multi-agency below-ground rail-based transportation systems in the NY/NJ metro region (including NYCT subway, LIRR, MNR, the Port Authority, New Jersey Transit, Amtrak, and others) will become flood-resilient as a whole. The working group would also engage with experts from vehicular tunnel operators (Port Authority and MTA Bridges and Tunnels), and state, county, and city agencies including DOTs, and power and communications utilities to ensure that a flood protection and general adaptation plan, with special emphasis on sea level rise, is comprehensive, system-wide, and performs in accordance with an agreed-upon performance standard for the benefit of all agencies and the public at large.

National Cooperation

Of course, New York State is not isolated, which is particularly relevant in the transportation sector. Not all regions of the nation will be affected equally by climate change. Those regions that are population centers and vital drivers of the national and global economy have generally the highest concentration of transportation infrastructure. If these major nodes of the transport systems fail and become unreliable, redundancy and diversity of the transport links between such centers cannot maintain the system capacity. These centers also serve to maintain a large state and federal tax base that needs to be stable. Their gradual or catastrophic failure could bring disproportionately large losses to state and national economies. Therefore these centers deserve special scrutiny and attention to sustain the economic viability of the state and nation at large, especially in the context of global economic competition. Without a climate-change-resilient transportation infrastructure, these economic centers cannot fulfill their role as reliable engines for the state and national economies, and hence warrant state and national support. Assessment of priorities is most effective when ranking is risk-based. Consequently, New York State may want to work closely with the federal government to pursue the following adaptation options:

• Set priorities for policies for providing sound knowledge and data, and direct financial support, to strengthen the nodes of transport infrastructures to make them climate-change-resilient.
• Consider a comprehensive program of research and technological development for advancing innovative and cost-effective climate-resilient urban and inter-urban transportation infrastructure.
• Devise incentives for states, regions, and cities with vital nodes and concentrations of transport

infrastructure to partner and exchange best practices in climate change adaptation, and to help set the national agenda for sustainable, energy-efficient transport systems.

Ground transport systems (roads and rails) of coastal population centers and estuaries (controlled by tides and brackish waters), are often placed underground in tunnels very close to or below sea level. Such systems, especially when built many decades ago without anticipating rising seas, are vulnerable to the combination of accelerating sea level rise and coastal storm surges. It is vital to make these low-lying transportation systems flood proof and to avoid systemic damage from saltwater intrusion before it is too late. To relocate such systems would require exorbitant resources. This poses new technological challenges and requires adequate resources to find innovative engineering solutions to protect these underground systems from the rising and encroaching seas. Consequently, it would be helpful for the federal government, in cooperation with states, to sponsor a technology assistance program to develop and install engineered protective measures targeting underground and near-shore transport systems that are under threat from sea level rise and saltwater damage.

Other transport facilities near New York State's coastline, and along the nation's coasts, including harbor facilities and their interfacing ground transportation links such as road, rail, storage, and freight transfer facilities, and many industries such as refineries and chemical plants that rely on marine shipping access, are also at risk from coastal storm-surge flooding amplified by accelerated rising seas. Inundation would not only damage these ports, ground transport, and industrial facilities, but also pose potentially severe environmental risks from spreading debris and toxic substances to nearby coastal population centers. Consequently, it would be helpful for the federal government to provide assistance to regions like New York State, with major port facilities and related industries that serve the nation's import/export demands. Such assistance should be aimed to develop and implement cooperative solutions among port operators, connecting transport systems, proximal industries, and nearby population centers and communities, with a goal of safeguarding them from coastal storm-surge flood hazards that will increase with rising sea levels. Federal assistance would greatly foster the development and installation of technical solutions

that can reduce related environmental and health risks from potentially toxic materials and debris being carried by flood waters into communities, natural and developed land, ground-water, beaches, and/or fisheries.

FEMA flood insurance rate maps (FIRM), whether near rivers or coasts, have become an important guiding tool for local zoning, planning, land-use, construction permits, environmental impact statements, etc. These now-widespread uses are far beyond the original intent of FIRM maps for guiding the National Flood Insurance Program (NFIP) aimed mostly at residential housing in flood-prone areas. FIRM maps are based on *past* data and information, in terms of land use and climate. Therefore they are not suited for planning *future* sustainable development of communities and the transport systems that need to serve these communities under new and *changing* climate conditions.

Consequently, the federal government could establish a technical assistance program to help states and communities and their transportation agencies develop sound science-based flood zoning tools that allow forward-looking adaptation to climate change, including the associated engineering guidelines. Such guidance tools would be more appropriate than the FIRM maps for coastal zones and other flood-prone areas to cost-effectively plan and design new, or to modify existing, transportation and other critical infrastructure, and to support future community development that is sustainable for periods of time not shorter than the expected lifetime of the respective infrastructure.

Other needs exist, as well, that could best be met with coordination between New York and federal organizations. For example, accurate, high-resolution LIDAR (light detection and ranging) surveys need to be flown to facilitate the development of digital elevation models (DEM) of sufficiently high vertical and horizontal resolution to perform forward-looking flood risk assessments and regional planning of sustainable developments.

A similar need exists for forward-looking climate normals (in contrast to traditional climate normals, which are produced by NOAA based on past climate data). Future temperature normals are needed to guide the design of transportation cooling and ventilation systems that can meet increased demand, for heat

resistant pavements on roads and airport runways, and for designing airport runways with sufficient length to ensure safe takeoff during extremely hot days. Future precipitation normals are needed to design drainage systems that can handle future extreme rainfalls. New York State should undertake formal steps to work with the respective federal agencies to produce these products in a timely fashion, with clear presentation of uncertainties and regular updates as new climate projections are produced.

Regional Cooperation

Regional transportation agencies own and operate assets that are often fully or partly self-insured. Insurance against climate-related disaster losses works best when the risk is spread geographically, by diversity in asset ownership, and by exposure to diverse, independent, and uncorrelated hazards and risks. The risks to regional transportation agencies from climate change are instead highly concentrated geographically and exposed to process-related climate hazards. Therefore, the principles for effective self-insurance are violated since all assets can be hit by the same event. Furthermore, one event may entail a number of correlated perils (e.g., wind, lightning, flood, debris impact, power outages, and saltwater damage), which may strike at the same time caused by the same event (e.g., the same hurricane).

Consequently, regional transportation authorities may want to spread their risks from climate-related weather events by entering insurance pools of transportation owners spread over diverse geographical regions across the nation. This may be achieved by a blend of mutual and self-insurance (with or without participation of federal or state governments and/or the private insurance and reinsurance sectors), or by floating catastrophe bonds on capital/equity markets. The federal and/or state governments may provide the regulatory framework for such sharing of the risks to public transportation lifelines across the entire nation, and set standards by which the insured and insurers shall abide. Another option is for federal and/or state governments (i.e., the taxpayers) to become the ultimate bearers of climate-change-induced risks for regional public transportation systems. In either case, a federal or joint federal/state program for assessing the climate change risk exposure of regional transportation agencies and of insurance options vis-à-vis climate change risks appears to be a desirable and much needed risk management measure.

9.5 Equity and Environmental Justice Considerations

Transportation planning is a longstanding priority of environmental justice advocates. In transportation analyses, core equity concerns often include unequal access to different types of transportation, the spatial mismatch of jobs and residences, the disproportionate health burden of automobile pollution, and a commitment to affordable public transportation (Bullard, 2007; Sze and London, 2008; Chen, 2007). Constructing adaptive, climate-secure transportation provides opportunities to build social equity into the infrastructure, but with less care it may exacerbate some of these existing inequities as well as create emergent burdens.

9.5.1 Social Vulnerability and Equity

Social, economic, and geographic marginality add to the challenges of transportation planning. For the United States as a whole, the poorest 20% of households spend more than 13 percent of their income on transport (U.S. Bureau of Labor Statistics, 2010). In urban centers, and increasingly the inner suburbs, lower-income people of color are disproportionately dependent on public transportation to get to their jobs (Pucher et al., 2003). African Americans and Latinos, in particular, are less likely than whites to own a car (Sanchez et al., 2004). Across most cities in the country, including New York City, there is a correlation between carless populations and poverty and minority status (Milligan, 2007). While reliance on public transport has positive implications for environmental quality and mitigation of climate change, reliance on public transport also creates vulnerabilities in times of natural disasters and climate-stress events. In one extreme example, Hurricane Katrina exposed the severity of this transport disadvantage: Upper-income populations left New Orleans by car, while disabled, low-income, and African American populations were stranded (Litman, 2005).

Some of the largest urban centers in the United States, including New York City, have detailed evacuation plans incorporating varied levels of social disadvantage. The strengths and limitations of New York City's plans are discussed in the case study later in the chapter. In contrast, one analysis discovered that central cities elsewhere in New York State were even less prepared to deal with transport disadvantage (Hess and Gotham,

2007). In general, they found that most evacuation plans did not seriously consider multimodal transport strategies or incorporate carless populations. At the same time, the rates of households without cars in Albany (28 percent), Buffalo (31 percent), Rochester (25 percent), and Syracuse (27 percent) are similar to rates in New Orleans at the time of Katrina (27 percent). Two of the case studies in this ClimAID report involve climate-related disasters in central and northern New York (i.e., ice storm in Chapter 10, "Telecommunications," and a Susquehanna river flood in Chapter 4, "Water Resources"). As cities in these areas contemplate emergency measures and adaptation strategies in the context of climate-related disasters, one possible way to improve equitable opportunity is to place additional emphasis on the needs of carless populations.

Even less catastrophic failures, such as localized power disruptions or small-scale flooding, can have uneven effects if they cause cutbacks or interruptions in transportation service or limit affordable options. Low-income people are likely to be more dependent on limited service options and less able to take advantage of a range of transport systems. At the same time, they tend to live farther from their places of work, so they are the most likely to be affected by lost wages (Chen, 2007). Of the three-quarters of a million New York City workers who commute more than an hour, two-thirds of them earn less than $35,000 per year (Byron, 2008).[28] Many low-income individuals living at the periphery of the outer boroughs, especially parts of Queens and Staten Island, have access only to unreliable, inefficient, or inconvenient public transit (NYMTC, 2009). Even minor service disruptions create hardship for them relative to individuals in areas with transit redundancies. Transport interruptions take a particular toll on working women, who tend to have less spare time because of child and family care and on average earn less than men (Root et al., 2000; Morrow, 1999).

9.5.2 Adaptation and Equity

A particular challenge for developing an environmental justice component to transportation adaptation is the need to project into the future for many decades. Because transportation design is generally locked into the landscape, an array of equity dilemmas extends throughout the lifecycle of the infrastructure. Most immediate questions include, where is a new or upgraded route going to be sited? Who will be displaced by the construction? In the medium term, what demographic groups or regions will benefit from the adaptation? Decommissioning highways, roads, and other infrastructure for climate protection could involuntarily leave communities isolated from job centers or otherwise stranded. Some communities may have increased traffic and demand for services, while others experience shrinkage. And in the long term, how will new transportation flows induce new patterns of mobility and new patterns of migration into and out of an area? Who are the winners and losers in this process? Land-use changes are likely to follow, and how will these changes benefit some and not others?

These questions raise the fundamental challenge of balancing the need to prioritize climate-proofing system-wide transportation flows against particular transportation imbalances that may decrease access to opportunities for various groups. Questions of whether to retrofit and renovate old infrastructure versus building new climate-adaptive infrastructure may also raise equity issues. For example, an adaptation policy concentrating on designing new road construction outside of floodplains could be biased toward exurban, high-income fringe suburbs of the various cities at the expense of inner-ring suburbs and central city areas that are more set in place and would most benefit from other types of measures such as increasing bus capacity.

9.6 Conclusions

Transportation in New York State is vulnerable to and consequently at risk from climate change as shown by the statewide survey in this ClimAID chapter and, in particular, by the case study analysis (following Section 9.6) of storm surge risks of the metropolitan and coastal regions. The degree of vulnerability statewide is, at present, still largely indeterminate since it requires extensive engineering analyses. Therefore, the most effective adaptation solutions cannot be selected with confidence until the vulnerabilities are fully explored. Nevertheless, certain general patterns of vulnerabilities and opportunities (for details see Section 9.3), of adaptation options (Section 9.4), and of knowledge gaps can be discerned, given the current state of knowledge. These findings and recommendations are summarized below.

9.6.1 Main Findings on Vulnerabilities and Opportunities

- Ground transportation is vulnerable to increased flooding during extreme precipitation events inland, and to coastal storm surges combined with sea level rise in coastal regions (and along the tide-controlled sections of the Hudson River below the Troy Dam).
- Port facilities, including piers, warehouses, and transshipment facilities to rail and road, may be exposed to sea level rise and coastal storm surges.
- More frequent and more severe extreme high temperatures may require more heat-resistant materials and design criteria for highways, bridges, rails, and catenaries; high temperatures can cause heat exposure to maintenance and construction crews and to commuters in subways. High temperatures also can impede airplane lift during takeoff and landing.
- In coastal regions, less salting and snow removal may create benefits.
- The Great Lakes shipping season may be lengthened and may eventually be year-round, but it may become vulnerable to lower lake levels necessitating shallower vessel drafts.
- More extreme weather conditions may require traffic restrictions (e.g., on bridges exposed to high winds), and may cause delays and cancellations in air traffic.

9.6.2 Adaptation Options

- Perform engineering-based climate change risk assessments of assets and operations and develop adaptation master plans based on these assessments.
- Form alliances between agencies to set region-wide performance standards and work together to reduce physical risks and intermodal weather-related traffic problems propagating through the interconnected systems. Also, form mutual insurance pools that spread risks across time, space, and type of peril.
- Implement operational measures based on incorporating weather forecasts and climate projections into operations and construction planning, on posting warnings, and on intelligent signs, which in some cases may be linked to monitoring devices (e.g., measuring wind speed on bridges).

- Raise or relocate to higher ground, where necessary and feasible, critical infrastructure to avoid current and future flood zones. Elevating infrastructure may apply to bridge landings, roads and railroads, and collision fenders on bridge foundations.
- Evaluate, and where found feasible and sustainable, create engineering-based solutions to protect against coastal hazards by constructing levees, sea walls, barriers, and pumping facilities, and by designing innovative gates at subway-, rail-, and road-tunnel entrances.
- Develop engineering-based solutions to protect against heavy precipitation hazards, including increasing the capacity of culverts and other drainage systems, raising and/or strengthening road and rail embankments to make them more resistant to flood-related erosion and river scour, and creating more permeable surfaces or regrading slopes to direct runoff away from critical transportation infrastructure.
- Create strategies to protect against heat hazards, e.g., by increasing the seat length of expansion joints on bridges, lengthening airport runways, and increasing and upgrading air conditioning on trains, subways, and buses.

9.6.3 Knowledge Gaps

Measures needing to be undertaken to fill existing knowledge gaps include the following:

- Accurate, high-resolution LIDAR surveys of current and expected future coastal and inland flood zones to facilitate the development of digital elevation models of sufficiently high vertical and horizontal resolution to perform forward-looking flood risk assessments and regional planning of sustainable developments.
- Development of updated region-specific climate information that includes climate change scenarios (and forward-looking climate normals) for design standards, regulations, and technical design guidelines (e.g., for proper design of culverts and drainage systems).
- A comprehensive federal/state/private-sector program of research and technological development for advancing innovative, cost-effective, and climate-resilient urban and inter-urban transportation infrastructure.

Case Study A. Future Coastal Storm Impacts on Transportation in the New York Metropolitan Region

The purpose of this ClimAID case study is to provide a largely qualitative assessment of the geographic reach and of the impacts of a 100-year Base Flood, and how the flooding conditions and impacts change as a function of sea level rise. The quantification of risks and losses are attempted where possible within the scope of the study. We use three scenarios, which are consistent with the ClimAID projections:

*   Scenario S1—current sea level with a 100-year coastal flood along the coast and tide-controlled estuary
*   Scenario S2—2-foot rise in sea level, combined with a 100-year coastal flood along the coast and tide-controlled estuary
*   Scenario S3—4-foot rise in sea level, combined with a 100-year coastal flood along the coast and tide-controlled estuary

While the 2-foot and 4-foot sea level rise increments are not tied to any particular time horizon via a specific sea level rise forecast, these two sea level rise increments would be attained in the 2050s (2 feet) and 2080s (4 feet) under the rapid ice-melt (RIM) sea level rise scenario put forward by the New York City Panel on Climate Change (NPCC, 2010; see also Chapter 1, "Climate Risks"). Slower sea level rise, which is more likely than not, would delay the arrival of these sea level increments. A faster sea level rise than RIM, which is less likely, would advance the arrival of these increments to earlier times during this century.

The coastal flood scenario used in this case study for baseline purposes is that which occurs, on average, once every 100 years (i.e., a chance of 1 in 100 in any given year) at any given location along the coastal or estuarine waterfront of New York State. It is conceivable, but not likely, that two or three such 100-year storm surge heights are reached or exceeded only a few years apart. It is also possible that such coastal storm surges and related flooding do not occur for a period of more than 100 years.[29]

The 100-year storm, as assumed in this case study, is similar to a non-direct but nearby hit of a category 1 to 2 hurricane, or to the conditions at the marginal periphery of a category 3 hurricane (e.g., one that makes landfall in southern New Jersey or in Rhode Island). This case study storm could also be a severe winter nor'easter storm that stalls for a few days off the mid-Atlantic coast, especially if it coincides with a period of high tides (i.e., during a new or full moon). The Dec. 11–12, 1992, nor'easter was just below, but close to, this strength.

This case study only addresses flooding due to coastal storm surges along the coast and estuarine (i.e., tide-controlled) shorelines. It does not address any inland urban, street, or non-estuary river flooding that often occurs simultaneously during nor'easters or hurricanes because of heavy rainfall and runoff that may exceed the carrying capacity of drainage areas and stream-beds. The impacts of these types of inland floods are not amplified by sea level rise. But the impacts and losses from this urban street and river flooding must be added to the impacts and losses assessed in this case study if a full assessment of climate-related risks is undertaken.

Study Parameters and Focus

The parameters for this case study were developed by the ClimAID Transportation, Climate, and Coastal Teams, with inputs from the Energy and Telecommunications teams.

The climate hazards considered are sea level rise in combination with coastal storm surges. The scenario storm is assumed to be one that produces a coastal storm surge consistent with the 100-year flood along New York State's Atlantic shorelines and estuaries, as defined in FEMA Flood Insurance Rate Maps.

Affected Area (see **Figure 9.6***):*

*   *Primary focus:* New York City
*   *Secondary focus:* The New York City metropolitan area, including Long Island (ClimAID region 4), Westchester (part of ClimAID region 2) and the lower and mid-Hudson Valley tide-controlled shorelines (part of ClimAID region 5). Note: for ClimAID climate regions see Chapter 1, "Climate Risks."

Impacts:

*   *Primary focus:* Transportation infrastructure

- *Secondary focus:* Communication infrastructure, electric power grid

The ClimAID team did *not* select a hurricane of category 3 for this case study for a number of reasons. Such a hurricane struck Long Island and New England in 1938. If such a hurricane were to directly strike New York City today or in the coming decades, it would cause losses of several hundred billions of dollars and, less certainly, several hundred lives (Jacob et al., 2000, 2001). The probability for such a hurricane-3 direct-hit disaster to occur is less than 1 in 1,000 in any given year. Instead, the ClimAID team chose a more moderate storm about 10 times more likely than a 1938-type hurricane. The scenario storm is more severe, and 10 times less likely than, for instance, the December 1992 nor'easter storm that flooded many transport systems (including a commuter transit tunnel under the Hudson) and coastal areas. The case study chose a coastal flood scenario commonly used for planning, zoning, and design and code decisions on a daily basis: It is a coastal storm that produces a storm surge consistent with flood heights and inland reach as mapped by FEMA's 1 percent per year flood zone maps, better known as the "100-year" flood.

The case study focuses on the Metropolitan Area of New York City, but extends to Long Island, Westchester County (and adjacent parts of Connecticut), and the entire mid-Hudson Valley to the Federal Dam at Troy, that is, the extent of the tide-controlled Hudson River Estuary. Since the metropolitan area is linked by transport to New Jersey, storm effects there need to be considered too. The area of general interest for this case study is shown in **Figure 9.6**. The primary focus area around NYC is highlighted.

Use of FEMA Flood Insurance Maps

Individual storms are unique. They follow a given path, have an associated wind field, their eyes have a specific forward speed, etc. Storm surge heights depend on exposure to wind, waves, the effects of near-shore water depth in the ocean (i.e., bathymetry), shoreline geometry, and nearby land topography. Because such physical details determine local storm surge heights along the coast, any scenario-specific storm surge heights will differ for an actual storm from the flood elevations mapped by FEMA on its flood insurance rate maps (FIRM). These maps are probabilistically derived and show the outlines
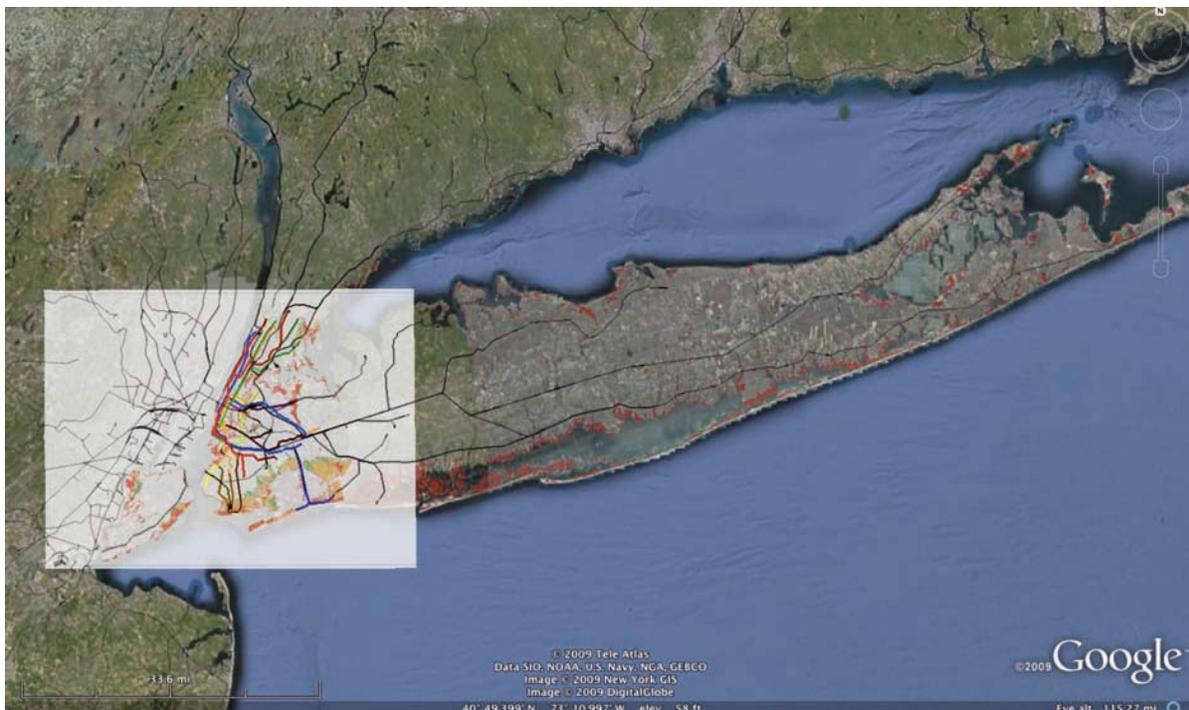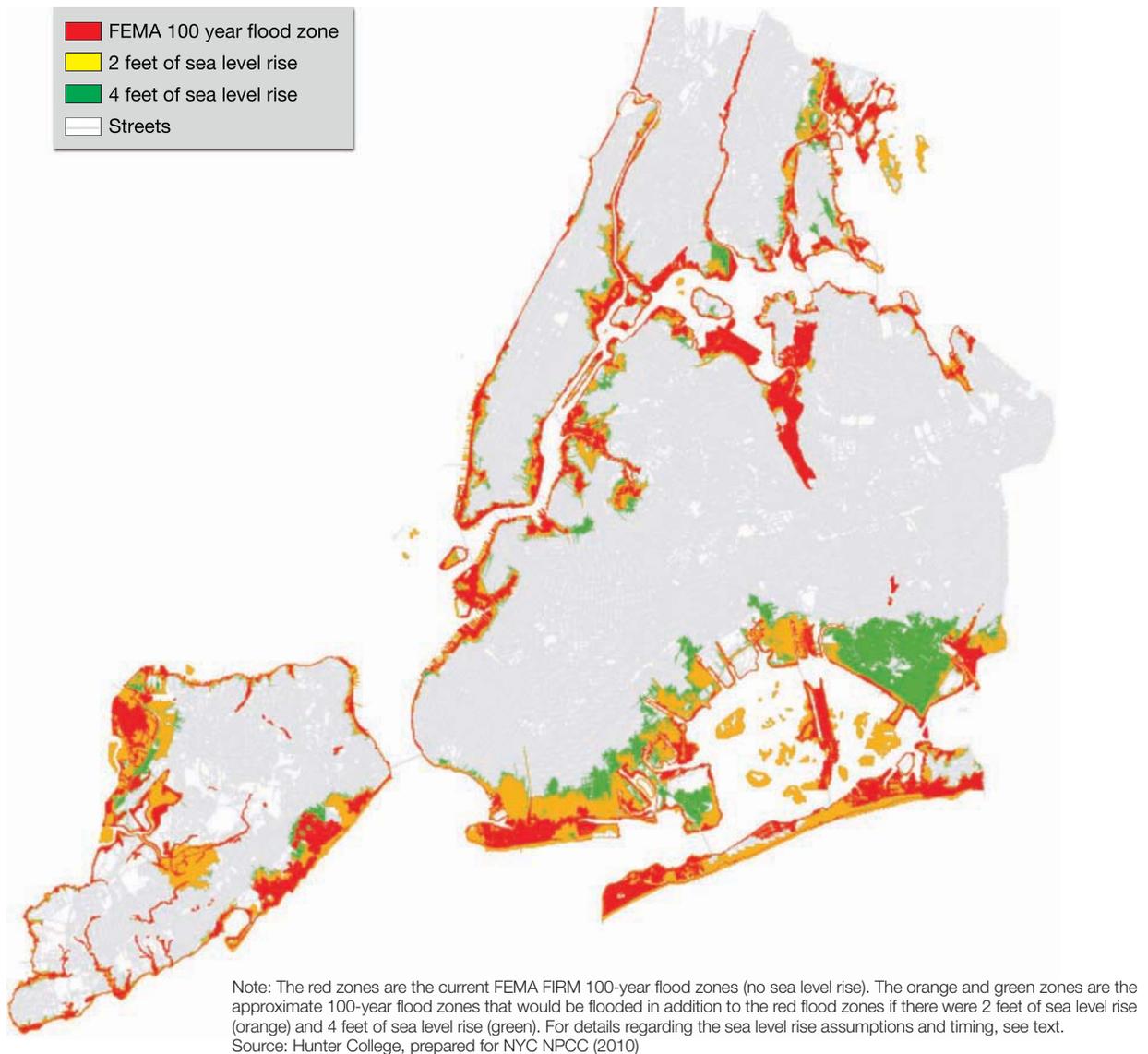

Note: The three scenarios considered comprise a 100-year coastal storm surge: S1 at current sea level, and no sea level rise; S2 with a 2-foot sea level rise; and S3 with a 4-foot sea level rise. The highlighted inset is the primary focus area around New York City. Black lines are railroads; colored lines are subways. For details of the three-colored scenario flood zones in the highlighted area, see Figure 9.7. The red zones outside the highlighted area (in Long Island and Westchester County) depict low-lying coastal areas below about 10 feet in elevation (NAVD 1988 vertical datum). Source for Base Map: Google Earth

Figure 9.6 New York State coastal zone and Lower-Hudson Estuary for which the case study analyzes the impacts on transportation by a 100-year coastal storm surge in combination with sea level rise

of the base flood elevations (BFE) for the 100-year flood probability (**Figure 9.7**, red areas). Importantly, these base flood elevations are not scenario-specific. Thus, variations from the portrayed FEMA flood map estimates can and will occur. The reach of the added flood zones due to sea level rise and the added impact of sea level rise on the transportation infrastructure are also uncertain.

The FEMA maps are used as a starting point for a number of reasons, despite the fact that some locations have been flooded more than once during the last 100 years at flood levels higher than depicted by the maps, and other locations have not been flooded during the last 100 years to the degree that the maps predict. A number of the deviations can be explained by changes that have occurred since the FEMA maps were created. For example, many of the floods that are more severe than expected by FEMA's baseline flood elevation standards have occurred along inland rivers, where upstream development and changes in land use have increased runoff since the FEMA maps were produced. Along some coastal locations, beach erosion and, in a few cases, ill-conceived coastal management practices, have increased coastal flood hazards since FEMA completed its flood mapping. Adding to these hazards, local sea level along New York State shorelines has been rising at a rate of almost 1 foot during the last century. On the other hand, new sea walls and other protective structures may have reduced flood hazards in some locations. Lastly, the 100-year flood is a statistical

Note: The red zones are the current FEMA FIRM 100-year flood zones (no sea level rise). The orange and green zones are the approximate 100-year flood zones that would be flooded in addition to the red flood zones if there were 2 feet of sea level rise (orange) and 4 feet of sea level rise (green). For details regarding the sea level rise assumptions and timing, see text.
Source: Hunter College, prepared for NYC NPCC (2010)

Figure 9.7 100-year flood zones in New York City (i.e., with a probability of being flooded of 1 percent per year) for current and two different ClimAID sea level rise scenarios

estimate that describes the *average* occurrence of a randomly distributed sample of flood occurrences; each location has only a 63-percent chance of experiencing a 100-year flood within the 100-year timeframe.[30]

Methods: Averaged 100-year Flood Elevations and Sea Level Rise Added

This case study uses sea level rise estimates of 2 and 4 feet, which are added to FEMA's 100-year base flood elevations (for details, see Appendix B). For convenience, the base flood elevations were rounded, within the boundaries of New York City only, to the nearest full foot. The method involves averaging the flood heights into an average flood elevation[31] for each of the waterways surrounding New York City, as depicted in **Figure 9.8** and listed in **Table 9.13** in Appendix B.

To determine the risk that flooding poses to transportation infrastructure, the elevation of the structures relative to the elevation of the floodwaters according to FEMA's 100-year flood maps were analyzed. The new flood zones that account for the anticipated 2- and 4-foot sea level rise were then used to assess the vulnerabilities of transport structures and systems.

Note that the original base flood elevations from FEMA's Flood Insurance Rate Maps are generally (at least for New York) referenced to the National Geodetic Vertical Datum of 1929 (NGVD, 1929). The investigators chose, however, for their newly computed, averaged sea level rise-dependent flood-zone elevations to reference to the more recent, and now more commonly used, North American Vertical Datum (NAVD, 1988). Note that in contrast to FEMA maps in New York, FEMA maps for New Jersey use the NAVD 1988 datum. A constant difference of 1.1 feet between the two datums was applied throughout the New York City area such that the numerical elevations above the two vertical datums relate to each other by Equation 1:

Equation 1. Elevation (ft) above NAVD'88 = Elevation (ft) above NGVD'29 - 1.1 ft

The area-weighted average base flood elevations (in the NAVD 1988 reference frame) were, for the New York City waterways, rounded to the nearest integer foot for assessing the flood and sea level rise impact on transport in the region. The averaged flood elevations, Z_i, were

then compared to the lowest critical elevations (LCE) of the transportation systems.

In the regions outside New York City, including Long Island (Nassau and Suffolk Counties), Westchester County and the Lower Hudson Valley, and Connecticut, more generalized approaches were used, for a number of reasons. First, no high-resolution digital elevation model with a 1-foot vertical resolution was uniformly available for these regions outside of New York City (Suffolk County is an exception). Additionally, for these areas, the lowest critical elevations are not known for many of the transportation systems and related structures as well as they are known within New York City. The New York City estimates were largely obtained from the Hurricane Transportation Study (USACE, 1995), and the metropolitan east coast (MEC) climate change infrastructure study (Jacob et al., 2000, 2001, and 2007).[32]

This lack of basic information points to the need for accurate, accessible digital elevation models in all the storm-surge-prone coastal zones of New York State. These models need a vertical resolution of substantially less than 1 foot.

Case Study Results for General Inundation Patterns

A 2-foot rise in sea level would have significant impacts in many parts of New York City, and especially along the Brooklyn and Queens shorelines, around Jamaica Bay, and on the Rockaway Peninsula. As shown in **Figure 9.7,** the increase in additionally flooded area from a 2-foot rise to a 4-foot rise in sea level is less significant than the increase in flooded areas from current sea level to the first 2-foot sea level rise. This is a result of the topography of the area and has to do with the presence of glacial landforms. In the subject regions, the terrain slopes between the 100-year base flood elevations (at current sea level) and the next 2 feet of higher elevations tend to be minimal, while terrain slopes tend to become steeper at elevations above base flood elevations of 2 feet. This is typical for former flat glacial-outwash regions. They are interspersed with remnants of glacial end moraines that stand above the plains and are now coastal flats or marshes, after more than 400 feet of sea level rise during the last 18,000 years of glacial retreat.

The areas indicated as additionally flooded zones under the 2- and 4-foot sea level rise scenarios in **Figure 9.7** will be flooded only if protective measures such as levees and/or sea walls are not kept in good repair where available or newly constructed. Such measures could diminish the additional flooding, but issues of sustainability (discussed below) will need to be considered.

A sea level rise of 2 or 4 feet will cause more streets to be flooded during a coastal storm surge (**Figure 9.9**).[33] The increase in total length of streets flooded during the first 2 feet of sea level rise over the current sea level is almost twice as much as the increase in the total length of streets flooded during the second 2 feet of sea level rise (from 2 feet to 4 feet of sea level rise).

Flooding of Transportation Infrastructure and Expected Impacts

Flooding of city streets affects the flow of vehicular and pedestrian traffic, parking patterns, and many of the
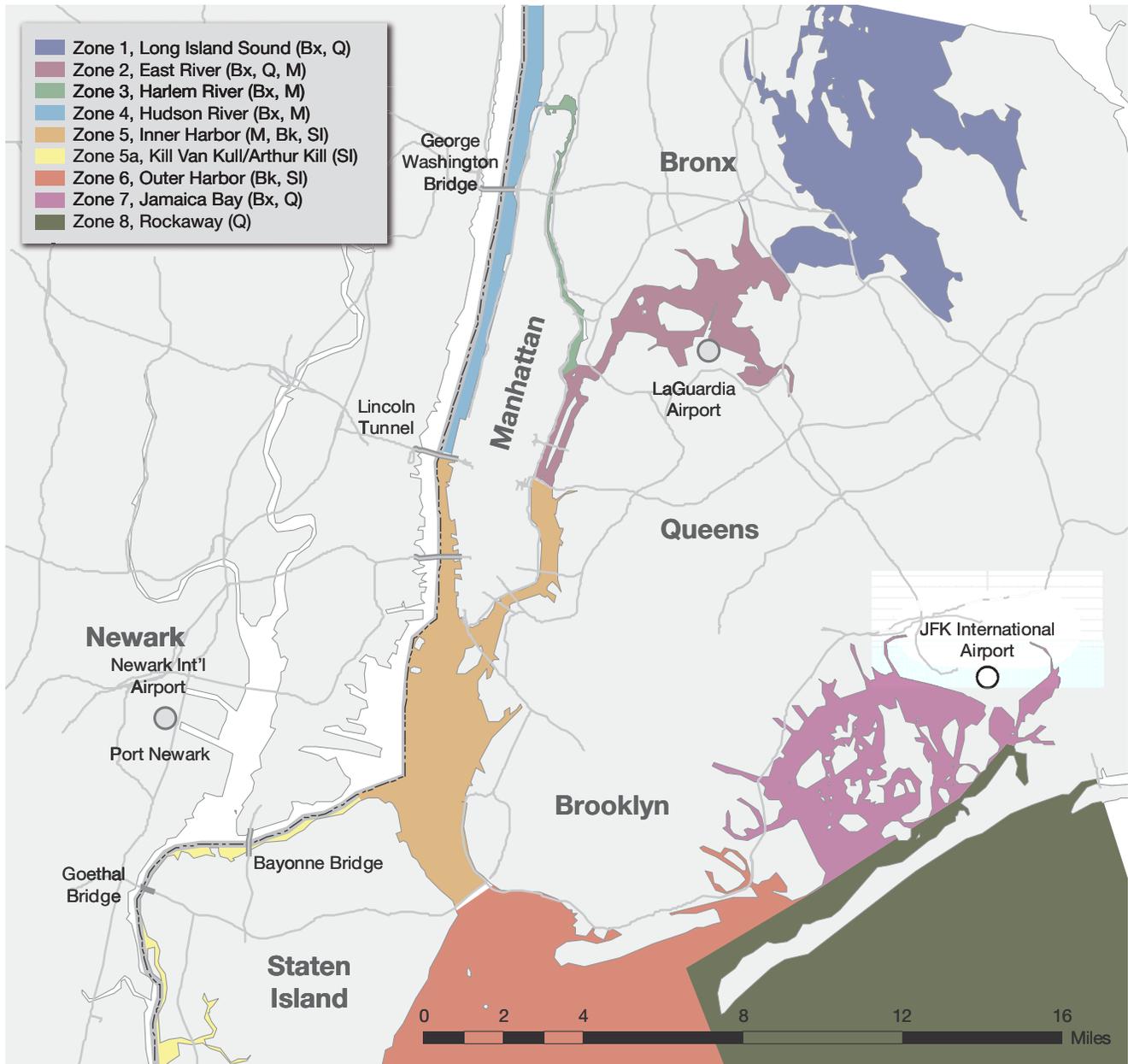
Note: Legend gives color code and ID number for the nine zones, and lists the boroughs (in parenthesis) that share a shoreline with the zone. The obtained numerical AW BFEs (Z_i values) are listed in Table 9.13 (Appendix B). Legend abbreviations are: Bx = Bronx, Q = Queens, M = Manhattan, Bk = Brooklyn, SI = Staten Island. Sources: Base map, The Port Authority of New York and New Jersey, 2001; Overlays, by ClimAID team

Figure 9.8 Delineation of waterway zones for which area-weighted base flood elevations (AW BFE) are calculated
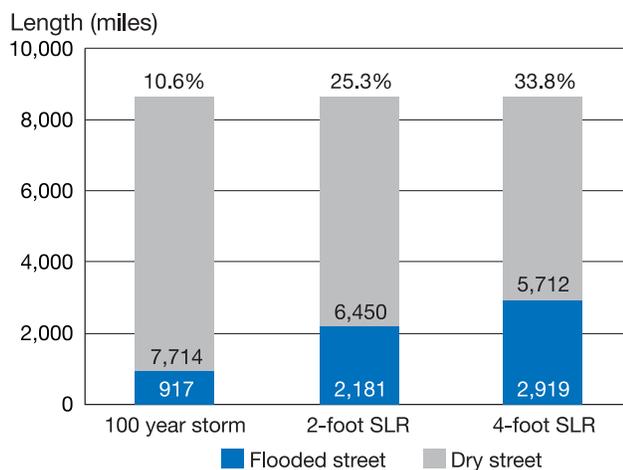
Length (miles)

Note: The length of flooded streets that fall into the three flood zones increases from 917 to 2,181 to 2,919 miles, or from 10.6, to 25.3 and 33.8 %, respectively, of the total NYC street length, which measures about 8,600 miles.

Figure 9.9 Total length (miles) of NYC streets that fall inside (blue) and outside (gray) the respective flood zones as a function of sea level rise, for current sea level and with 2-ft and 4-ft sea level rise, respectively

MTA-NYCT bus routes. It also can slow access by first responders and emergency vehicles.

There are currently no centralized GIS- or CAD-based (computer-aided design) or other digital databases that show the as-built elevations of engineered transportation systems, including subways, railroads, state highways and/or major bridge access ramps, roads, toll plazas, tunnels, and airports and seaports in the New York City metropolitan region. It is generally very difficult to compile the needed information from hardcopy blueprint plans that must be retrieved from archives one by one. ClimAID transportation stakeholders, and in particular the Port Authority, MTA, NYSDOT, and NJ TRANSIT, provided the needed information, in addition to data already available from the U.S. Army Corps of Engineers (USACE, 1995), including tunnel elevations, volumes, pumping capacity, etc. As climate adaptation efforts advance, the assembly of such a database on a statewide basis is urgently needed, but should at least be developed on an agency-by-agency basis. This points to data and information needs we address later.

Focus of Impact Analysis and Assumptions

The only structures considered in this case study are those that are near or below sea level and are potentially vulnerable to coastal storm surge inundations. Where available, the lowest critical elevations are listed, indicating the elevation at which water will inundate a portion or all of a given structure if storm surge waters reach it. Water damage at these elevations is likely to occur and operation will be impeded. Lowest critical elevations are given in feet and are referenced to NAVD 1988.

The case study assumes that no adaptation or protection measures are taken now or in the future, unless indicated. Implementation of any structural or protective adaptation options or, in some cases, operational protective emergency measures, could diminish to various degrees the extent and impact of flooding depicted here.

Tunnels and Underground Structures

For tunnels and other underground structures, once storm waters reach the lowest critical elevation, water will flow down into the tunnel or underground structure. If the floodwaters stay above this critical elevation for sufficiently long, the tunnel and connected structures can fill completely to at or below the lowest critical elevation.[34]

The flood potential of the transportation systems listed below can be inferred by comparing the flood scenarios for the respective waterways listed in column 4 of **Table 9.13** (Appendix B) with the lowest critical elevations given, to determine whether the base flood elevation (2 and 4 feet, respectively) exceeds the lowest critical elevation (see **Table 9.13**, Appendix B).

Note that all elevations are uniformly relative to the NAVD 1988 datum. For all listings below, it can be inferred in conjunction with the data from **Table 9.13** whether:

- the lowest critical elevation is at or below the area-weighted average (Z_i) (or below Z_i for the 2-foot or 4-foot sea level rise scenarios, respectively), implying that the structure is within the 100-year flood zone for the given sea level, now or in the future; or
- the lowest critical elevation is above the area-weighted average (Z_i) (or above Z_i for the 2-foot or 4-foot sea level rise scenarios), implying that there is no 100-year flood hazard for the structure under the given sea level scenarios.

When the flood potential of a structure located outside New York City and outside the mapped waterways is assessed where no area-weighted average value Z_i was computed, the current FEMA 100-year base flood elevation is used directly (corrected for NAVD 1988 datum where needed) to allow similar inferences.

These methods were used to assess the flood potential for each of the structures discussed below.

New York City Transit Subway System

Most of the tunnel flooding analysis focused on the following three areas (**Figure 9.10**):

• Downtown Manhattan, with tunnels connecting below the East River to Brooklyn (six river crossings) (**Figure 9.11**)
• Midtown East Side Manhattan, with four tunnels crossing below the East River to Queens (Long Island City) with one nearby additional river-crossing tunnel segment (**Figure 9.12**) across the Newtown Creek at the boundary between Brooklyn and Queens
• Uptown Manhattan, with three tunnels crossing beneath the Harlem River into the Bronx (**Figure 9.13**)

The ClimAID subway flood study was cross-checked against an MTA-internal flood mapping effort,[35] which was carried out in 2006 for developing storm emergency plans. The study modeled the effects of the storm surge heights for "worst track" (i.e., direct hit) hurricanes of categories 1, 2, 3, and 4 as given by USACE (1995) based on NOAA's SLOSH (Sea, Lake, and Overland Surges from Hurricanes) computations then available. We reproduce here only the MTA map for the category-1 hurricane scenario (**Figure 9.14**).

This storm scenario has coastal storm surge elevations roughly comparable to the 100-year coastal storm
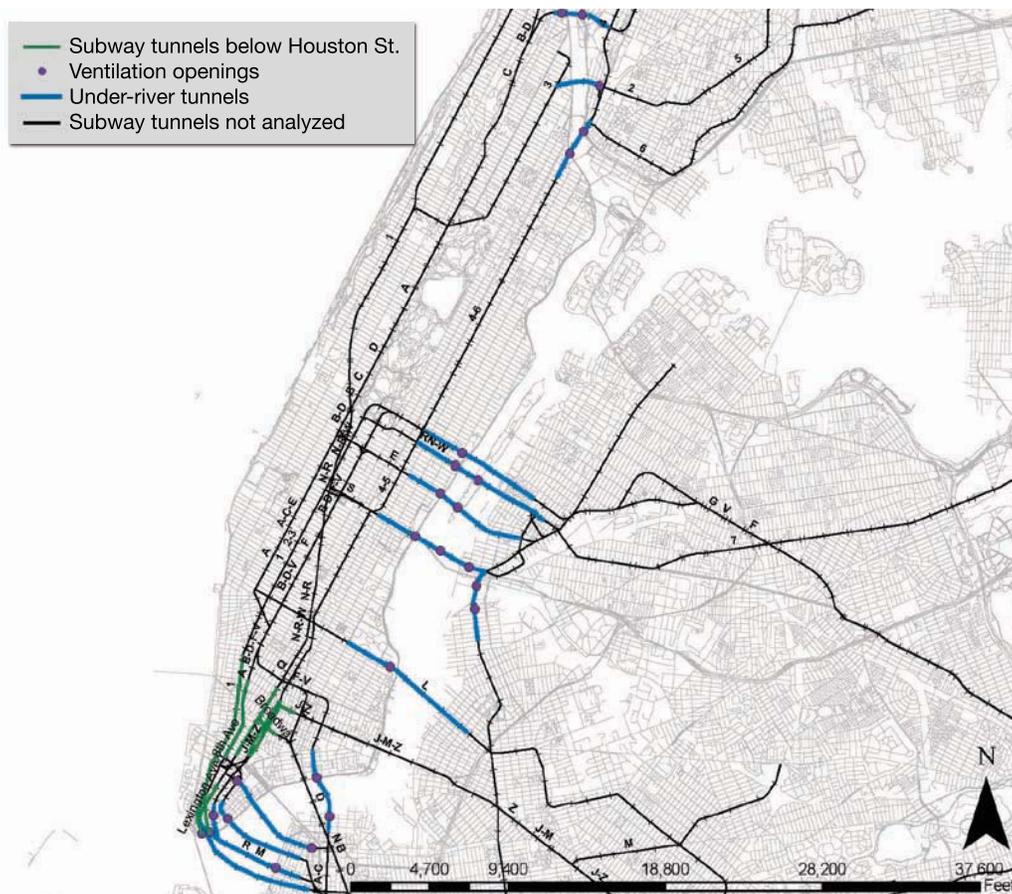
Note: Only the colored segments were considered in the ClimAID flood analysis. Purple lines are river-crossing tunnels and adjacent segments to the nearest land stations; green lines are analyzed tunnel segments on land, near or beneath flood zones. Subway stations are not shown, but non-station openings subject to potential flooding are indicated by circles. Source: LDEO/Civil Engineering, Columbia University

Figure 9.10 NYCT subway lines analyzed in the case study
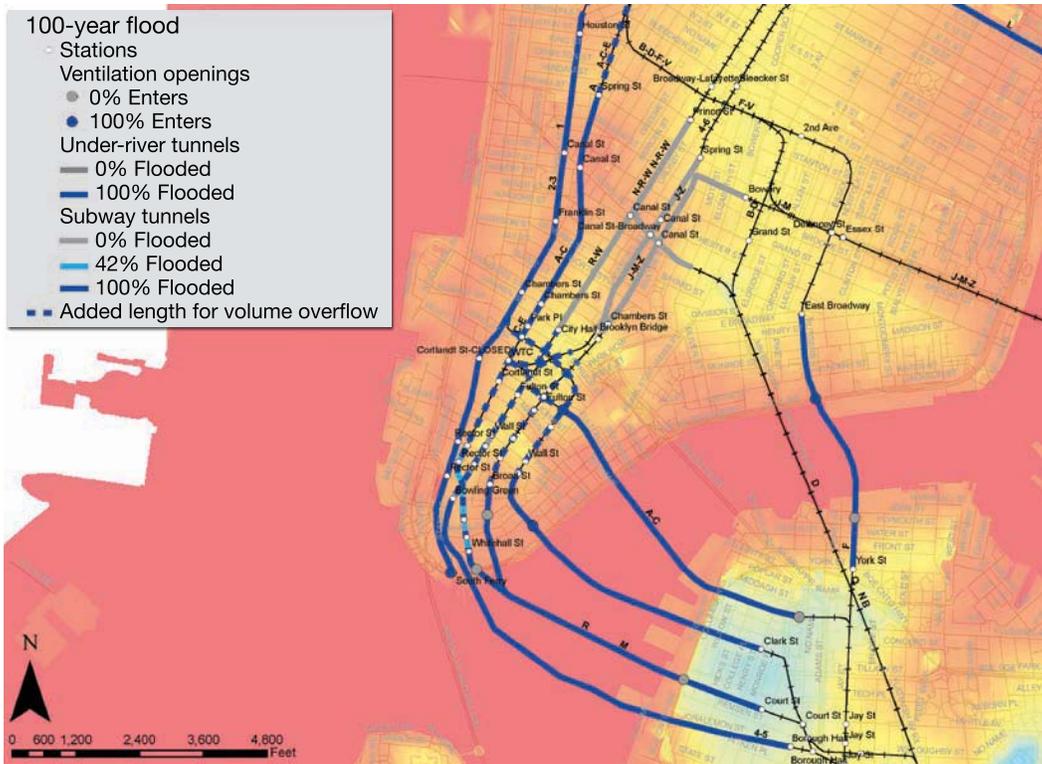
Source: LDEO/Civil Engineering, Columbia University

Figure 9.11A 100-year flooding without sea level rise of Lower Manhattan subways and adjacent East River tunnels crossing to Brooklyn; the heavy blue lines indicate fully flooded tunnels, and broken lines show overflow into tunnels located in areas that are not flooded above-ground; background colors show topographic surface elevations (yellow≥30ft)
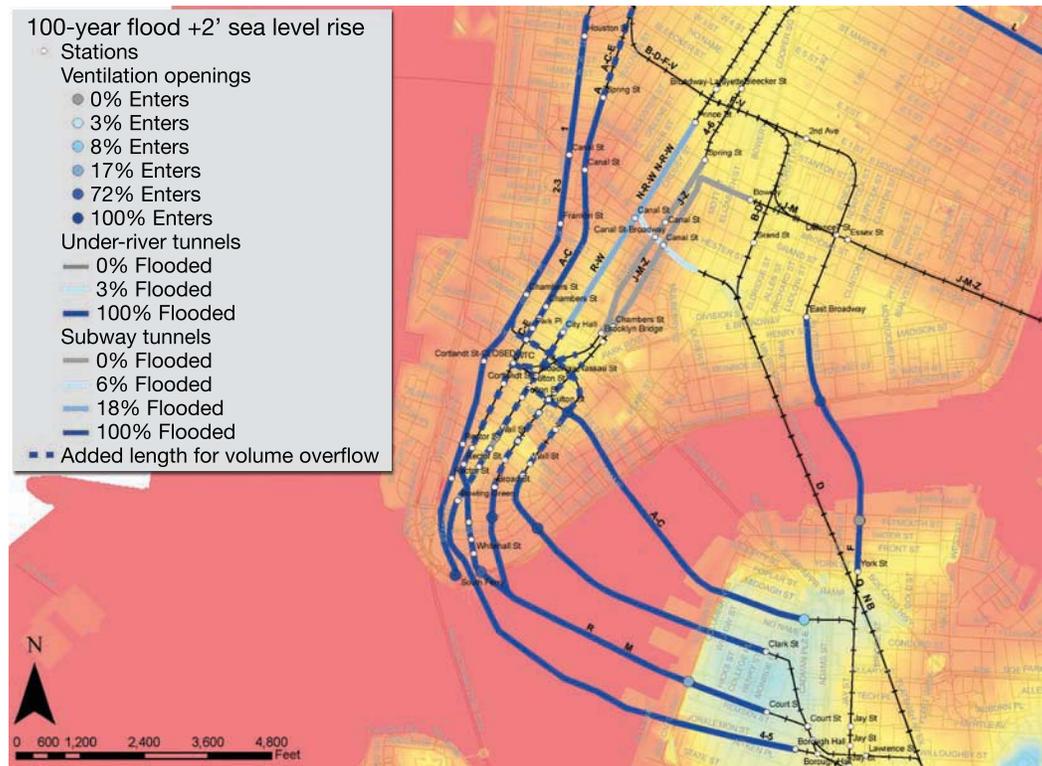
Source: LDEO/Civil Engineering, Columbia University

Figure 9.11B Same as A, but with 2-ft sea level rise; light blue lines are partially flooded

Source: LDEO/Civil Engineering, Columbia University

Figure 9.11C Same as A, but with 4-ft sea level rise; blue lines show additional partial or full flooding near Canal Street (Lines 4-6, J, M, Z); in all three cases East River tunnels for the 4, 5, R, M, 2, 3, and F lines are fully flooded

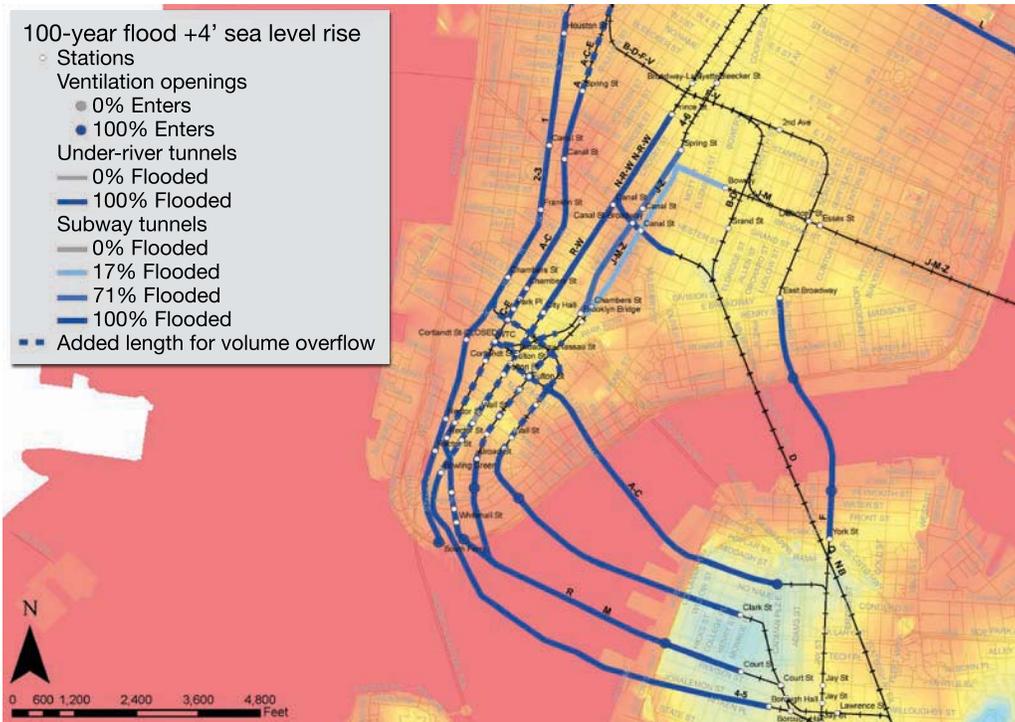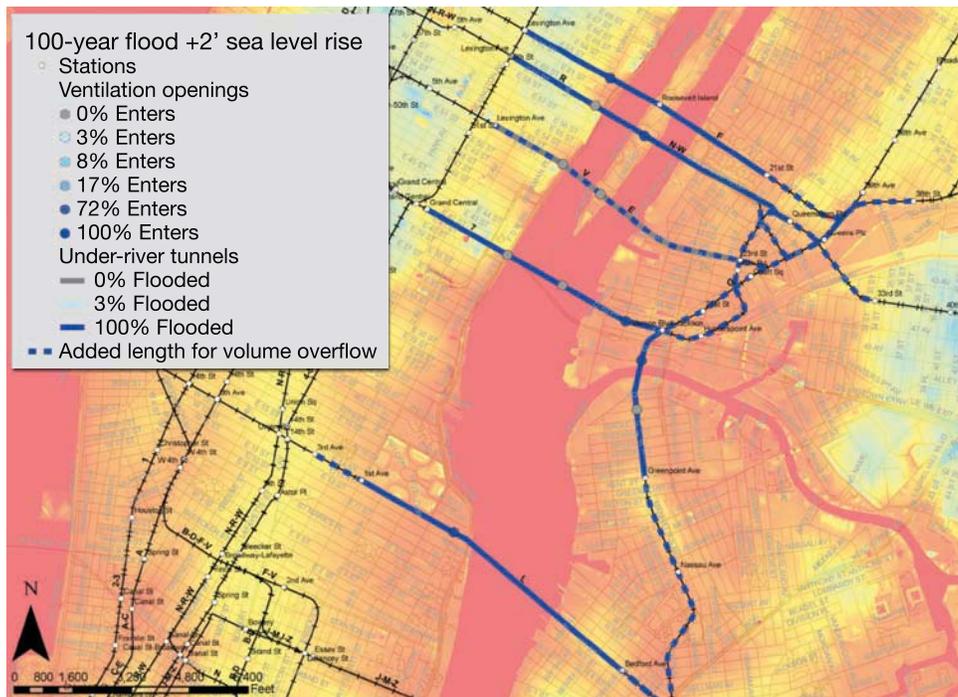Note: Symbols as in Figure 9.11. The ClimAID team also performed hydraulic computations for S1 and S3 scenarios (no and 4ft SLR). They are omitted for brevity. Source: LDEO/Civil Engineering, Columbia University

**Figure 9.12** 100-year flooding with 2-ft sea level rise of Midtown Manhattan subways and tunnels across the East River to Brooklyn (L line) and Queens (F, N-W, V-E, and 7 lines), and across the Newtown Creek between Queens and Brooklyn (G line).

surge of the ClimAID case study S1, without sea level rise, but the MTA study assumed that the maximum flood height would be sustained sufficiently long to fill the tunnels to the full surge elevation. Therefore the map shows the maximum extent of tunnel flooding possible for the MTA category-1 hurricane scenario. Nevertheless, the map (**Figure 9.14**) shows a striking similarity in tunnel flooding extent to the ClimAID maps (**Figures 9.11** to **9.13**), despite the different coastal storm surge elevation patterns for this hurricane-1, storm-track-specific scenario used in the MTA study, and the more elaborate, time-dependent hydraulic flooding computations by the ClimAID team. The findings of very similar results of the two studies using different storm surge patterns and methodologies support two important points:

- It provides some validation of the results of either study carried out entirely independently from each other.
- It shows that, to a first order, the subway system in certain low-lying areas is flooded or not flooded depending on whether the flood surge height exceeds the critical ground elevations of 8 to 9 ft

(NAVD, 1988). Any additional flood elevations somewhat extend the underground reach of the tunnel flooding, but not by very much. The reasons for this similarity of outcomes are twofold: 1) the effect of topography (discussed in more detail in Appendix B; extreme flood heights such as from category-3 or -4 direct-hit hurricanes would, however, extend the flooding considerably, especially on lines with modest tunnel climbing slopes); and 2) flooding of the tunnels occurs very fast to virtually the full height that the time-dependent storm surge elevations allow (see Appendix B).

One major difference between the MTA and ClimAID flood analyses is that ClimAID calculated, using hydraulic equations, the water entering the subway system as a function of time-dependent surge behavior. This approach tells how fast the tunnels are flooded, and how fast and far the flooding will spread, dependent on the amount of water that can enter the system, as long as the surge height is above the tunnel opening's lowest critical elevation (LCE). The LCE can be a station entrance, emergency exit, ventilation
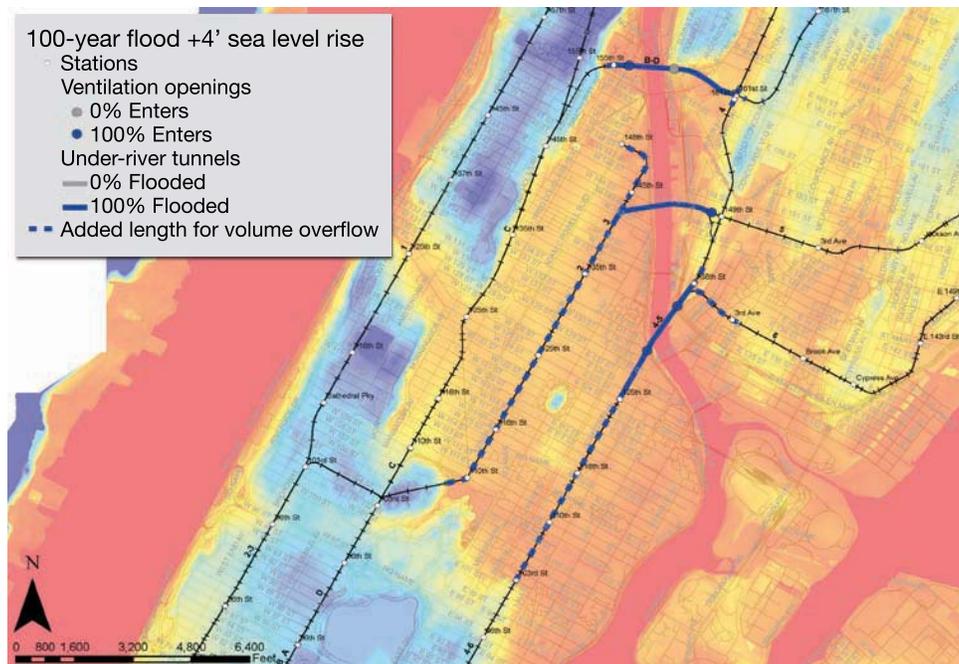
Note: The most northern tunnel (B-D lines), flooded for the 4-ft SLR scenario shown here, does not flood without SLR, and only partially floods with 2-ft SLR. Also the overflow extending towards midtown Manhattan is entirely absent along the #2/3 lines for 0 and 2-ft SLR, but extends for all 3 storm scenarios to 103rd Street along the #4, 5, and 6 lines. Subway tunnel and track elevations tend to follow the surface topography (track elevations are typically about 20ft below street grade; but many exceptions exist). It is therefore not surprising that where surface topography reaches an elevation of about ≥30ft (yellow shading), it creates a "dam" against underground flooding to proceed further, at least for these three storm scenarios [30 ft (topography) – 20ft (track depth) = 10 ft (approximate surge height)]. The ClimAID team also performed hydraulic computations for S1 and S2 scenarios (0 and 2-ft SLR). Blue shadings: ≥60-ft elevations. Source: LDEO/Civil Engineering, Columbia University

Figure 9.13 100-year flooding with 4-ft sea level rise of Uptown Manhattan subways and tunnels crossing into the Bronx beneath the Harlem River

shaft, or string of street-level ventilation grates or, as in most cases, combinations thereof.

The ClimAID hydraulic calculations show that *in most instances the tunnels fill up in less than 1 hour* as long as outside flood heights exceed the LCE, almost regardless of by how much. The total volume of water that needs to be pumped from the tunnels is discussed below.

The MTA analysis (**Figure 9.14**) for the category-1 Hurricane Flooding Scenario assumes that the flood surge and the corresponding high water level takes place for several hours; in other words, there is ample time for the subway flooding to occur, at least without any prevention response (e.g., possible sandbagging, or covering of vulnerable entry points such as entrances, vents, emergency exits, etc.). Thus, the extent of flooding depicted in **Figure 9.14** could be considered the "worst case" scenario for NYCT's system flooding for a category-1 hurricane.

Neither the MTA nor the ClimAID flood analyses take into account, however, recent ameliorative measures begun by the MTA, on a location-by-location basis, to address the propensity for storm-related flooding. For instance, planning is currently under way within the MTA to raise the Harlem River seawall along the 148th Street and Lenox Avenue subway train yard to protect the subway portal to the tunnels at that location. A program to raise ventilation grates to prevent water entry is also under way at some locations subject to recurrent flooding from high precipitation events.

Highway and Non-Subway Rail Tunnels

Discussed in this section are the potential flooding impacts to highway and non-subway rail tunnels. Critical parts of the road and rail system are vulnerable to flooding from sea level rise.

Highway Tunnels
There are four major highway tunnels connecting Manhattan with two other NYC boroughs: the Brooklyn-Battery (LCE=7.5 feet, Z1=9 feet) and Queens-Midtown (LCE=9.5 feet, Z2=11 feet) tunnels across the East River and its extension into the NY Inner Harbor (for locations see **Figures 9.2** and **9.3**); and two highway tunnels that connect Manhattan with New Jersey beneath the Hudson River, i.e., the Holland (LCE=12.1 feet*,[36] Z5=9 feet) and Lincoln (LCE= 22.6 feet*, Z5=9 feet) tunnels. The Lincoln tunnel has three tubes; all others have two tubes, with two lanes per tube.
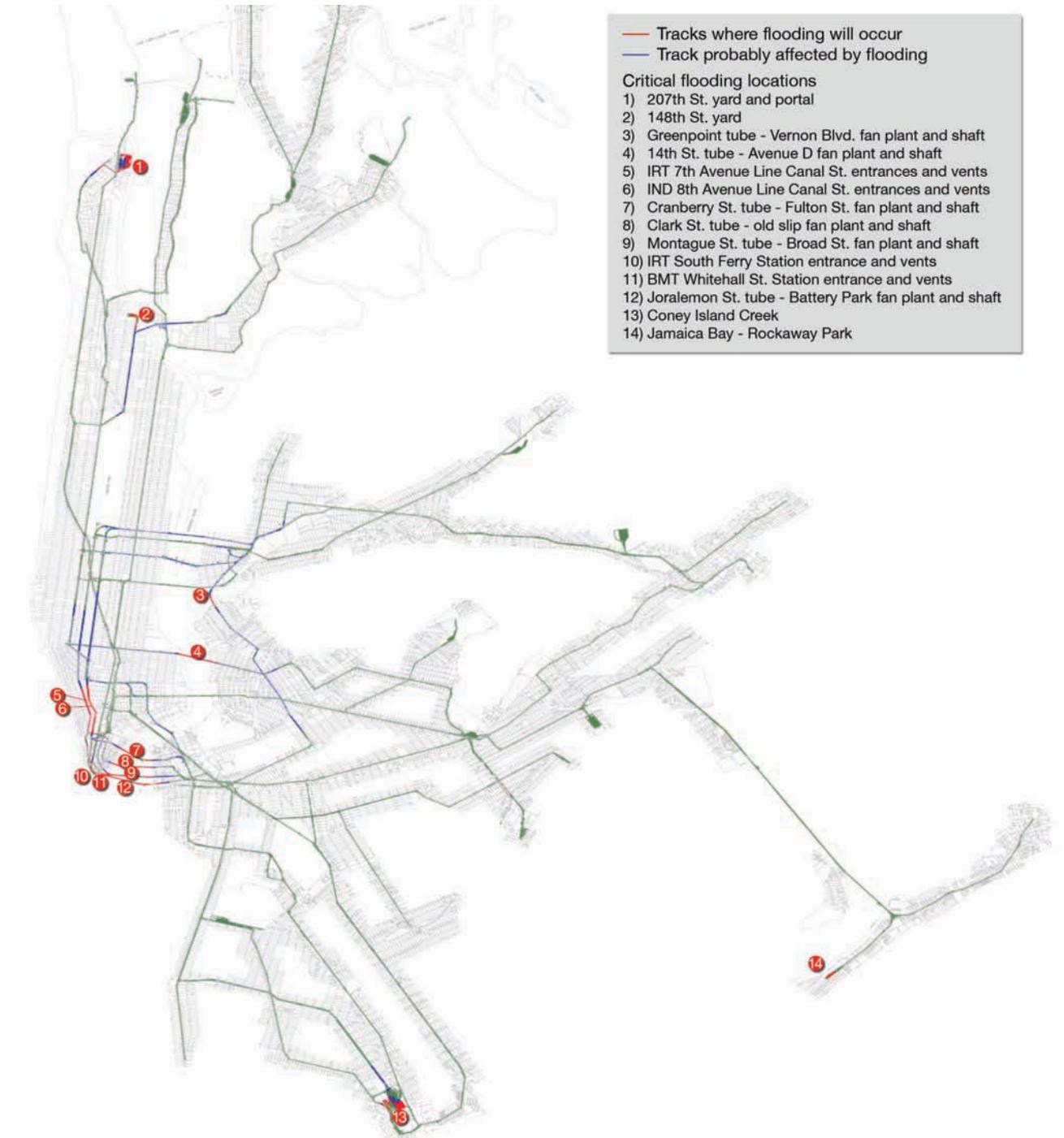
Railroad Tunnels
In addition to the subway tunnels, the following river-crossing railroad tunnels exit from Manhattan and are used by Amtrak, Long Island Rail Road (MTA-LIRR), Metro-North (MTA-MNR), Port Authority Trans-Hudson (PATH), and NJ TRANSIT:

• **North River (Hudson) Railroad Tunnel**—The North River railroad tunnel has two tubes from New Jersey into Penn Station used by Amtrak and NJ TRANSIT. The tubes are connected into Penn Station, and therefore flooding could also potentially affect LIRR facilities in Penn Station and the West Side Rail Yard (LCE = 8.9 feet, Z5=9 feet). The top-of-rail (track) elevation in Penn Station is below sea level (LCE = -7.4 feet).
• **Two Pairs of PATH Tunnels**—Two pairs of PATH tunnels cross beneath the Hudson River with LCE=9.9 feet*, and Z5=9 feet. The critical elevations are located in New Jersey and imply closing the installed floodgates at the Hoboken station (without the Hoboken station flood gates, LCE would be 6.5 feet). Parts of the PATH system, both in Manhattan, and the much longer, also entirely below-ground system in New Jersey, are in their current configuration nominally flood prone, once the surge exceeds the LCE at various locations. Also note that PATH stations have internal passages that connect to NYCT subway stations along 6th Avenue at 14th, 23rd, and 33rd Streets, Manhattan.

All PATH tunnels are interconnected in New Jersey and extend below grade into the Hackensack/Passaic River basin subject to tides and coastal storm surges. Several projects are currently under design to locally raise LCEs for some of the system openings (e.g., Washington Street Powerhouse and 15th Street Shaft, both in New Jersey). Until *all* lowest critical elevations within the system are raised above the respective base flood elevations plus sea level rise, the system may still remain vulnerable to floods, albeit may flood more slowly and hence potentially with less water to pump out.

---

* All LCE with an asterisk* attached are dependent on emergency operational measures (e.g., by sealing ventilation shaft doors etc.).

Tracks where flooding will occur
Track probably affected by flooding

Critical flooding locations
1) 207th St. yard and portal
2) 148th St. yard
3) Greenpoint tube - Vernon Blvd. fan plant and shaft
4) 14th St. tube - Avenue D fan plant and shaft
5) IRT 7th Avenue Line Canal St. entrances and vents
6) IND 8th Avenue Line Canal St. entrances and vents
7) Cranberry St. tube - Fulton St. fan plant and shaft
8) Clark St. tube - old slip fan plant and shaft
9) Montague St. tube - Broad St. fan plant and shaft
10) IRT South Ferry Station entrance and vents
11) BMT Whitehall St. Station entrance and vents
12) Joralemon St. tube - Battery Park fan plant and shaft
13) Coney Island Creek
14) Jamaica Bay - Rockaway Park

Note: Red symbols indicate definite flooding, blue ones potential flooding, the latter corresponding closely to the "overflow" segments in Figures 9.11–13. Green areas near the line tracks indicate locations of yards. Two yards along the Harlem River (upper left) are flooded, and so are facilities in Coney Island and Rockaway (bottom center and right). Source: MTA—NYCT, 2006, A. Cabrera (see Endnote 35)

Figure 9.14 MTA subway flooding map for a category-1 hurricane based on surge heights listed in USACE (1995)

The ClimAID team did not have proper terrain data (detailed digital elevation model data) to verify the flood potential of all New Jersey-based PATH stations and other potential entry points. While the Port Authority provided the lowest critical elevations for all stations, the topography by which the floodwaters may reach these potential entry points needs further investigation to fully assess their flood potential under the 100-year storm height and the 2-foot and 4-foot sea level rise

scenarios. According to FEMA's Flood Insurance Rate Maps, several PATH system entry openings appear to be flood-prone. But it should be noted that during the December 1992 nor'easter storm, only the Hoboken station was flooded (then LCE=6.7 feet), while the next lowest entry point, Exchange Place (LCE=7.6 feet), was not. The World Trade Center PATH station, in New York, and adjacent terrain are currently in a state of reconstruction and, therefore, their current and future flood potentials are highly uncertain at this time. Based on the previous lowest critical elevation of the PATH system (USACE, 1995), this system appears to be flood-prone at the various states of sea level rise without additional protective measures. A more detailed analysis of all PATH entry points with updated digital elevation models and floodways is needed to better understand the flood vulnerability under current sea level and future sea level rise scenarios.

Flood vulnerability in tunnels varies, depending on whether adaptive or preventive structural (or even just operational emergency) measures are undertaken. They can best be implemented where only a limited number of openings provide flood access to the underground structures and systems. Such engineering measures are the prototype model for effective, albeit perhaps temporary, adaptation to sea level rise for tunnel systems with closed ventilation. This is unlike the ventilation system of the New York City subway, which is largely open to, and connected with, the street grade

Other Tunnel Systems
- **East River Tunnel**—This railroad tunnel is used by Amtrak and LIRR. It has a lowest critical elevation of 7.9 feet (Z2=11 feet), located in Long Island City, Queens. The tunnel provides an access route westward across midtown Manhattan into Penn Station and could potentially lead to flooding there into LIRR, Amtrak, and NJ TRANSIT facilities. The North River (Hudson) and East River tunnels and Penn Station have sump and ejector pump systems. Penn is also protected from flooded river tunnels by floodgates at the east and west ends of the station.
- **Access to the Region's Core (ARC) Mass Transit Tunnel**—A new tunnel system, the ARC Mass Transit Tunnel across the Hudson River, is currently under construction.[37] It will increase the capacity for

NJ TRANSIT commuter trains and more than double commuter rail capacity between New Jersey and New York. The ARC project also includes a new expansion to Penn Station, New York. There is no interconnection between the ARC Mass Transit Tunnel tracks and the existing New York Penn Station tracks. However, NJ TRANSIT is building a pedestrian connection between the expansion and the existing Penn Station (the LCE of the pedestrian connection is 9.7 feet, while Z=9.0 feet, both relative to NAVD 88). Therefore the new Penn Station extension may become vulnerable to flooding via the pedestrian connector to the existing Penn Station for the scenario that assumes a 2-foot sea level rise (S2), or whenever sea level rise exceeds 0.65 feet. The ARC rail tunnel itself has the same LCEs (11.553 feet at both its Hoboken and the 12th Avenue, NYC, shafts). It therefore may become directly vulnerable to flooding from either end for a 100-year flood for scenario S3 (which assumes a sea level rise of 4 feet) or whenever sea level rise exceeds about 2.5 feet. Modifications to the Hoboken and 12th Avenue shaft designs and to the pedestrian connector design may have to be made to avoid future flooding on either side of the Hudson.

- **The 63rd Street Tunnel**—Another new railroad tunnel under construction is the MTA-LIRR's 63rd Street Tunnel. It crosses the East River as part of the East Side Access Project. Construction began in 1969 and the tubes making up the river-crossing tunnel were in place in 1972. The tunnel runs from the intersection of 63rd Street and 2nd Avenue in Manhattan to the intersection of 41st Avenue and 28th Street in Queens. The tunnel can accommodate four tracks on two levels (two for the subway on the upper level and two for the LIRR on the lower level). The MTA connected subway lines to the tunnel in 1989. The current East Side Access Project will build new tunnels in Manhattan to connect the LIRR portion of the 63rd Street Tunnel to Grand Central Terminal and the LIRR tracks in Queens. This connection brings the LIRR into Grand Central Terminal. The original 63rd Street Tunnel (used only for the B&Q subway lines) has an LCE of 11.6 feet (Z2=11 feet) on the Queens side. The new LCE is unknown at this time. The new LIRR train platforms in Grand Central Terminal will be at levels below the Metro-North track. Grand Central Terminal's current flooding potential is via the Steinway subway tunnel across the East River (42nd Street, No. 7 Line) (LCE=9.9 feet; Z2=11 feet).

Notes: The red arrow shows the lowest critical elevation, LCE=6.6 feet, of the rail tracks located in waterway zone Z3=9 feet. The elevated concrete structures are the passenger platforms at an elevation near 11 feet. Note the low-lying parking lot in background.
Source: http://en.wikipedia.org/wiki/Spuyten_Duyvil_(Metro-North_station)

Figure 9.15 Lowest critical elevation of the MTA-Metro-North Railroad Spuyten Duyvil Station, Bronx, next to the Harlem River

At- and Above-Grade Railroads (Commuter, Passenger, and Freight)

Outside Manhattan, many of the NJ TRANSIT and (below-ground) PATH tracks in the Hudson, Hackensack, and Passaic River Basins are flood prone, as demonstrated by the December 1992 nor'easter (USACE, 1995). MTA Metro-North trains can encounter flood-prone segments. Examples are near Spuyten Duyvil on the Harlem River (Bronx; LCE=6.6 feet; Z4=8 feet, see **Figure 9.15**) and Croton on Hudson (Westchester County, LCE=5.2 feet; 1%BFE=5.9 feet in 2000) for the Hudson Line. The LIRR may encounter flooding in Oceanside (Nassau County; LCE=8.5 feet; near Z7=8 feet; 1%BFE=6 feet) along the Long Beach Line; at Flushing (Queens, LCE=8.1 feet; Z2=11 feet) for the Port Washington Line; at low points along the Far Rockaway Line (LCE=8.1 feet; Z7=8 feet); and at the Oyster Bay Station (Nassau County, LCE=8.4 feet; near Z1=14 feet).

Hell Gate is a massive railroad bridge over the East River, connecting Astoria (Queens) with the now-joined
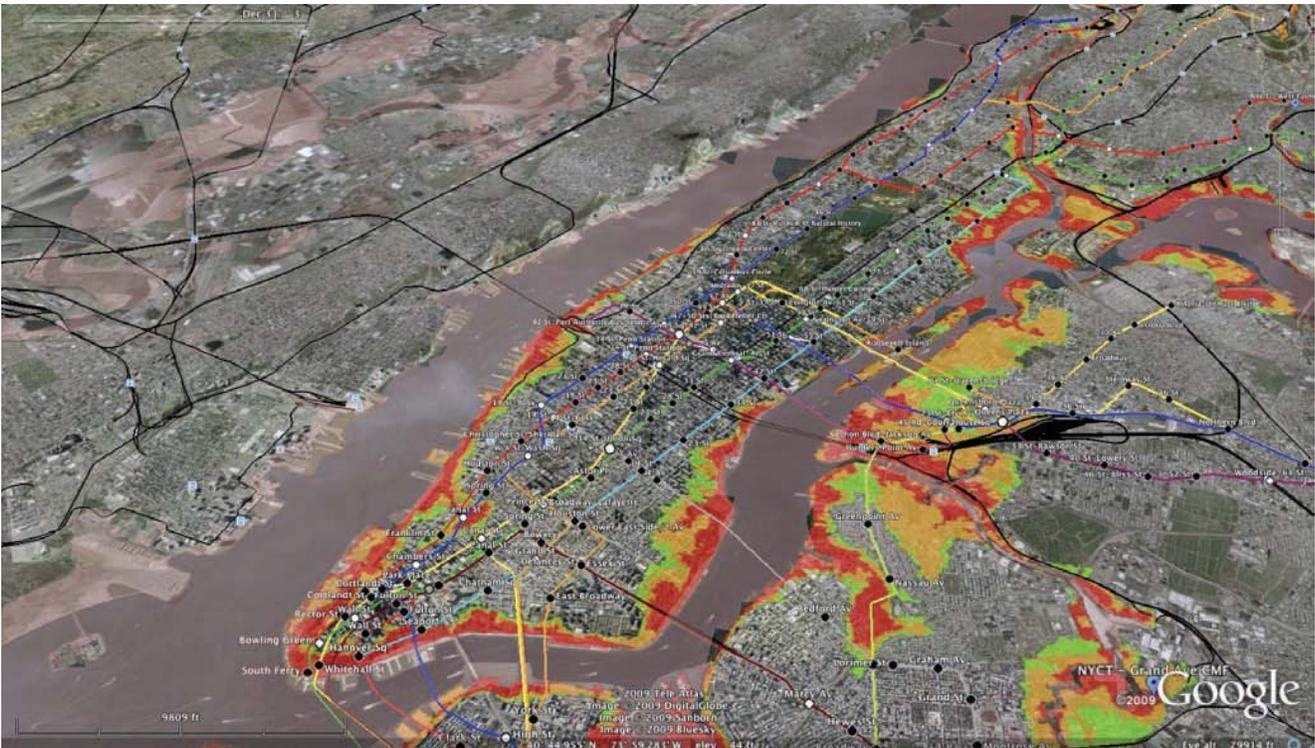
Notes: For Manhattan and parts of the Bronx and Queens (red=100-year base flood elevation at pre-2000 sea level; yellow=2-foot sea level rise scenario; and green=4-foot sea level rise scenario). The red-colored water-flooded areas in the Hudson River represent 9-foot sea levels (all measured in NAVD, 1988). The black lines represent railroads; the colored lines indicate various subway lines. Note that many of the railroads and subways traverse the outlined flood zones or natural bodies of water. For the details of their lowest critical elevations relative to the flood elevations, grouped by waterways in Table 9.13, see text. Source: Image from Google Earth (©2009 Google; ©2009 Tele Atlas; Image ©2009 DigitalGlobe; Image ©2009 Sanborn; Image ©2009 Bluesky); added data by ClimAID team

Figure 9.16 The Hudson, East, and Harlem Rivers and adjacent flood zones

Randall and Ward's Islands (located near the confluence of the Harlem and East Rivers, **Figure 9.16**). The two islands are politically part of the borough of Manhattan. The bridge is owned and used by Amtrak as part of its electrified Washington-to-Boston Northeast Corridor. The bridge is also used by freight trains, including CSX and various other operators, and currently provides the only rail connection from the mainland (i.e., the Bronx) to Long Island. As the elevated tracks descend northward over a narrow arm of the East River into the Bronx, the tracks approach ground level in a 1-percent-per-year flood zone (Z2=11 feet). Therefore, they are likely to be flood prone and block access to the bridge under sea level rise. However, their exact LCE is not known at this time.

CSX operates a freight line along the west shore of the Hudson River of the tidal Mid-Hudson Valley. The exact LCEs for various segments of the freight line between Haverstraw Bay and Albany are not well known at this time. But some track segments are suspected to be prone to flooding at multiple locations at the 100-year flood level, if not at current sea levels then very likely for the 2-foot and 4-foot sea level rise scenarios.

Yards and Depots for Subway, Commuter Rail, and Bus Maintenance and Storage

The MTA-NYCT, MNR, LIRR, and LI Bus Agencies operate extensive yards and shops for storing and maintaining their rolling stock used in the greater New York City metropolitan area. Most of these are located at low elevations. Subway yards on 207th and 148th Streets in Manhattan bordering the Harlem River and Coney Island Creek Yard in Brooklyn are vulnerable (**Figures 9.13** and **9.14**). A systematic evaluation of railroad yards (MNR, LIRR) and of bus depots has not been made for this case study, but needs to be performed in the future.

Major Highways and Access to Major Bridges

The following information is compiled from data provided by NYSDOT (Arthur Sanderson, personal communication, August 2009), USACE (1995), and MTA B&T. NYSDOT compiled a list of locations along interstate highways and state highways crossing locations where the digital elevation model (DEM) gave ground elevations at or below 10 feet above sea level (**Figure 9.17**; **Box 9.1**). This determination was performed using a USGS digital elevation model with 10-meter (about 33 feet) *horizontal* grid spacing. The vertical reference datum is NAVD 1988.
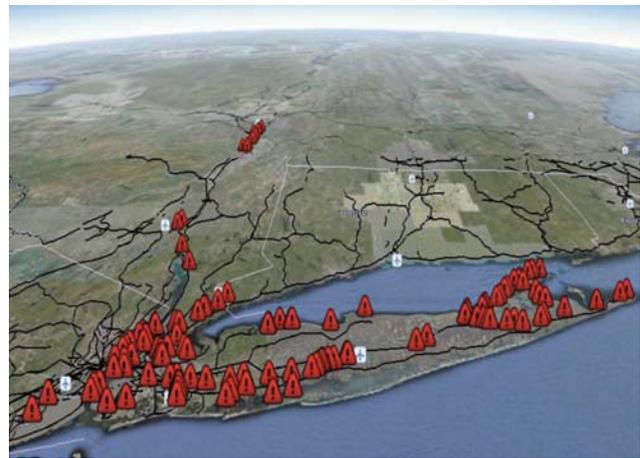
Notes: These sections may be flood-prone either now or become so in the future with elevated sea level, since the terrain on which they are built is at or below about 10 feet in elevation (NAVD, 1988). A more labor-intensive analysis of as-built plans and elevations will be required to determine the exact pavement elevations and their vulnerability as a function of flood probability and sea level rise. County and town roads are not considered. Black lines are railroads. Airports are also indicated. Potential flood points in New Jersey, Connecticut, and Rhode Island are not shown. Source: Base map from Google Earth (©2009 Google; ©2009 Tele Atlas; Data SIO, NOAA, U.S. Navy, NGA, GEBCO; Image ©2009 New York GIS; Image ©2009 DigitalGlobe); NYS DOT data added by ClimAID team

Figure 9.17 The 123 sites identified by NYSDOT as potentially flood-prone state highway or interstate highway sections

---

Box 9.1 Number of interstate and major state highway segments in potentially flood-prone terrain
- 35 locations within the 5 boroughs (counties) of NYC
- 13 locations within Nassau County, Long Island
- 56 locations within Suffolk County, Long Island
- 6 locations in Westchester County (5 along Long Island Sound, 2 along the Hudson).
- 2 locations in Orange County, Mid-Hudson Valley
- 3 locations in Greene County, Mid-Hudson Valley
- 4 locations in Columbia County, Mid-Hudson Valley
- 1 location in Albany County, Mid-Hudson Valley
- 3 locations in Rensselaer County, Mid-Hudson Valley

Name	Location	LCE	Z
Marine Parkway Bridge	Brooklyn to Rockaway/Queens	6.9 feet	Z8 = 9 feet
Cross Bay Bridge	Broad Channel to Rockaway, Queens	6.9 feet at north approach	Z8 = 9 feet
Bronx Whitestone Bridge	Bronx to Queens across East River	10.9 feet on Bronx side	On the border between Z1 = 14 feet and Z2 = 11 feet
Throgs Neck Bridge	Bronx to Queens across East River	8.9 feet on Bronx side	Z1 = 14 feet
Robert F. Kennedy (formerly Triboro) Bridge	Manhattan and Bronx with Queens	13.9 feet in Manhattan	On the border between Z3 = 9 feet and Z2 = 11 feet
Verrazano-Narrows Bridge	Brooklyn to Staten Island	7.6 feet	Z5 = 9 feet, only for its Shore Parkway approach, in Brooklyn

Table 9.1 Metropolitan Transportation Authority - Bridges & Tunnels bridge access ramps in potentially flood-prone terrain, with lowest critical elevation (LCE) and base flood elevation (Z)

Note that county, town, and village roads are not included in this list. Also, engineered road surface elevations are different from terrain elevations and this difference is not accounted for at this time. It will require considerable personnel efforts for this information to be extracted from as-built engineering drawings. Since most highway roadbeds are slightly elevated above the surrounding terrain (excluding road cuts), the list may overestimate the number of highway segments at potential flood peril from sea level rise and coastal storm surge.

While not located in New York State, there are about two dozen New Jersey locations in the tidal Hackensack/Passaic River Basin listed as flood prone (some of them were flooded during the December 1992 nor'easter storm; USACE, 1995). This flooding could affect the return of New-Jersey-bound commuters from New York City and impede disaster assistance transport into the city during and after a storm surge.

The MTA B&T bridge access ramps and/or some related toll plazas listed in **Table 9.1** are potentially
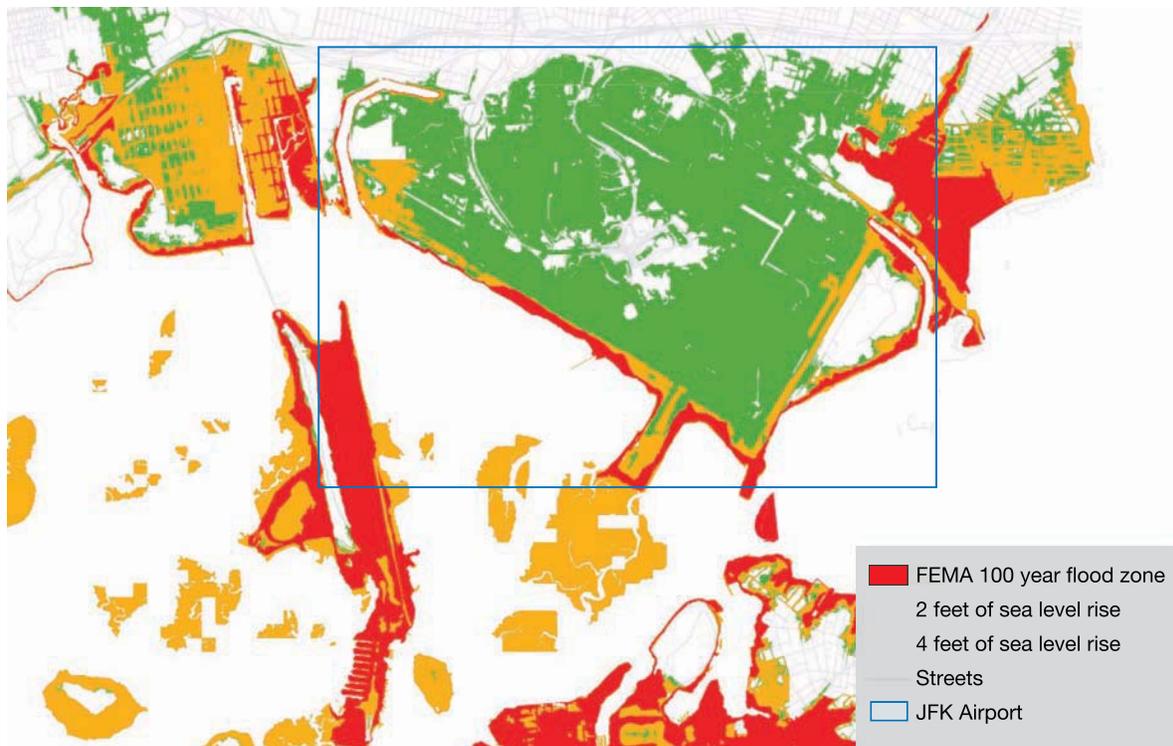
Note: For 100-year base flood elevations under current sea level conditions (red) as well as flooded areas under the 2-foot sea level rise scenario (yellow) and the 4-foot sea level rise scenario (green). JFK is in the center upper half, with a nominal runway lowest critical elevation equal to 10.6 feet and Z7 = 8 feet (NAVD 1988). Flooding at much of JFK for the 100-year storm is largely limited to the 4-foot sea level rise scenario (green shading). Map source: Hunter College, prepared for NYC NPCC, 2010

Figure 9.18 Flood zones near Jamaica Bay, Broad Channel, and JFK Airport

flood prone, either for current conditions or for the 2-foot or 4-foot sea level rise scenarios (LCE and Z in NAVD, 1988).

Airports

Seven airports serve the greater New York City metropolitan region and southeastern New York State area: JFK and LaGuardia (both in Queens), Newark, Teterboro, McArthur (Town of Islip, Suffolk County, Long Island), Westchester County Airport, and Stewart Airport (Orange County, New York). The first four and the last one are operated by the Port Authority, while the two others are owned by the Town of Islip and by Westchester County, respectively. Of these, only the first four are located close to sea level and need assessment regarding the exposure to coastal storm surge and sea level rise (**Table 9.2**).

There are several heliports on the waterfront in Manhattan, but because their fixed infrastructure is minimal they are not considered here.

The lowest critical elevations of the four airports serving the New York metropolitan region that are potentially vulnerable to coastal storm surge are as follows:

- **LaGuardia**—LaGuardia already has levees and pumping systems to protect major portions of the facility. While the runway has a lowest elevation of 5.7 feet (range of 5.7 to 20.8 feet), the actual lowest critical elevation is raised by the levees to about 10.0 feet, which nominally is still below the average Z2=11 feet. Sea level rise will eliminate the existing levee's effectiveness even for lesser storms.
- **Teterboro**—Teterboro airport largely serves private and business jet air traffic. It has the lowest nominal LCE of any of the facilities (USACE, 1995): LCE=3.9 feet; Z5a=8 feet.
- **JFK**—As can be seen from **Table 9.2** and **Figure 9.18**, most of JFK airport is susceptible to a 100-year storm only in the 4-foot sea level rise scenario (**Figure 9.18**, green area). Hence its runways should be relatively safe from coastal storm surge flooding, at least for 100-year and lesser storms, for several decades into the future. There may be street and underpass flooding potential during more frequent heavy precipitation events at access roads, but this is unrelated to sea level rise.

- **Newark**—Newark Airport has a nominal LCE of 9.2 feet (USACE, 1995). Since it is located in New Jersey, no Z value for the 100-year flood has been determined for this study. However, it is located close to a Z5a of 8 feet and therefore is assumed to be nominally subject to flooding for the S2 scenario (SLR of 2 feet).

Shipping Ports

Most major shipping ports, container storage, and transfer facilities (to road or rail) for the greater NYC metropolitan area are operated by the Port Authority and are located in New Jersey (see **Figure 9.19**), except for the Howland Hook Marine Terminal (Staten Island, LCE=8.5 feet; Z5a=8 feet) and Brooklyn Marine Terminal/Red Hook Container Terminal, both in Brooklyn (LCE=8.7 feet; Z5=9 feet). There are many other independently owned and operated port facilities associated with petroleum, dry, and liquid bulk cargos in the greater metropolitan area that are not associated with the Port Authority.

Name	Location	LCE	Z
JFK International	Queens, NY	10.6 feet	Z7 = 8 feet*
La Guardia	Queens, NY	10.0 feet**	Z2 = 11 feet
Newark International	New Jersey	9.2 feet	Z5a = 8 feet
Teterboro	New Jersey	3.9 feet	Z5a = 8 feet***

* See Figure 9.18
** Levee crest; The elevation range for the runways is between 5.7 feet and 20.8 feet in NAVD 1988.
*** Partly sheltered from Z5a and hence attenuated to probably 4 to 5 feet.

Table 9.2 Lowest critical and base flood elevations (LCE, Z) of airports
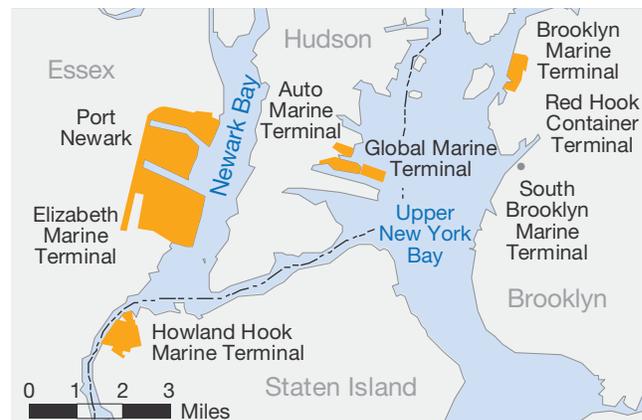
Notes: For smaller port facilities, see text. Source: The Port Authority of New York and New Jersey, 2001

Figure 9.19 Major port facilities in the Greater New York City Metropolitan Area operated by the Port Authority

Other port facilities serve the Staten Island Ferry (Manhattan to Staten Island); the New York Waterway Commuter Ferries leaving Manhattan from West 39th Street, World Financial Center, and Pier11/Wall Street; and various water taxi services throughout the New York Inner Harbor and lower Hudson Valley. The International City Passenger Terminal (west side of Manhattan between W48th and W54th Streets; LCE=7.8 feet; Z4=8 feet) is a privately operated facility mostly serving large cruise ships.

Most of the piers themselves can accommodate, or could be modified to accommodate, coastal storm surges and sea level rise, although under severe storm conditions their services may be curtailed or stalled because of wind and wave safety conditions. However, the freight and container storage and transfer facilities, (including derricks, cranes, access roads, and rail tracks), may be flooded. The flood conditions for such harbor facilities and their potential vulnerabilities are not yet sufficiently researched and need future attention. Most of these facilities in the New York/New Jersey harbor area appear to have their lowest critical elevations near 8 to 9 feet, while their baseline flood elevations are: Z4=8 feet; Z5=9 feet, and Z5a=8 feet (see **Table 9.13** of Appendix B, and **Figure 9.8**). Thus some are at risk of flooding.

Other Facilities

For transportation systems to operate properly, support systems are needed. The most prominent among these—and potentially vulnerable to coastal storm-surge flooding—are the following:

Electric Grid Power
This is either needed for direct propulsion (e.g., via supply from the third rail of the NYCT subway, or the MTA-MNR and Amtrak overhead line contact wire), pumping out of tunnels, signal and control systems, fuel supply and storage pumps, and other support functions (e.g., general communications, ticketing, toll plazas, lighting, office operations, etc.).

Pipelines
Pipelines, either local or regional, provide the necessary fuel supplies to airports, power plants, and heating/cooling and other facilities, and often have pumping and control systems that depend on grid power.

Communication Systems
Many transport systems are dependent on communication systems working properly, from Federal Aviation Administration flight controllers relying partly on long-distance lines for airport-to-airport control tower communication, to intelligent road signs, wireless dispatchers' communications with bus drivers, and for monitoring safety control systems.

Many of the above-listed transportation support systems (e.g., communication, air traffic control systems) have uninterruptible power supply units for finite-duration back-up power, but such power supply systems are not available for transportation systems with large demands, such as subways, electrified trains, tunnel water pumping and ventilation, or even their signal and control systems. As long as the electricity grid is not functional for such priority users, these transportation systems cannot be restored and repaired to functionality, nor operated once restored.

Regional Impacts and Restoration Times

A risk assessment of the full impacts of flooding resulting from a 100-year coastal storm surge on the regional transportation infrastructure has yet to be made. The U.S. Army Corps of Engineers (1995) hurricane transportation study evaluated the New York City metropolitan area's emergency preparedness and ability to evacuate people given a category-1 through -4 hurricane along a worst-track trajectory, i.e., a direct hit. A very similar approach was taken by a study sponsored by the Department of Homeland Security (NISAC, 2006). The study, conducted by Sandia's National Infrastructure Simulation and Analysis Center (NISAC), focused on a direct hit by a category-3 hurricane on New York City, with landfall in a northerly direction crossing Staten Island and affecting the Mid-Hudson Valley and adjacent regions up to Albany. The analysis assumed a coastal maximum storm surge height of up to 19 feet, substantially higher than the proposed 100-year surge of this case study.

The Corps of Engineers study (USACE, 1995) and the NISAC study (NISAC, 2006) use scenario events that, in contrast to the ClimAID case study, have no probabilistic assessments attached. For this reason, the results of these studies are generally difficult to use for engineering decisions, unless a specific infrastructure owner opts to design according to worst-case scenarios,

which is rarely the case. Most engineering design standards and practices use probabilistic rather than deterministic hazard and risk characterizations. This is why the ClimAID analysis uses a probabilistic base for its case study—i.e., the 100-year coastal storm-surge base-flood elevation. Deterministic scenario events like those constructed by the Corps of Engineers (1995) and NISAC (2006) studies are, however, commonly used for emergency response and preparedness planning exercises. For these, worst-case scenarios at various levels (e.g., hurricanes of categories 1 through 4) are commonly used. This reflects a difference between the emergency and engineering professions.

Nevertheless, deterministic and probabilistic assessments are useful. Therefore, the ClimAID analysis builds on insights gained from the 1995 and 2006 studies. Another benefit to such studies is that the general public can understand a deterministic, "real" scenario much better than the conceptually more sophisticated and abstract probabilistic approach.

One of the pertinent results of the NISAC (2006) study emerges from its focus on the vulnerability of the electric power grid (see Chapter 8, "Energy"). The study estimates that it will take up to 15 days after determining the damage for the electric grid to be fully restored throughout the entire affected area (**Figure 9.20**). It did not, however, estimate how long it would take to sufficiently assess the damage after a coastal storm surge.

Other studies that looked at the total financial losses to the region from coastal storms are presented in the Metropolitan East Coast (MEC) study (Rosenzweig and Solecki, 2001; Jacob et al., 2000, 2007). Losses from direct hits of category-1 hurricanes for the New York City metro region were about $5 billion; losses from direct hits of category-4 hurricanes were about $250 billion (in 2000 dollars; in 2010 dollars, these figures would nearly double). These losses were derived without detailed technical risk- and vulnerability assessments of the major infrastructure systems. The costs associated with a direct hit of a category-3 hurricane on New York City, considered by the NISAC study (2006), were between $29 billion and $42 billion, including coastal storm surge and wind damages.

The ClimAID analysis takes a different approach to timing of recovery after a storm and valuation of damage, asking the question: How long would it take

to restore the transportation system to nearly full functionality after a 100-year storm under the three sea level rise scenarios? This outage time is then considered in the estimated economic impact on the region. A summary of the approach is given in **Box 9.2**.

A number of uncertainties are included in this analysis.[38] Currently, estimates of system vulnerability, repair, and restoration times and/or associated costs are not available because there are too many unknowns. Another uncertainty is whether grid power will remain uninterrupted and, if interrupted, how long it will take to restore. The analysis is site- and system-dependent, given the lack, to date, of a rigorous engineering risk and vulnerability assessment. The case study's findings need to be verified in the future through more comprehensive engineering risk assessments.

Underground Rail Systems

Many of the underground rail systems—especially the NYCT subways, NJ TRANSIT and Amtrak passenger systems, and the PATH, MTA-MNR, and LIRR commuter rails—are highly interconnected underground, and extend to considerable depth below sea level as they traverse bodies of water by tunnels or below ground. Even if some of the rail, commuter, and passenger systems are closed to the open air or to grade
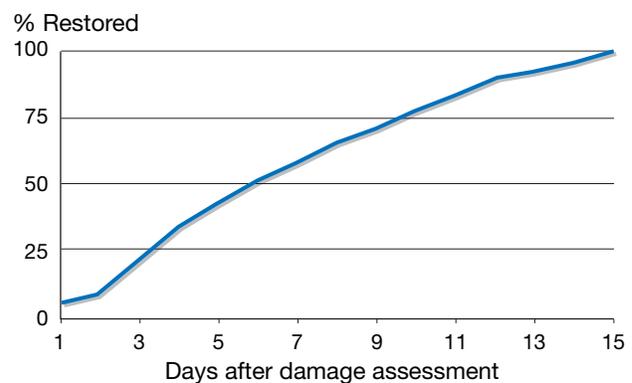
Notes: The analysis is based on a direct hit of a category-3 hurricane on New York City. The study estimates that priority users in New York City may have their power restored within 11 to 129 hours (a half day to five days after damage assessment). For the purpose of the 100-year coastal storm surge scenario considered in the ClimAID analysis, it is assumed that an average power outage for New York City's priority customers is at least one day after the floods recede, with a range of one to two days depending on sea level rise scenario (see Table 9.5, row 2). Note that the NISAC study largely considers damage to the distribution system (including substations) and not to the electric generation system; it also includes wind damage in addition to flood damage. Source: NISAC, 2006

Figure 9.20 Percent of electricity service restored for the amount of time after the storm damage has been assessed in New York City

Box 9.2 Methodology to estimate transportation and related system outage times (see Table 9.5)
1) Take the surge elevations of the three scenarios (1%/y base flood elevation, and add 2 feet and 4 feet sea level rise).
2) Map out which transportation systems above and below ground would be flooded.
3) Obtain the volume of below-ground flooded tunnel structures from the ClimAID team's hydraulic calculations.
4) Combine the volumetric information with available pumping capacity to arrive at time estimates of how long it would take to pump out the floodwater.
5) Consider the time it would take to restore electricity and for logistic and environmental preparations before pumping could actually start; in some instances it is possible that some limited pumping can be maintained throughout the flood event if mobile generators can feed some of the pumps.
6) Estimate the times it would take to repair the flood damage in the submerged structures.
7) Combine all the above times that result in total transportation outage (or the times needed to reach certain percentages of transportation capacity to be restored).
8) Estimate the economic impact from this sequence of events and outages and restoration of transportation systems.
9) Conclude what adaptation and protective options exist and what strategies and policies could be taken to adapt to the hazards and risks and make the systems resilient and sustainable.

Note: The time it takes to fill the tunnels at those locations where the flood surge can reach unobstructed openings is typically very short (less than an hour) and in most cases shorter than the time the surge exceeds the LCE. These calculations have shown that if floodwaters can reach tunnel openings at all, the tunnels typically flood to underground elevations that are approaching the maximum storm-surge elevations that the storm has reached outside the tunnel system.

level, except for their engineered and in some cases protected entrances and vents, they still may be prone to flooding by their connectivity (in many instances) to other tunnel systems. For example, over large portions of their length the New York City subway tunnels are open to street level, via ventilation grates and other openings. Once flooding starts in one of the systems at its lowest critical elevation, flooding will quickly spread to other low-elevation systems below ground, regardless of their respective surface (at-grade) lowest critical elevations. This was demonstrated in the ClimAID scenario analysis for the subway system (**Figures 9.11–9.14**).[39] The question that arises is: Will the installed pumping systems be able to maintain their pumping capacity? While no definite answer could be obtained, the consensus in stakeholder discussions was that, at least in the case of the subway pumps, they would likely cease to function. This would mean that pumping capacity, including power, would need to be provided from other sources in most cases. Currently NYCT has only three mobile pump trains available for the entire system. Each has a 5,000 gallons/minute pumping capacity.

Road Tunnels

Road tunnels across the Hudson and East Rivers are isolated from these interconnected rail systems and can therefore be more readily evaluated. The Lincoln Tunnel (across the Hudson) is not likely to flood

because operational emergency measures are in place that seal those openings that would be submerged. Despite similar measures, the Holland Tunnel is expected to flood under the 4-foot sea level rise scenario (i.e., only for scenario S3). Hydraulic computations for the two East River Tunnels show the results for total flooding, i.e., flood water influx exceeds 100 percent of the tunnel volume, for the three sea-level scenarios S1 through S3 (current sea level, 2-foot rise and 4-foot rise) (**Table 9.3**).

The ClimAID analysis then posed the following question: Assuming that grid electricity is fully available and the installed tunnel pumps would work without interruption, how long would it take to pump out one of the tunnels if it had filled 100 percent? The results are shown in **Table 9.4**. These times apply only for the assumptions stated and are not necessarily used later on in other parts of the scenario case study, where it is assumed that additional pumping capacity can be brought in, or tunnels are not completely filled (**Table 9.5**).

Flooding Via	Brooklyn Battery Tunnel			Queens Midtown Tunnel		
	S1	S2	S3	S1	S2	S3
Portals	36%	167%	254%	0%	22%	105%
Ventilation	0%	3%	49%	0.30%	4%	45%
Total	36%	170%	303%	0.30%	26%	150%

Note: Percentage volume of flooding in the tunnel by flood entry location under S1, S2, S3 sea level rise scenarios.

Table 9.3 Total flooding for the two East River Tunnels

For those tunnels that fully flood under the three scenarios, it would be desirable to shorten pumping times by bringing additional mobile pumping capacity to accelerate the process. Such options are discussed below in the context of subway tunnels.

The current and future interconnectivity between Penn Station and Grand Central Terminal is poorly defined. As a result, no technically based pumping time estimates can be provided for the Amtrak/NJ TRANSIT Hudson Tubes and the Amtrak/LIRR East River 42nd Street Tunnels and connected systems. The NJ TRANSIT ARC tunnel across the Hudson (postponed in 2010), leading to a new Penn Station, has not been fully assessed at this time. This is also true of the future LIRR 63rd Street Tunnel (across the East River) as part of the LIRR connection into Grand Central Terminal. Any time estimates for these facilities are therefore very preliminary (**Table 9.5**).

Pumping Time for NYCT Subway Tunnels

With respect to NYCT subway tunnels, it is convenient to differentiate between land-based sub-grade subway tunnels with elevations prone to flooding in the three scenarios, and those subway tunnels leading to and including river crossings.

The estimated total volume of flood-prone subway tunnel and station volumes *below grade and on land*, assuming unobstructed access of the floodwaters to tunnels at elevations below the respective flood heights, for the three flood scenarios (current sea level, 2-foot rise and 4-foot rise) is shown in **Table 9.6**.[40]

There are currently 14 operating subway tunnel crossings below the following rivers: East River (10), Harlem River (3), and Newtown Creek (1). Some of these tunnels are sunk from above into the excavated river mud, some are driven through hard rock, and some are shield-driven through deep, silty river sediments. The estimated total volume of flood-prone subway tunnels below rivers and their connections to the nearest land stations for the three flood scenarios has been found to be equal to or larger than the flood volume of on-land flooded tunnels. The total water volume to be pumped from the subways after a 100-year storm event is, therefore, estimated to be about 1 billion gallons. This is equal to one day of the entire New York City's average water consumption. The City water supply, however, does not need to be pumped; it is supplied by gravity from reservoirs farther north at higher elevations. However, water has to be pumped to tanks on buildings above 6 stories.

The volumes and lengths of flooded tunnels, whether below ground or rivers, are projected to increase slowly with sea level rise. This indicates that a) whether a tunnel floods depends on whether the lowest critical elevations have been reached by the flood waters (about 7 feet above NAVD 1988, for current system properties); and b) sea level rise increases the annual probability of flooding more than the impact of a given flooding event, once the critical flooding stage is reached.

Tunnel	Pumping time
PATH (Rail) Tunnels and all connected systems in NJ & NY*	5 to 7 days*
Lincoln (Road) Tunnel**	does NOT require pumping**
Holland (Road) Tunnel***	3 to 4 days***
Queens Midtown (Road) Tunnel (QMT)	approx. 16 days****
Brooklyn Battery (Road) Tunnel (BBT)	approx. 3 days
Pumping times for North (Hudson) and East River Tunnels, and connected Penn Station used by Amtrak, NJ TRANSIT and LIRR, were not yet considered for this Report, but need attention based on engineering assessments of floodways and flood gates.	

Note: Some of the listed tunnels (see * through ****) do not flood at all under the Scenarios S1 through S3, and others flood only partially as described above. For the actually used scenario pumping times see Table 9.5, which takes into account the flooding potential for S1 through S3 scenarios, and other factors such as availability of mobile pumps. BFE = base flood elevation.

* Note that the PATH tunnel system in NY and NJ does not flood for the S1 scenario, provided that protective gates installed at some locations in the system are fully effective. Its partial or full flood potential for S2 and/or S3 scenarios is discussed in the text, but has not been confirmed at this time.

** Note that the Lincoln Tunnel does not flood for scenarios S1 through S3, provided emergency operational measures of sealing ventilation shaft doors are fully effective.

*** Note that the Holland Tunnel does not flood for scenarios S1 and S2, provided emergency operational measures of sealing ventilation shaft doors are fully effective. Holland Tunnel may flood, however, under scenario 3 (BFE+4ftSLR); internal pumps would require ~3–4 days pumping. For both, Holland and Lincoln Tunnels mobile pumps are available that can significantly increase pumping capacity when needed.

**** Lower scenario times used for QMT in Table 9.5 in this chapter use calculated hydraulic flood volumes leading to only partial flooding, and use of additional mobile pumps in case of full flooding.

Table 9.4 Estimates of pumping times for fully filled major river-crossing, non-subway tunnels, and assuming use of only internally installed pumps

Modern tunnel pumps have a capacity of at least 1,000 to 1,500 gallons per minute per pump.[41] If four such pumps per tunnel could be mobilized in an emergency situation (working one pump on each of the two tracks, and from either end of the tunnel simultaneously), the pumping capacity would be about 4,000 to 6,000 gallons per minute per tunnel, or 5.8 million to 8.6 million gallons per day per tunnel, with an average of approximately 7.2 million gallons per day per tunnel.

If all 14 tunnels crossing the river were to fill with water, it would take about five days of pumping per tunnel to clear them of water. This assumes that the pumping capacity (on average) is available to pump out the flooded subway tunnels during an emergency situation, and that such pumping will occur in parallel for each of the 14 river crossing tunnels, each with an average volume of about 35 million gallons of water. It is questionable, however, whether pumping all the tunnels

#	Type of Delay	LCE (ft)	Z_i (ft)	1%/y BFE		BFE +2ft		BFE +4ft	
1	Surge Duration, D++			≤1		≤1		≤1	
2	Restore Power, E			≤1		≤1.5		≤2	
3	Logistics Set-Up, L |P>0			≤1		≤2		≤3	
4	Max{D, E, L}			≤1		≤2		≤3	
5	Facility	LCE (ft)	Z_i (ft)	Max{P,A,R}	T90 (days)	Max{P,A,R}	T90 (days)	Max{P,A,R}	T90 (days)
6	Lincoln Tunnel*	22.6*	Z5=9	{0,0,0}	T=1	{0,0,1}	T=1	{0,0,1}	T=2
7	Holland Tunnel*	12.1*	Z5=9	{0,0,0}	T=1	{0,0,1}	T=1	{3,2,6}	T=9
8	Queens-Midtown T.	9.5	Z2=11	{1,1,1}	T=2	{4,2,4}	T=6	{6,2,7}	T=10
9	Brooklyn-Battery T.	7.5	Z1=9	{2,1,2}	T=3	{5,3,6}	T=6	{6,3,7}	T=10
10	PATH System	9.9	Z5=9	{0,1,1}	T=2	{6,3,7}	T=9	{7,3,8}	T=11
11	LIRR/Amtr ERvr 42ndStr T	7.9	Z2=11	{6,3,10}	T=11	{6,3,11}	T=13	{6,3,12}	T=15
12	NJTHudsonTubesPennSt	8.9	Z5=9	{5,3,7}	T=8	{7,3,11}	T=13	{7,3,12}	T=15
13	NJT ARC Tunnel**	11.5	Z5=9	{0,0,0}	T=1	{0,0,0}	T=1	{5,2,7}	T=10
14	LIRR 63rdStrE-River>GCT	11.6	Z2=11	{0,0,0}	T=1	{7,3,11}	T=13	{8,3,10}	T=13
15	to GCT via Steinway T.	9.9	Z2=11	{6,3,10}	T=11	{7,4,11}	T=13	{8,5,12}	T=15
16	NYC Subway System	≥5.9	Z5=9	{7,5,20}	T=21	{8,6,23}	T=25	{9,7,26}	T=29
17	MNR Hudson Line along Harlem River (SpuytenDvl.Stn.)	6.6	Z4=8	{0,2,3}	T=4	{0,3,6}	T=8	{0,4,9}	T=12
	Bridge Access Ramps+ to								
18	MarineParkw-Rockaway	6.9	Z8=9	{0,0,0}	T=1	{0,1,1}	T=2	{0,1,2}	T=4
19	CrossBayBrdChnlRockaw.	6.9	Z8=9	{0,0,0}	T=1	{0,1,1}	T=2	{0,1,2}	T=4
20	ThrogsNeck	8.9	Z1=14	{0,0,0}	T=1	{0,1,1}	T=2	{0,1,2}	T=4
21	BronxWhitestone	10.9	Z1-2=12.5	{0,0,0}	T=1	{0,1,1}	T=2	{0,1,2}	T=4
22	RFK (Triboro)	13.9	Z3-2=10	{0,0,0}	T=1	{0,0,0}	T=1	{0,1,1}	T=2
23	Verrazano-Narrows	7.6	Z5=9	{0,0,0}	T=1	{0,1,0}	T=2	{0,1,0}	T=2
	Airports:								
24	JFK	10.6	Z7=8	{0,0,0}	T=1	{0,1,1}	T=2	{1,3,4}	T=6
25	LaGuardia*	10.0*	Z2=11	{2,2,3}	T=3	{3,2,4}	T=4	{3,2,6}	T=8
26	Newark	9.2	Z5a=8	{0,0,0}	T=1	{0,1,2}	T=3	{0,2,3}	T=5
27	Teterboro	3.9	Z5a≤8	{0,1,1}	T=2	{0,2,2}	T=3	{0,2,3}	T=5
28	Marine Ports:			Information currently not available					
29				Scenario 1		Scenario 2		Scenario 3	
30	T90 (days)			1 to 21		1 to 25		2 to 29	

Note: BFE and Zi = average and area-weighted base flood elevation (see Table 9.13); LCE = lowest critical elevation; D = surge duration; E = electric grid restoration time; L = logistic set-up time; P = pumping time; A = damage assessment time; R = repair time.
Flood color code: Red, Orange, Green: when Zi > LCE, for Scenario 1, 2, and 3, respectively. Dark grey: No Flooding (i.e. LCE > Zi)
* Except emergency-operational measures for Holland, Lincoln, and some PATH tunnels and LaGuardia airport (levees)
** Assumes that passenger connection (LCE=9.65 feet) between existing Penn Station (LCE=8.9 feet, Z5=9 feet) and the New Penn Station Extension will be gated.
\+ Assuming that bridges will be open to the public without toll collection, as some toll booths and/or EZ Pass equipment may be undergoing assessments and repairs.
++The duration during which the storm surge exceeds the LCE of any given structure varies between structures. For the 100-year storm these variations range from minutes to a few hours. Depending on this duration and the area of openings of the structure, it fills either partially or entirely.

Table 9.5 Estimates of number of days contributing to T90, the time needed to restore a transportation system to ~ 90% functionality, without adaptation measures except as noted

at the same time is logistically possible. Therefore, five days is the minimum amount of time it would take under a best-case scenario; one week per tunnel is, perhaps, more realistic. The river subway tunnel operations alone would require 56 powered mobile pumps (four in each of the 14 tunnels) (see subsequent sections in this case study).

Assuming that the land-based tunnels can be pumped out more or less during the same time as the generally deeper river-crossing tunnels, the operation may need something in the order of 100 such pumps if pumping is to be achieved within one week. A smaller number of pumps, or not pumping all tunnels simultaneously, would lengthen the pumping time required.[42]

Rigorous, engineering-based assessments, combined with logistic management plans of how to procure such pumping capacity simultaneously, are urgently needed that can determine more precise estimates of the pumping system needs for New York City metropolitan-area tunnels.

The environmental impacts on the waters in the New York Harbor estuary from the simultaneous pumping activities could be significant and would be in addition to those from the debris and spills from surface sources, including toxic sites that were reached by the floodwaters. It is assumed that environmental emergency permits for disposing of the pumped tunnel waters are pre-event approved and would require no extra processing times. If pre-event approved permits do not exist, then additional delays may need to be assumed.

Such a storm as analyzed in the ClimAID assessment not only damages flooded tunnels, but also affects external support systems (power, communication, logistic preparations) needed for the pumping operations, subsequent inspection of damage in the tunnels, and to make the necessary repairs. The total

Scenario	Flooded Tunnel Volume	Flooded Tunnel Length
S1 1%/y BFE*	400 million gallons	60,000 ft
S2 +2ft SLR	408 million gallons	60,600 ft
S3 +4ft SLR	411 million gallons	61,000 ft

* BFE = base flood elevation
  Note: Flooded tunnel volume and flooded tunnel length for each of the S1, S2, and S3 sea level scenarios.

Table 9.6 Estimated total volume of flood-prone subway tunnels

projected outage times for transportation systems are summarized in **Table 9.5**.

The estimates of recovery times given in **Table 9.5** remain highly uncertain and may change substantially when the necessary engineering vulnerability and risk assessments of complex systems are performed in sufficient detail and when the emergency response capability of transportation operators can be quantified. Such assessments may take years for some of the more complex and older transportation systems, where the as-built or current state of repair information is not always readily available. Each operating agency will need to make these assessments in years to come before a more realistic picture will emerge for the expected damage and costs to the operating agencies and of the economic impact to the public (see Section 9.5.7).

For instance, there are likely to be other significant restraints on the ability of the NYCT subway system to recover from flooding that have not been incorporated into this analysis. Even if emergency pumping can be implemented, the impact of salt, brackish, and/or turbid water will last long after the water itself is removed. Deposits will need to be cleaned from signal equipment and controls, which may need to be replaced either in total or by component, and only very limited service could be provided after pumping is completed until signals are restored. Much of the equipment in the subways is of a specialized nature that requires orders from manufacturers with long lead times, especially for significant quantities. There probably are not enough personnel trained to rebuild and refurbish equipment simultaneously in multiple subway lines even if the equipment could be procured. There is some existing equipment that, if damaged, cannot be replaced because it is obsolete and is no longer manufactured, nor are there replacement parts for it. Such equipment would have to be redesigned and then installed—a process that can take a long time.

Finally, if significant soil movement or washouts occur, it is likely that structures throughout the system may experience some settlement, and there could be structural failure of stairs, vent bays, columns, etc.

Together, such conditions could easily extend the time it takes to restore to a 90-percent functionality of the subway system (**Table 9.5**) by three to six months (and perhaps longer). It is estimated that permanent restoration of the system to the full revenue service

that was previously available could take more than two years.

In general, adaptation options (see sections 9.4, 9.6.2, and subsequent sections of this case study) will need to be carefully evaluated to arrive at a better understanding of the resources that will be needed to make the coastal and estuarine New York State transportation systems resilient to all types of climate change impacts, and to sea level rise in particular.

Methods for Calculating Restoration Time to 90 Percent of Functionality (T90, measured in days)

Table 9.5 represents ClimAID's best effort to combine stakeholder-provided information and publicly available data into outage/restoration time estimates. It is the basis for the case study, and contains key information, in compact numeric form.

The restoration time T90, after which a transportation system regains 90 percent of its pre-storm functional capacity, is computed for various transport systems as follows (see red numbers in columns 4, 5, and 6 in **Table 9.5**):

Equation 2. T90 (days) = Max{D, E, L|P>0} + Max{P, A, R} ≥ 1

All units are in days. The operator $Max\{x_1, x_2, x_3\}$ chooses the largest value of the values xi , where **D** is the surge duration; **E** is the electric grid restoration time; **L** is logistic set-up time (note that L|P>0 means that L is only counted when there is a finite pumping time P>0; otherwise L=0 since there is no logistic set-up time when pumping is not needed); **P** is pumping time; **A** is damage assessment time; and **R** is repair time. The maximum (largest value) rather than the sum of **D, E, L** is chosen since it is assumed that these times run largely in parallel, rather than being additive, although this choice may lead to underestimation of outage times from these causes.

A similar parallel set of activities is assumed between **P, A**, and **R**, although that may be even more optimistic. A minimum of T90≥1day is imposed on all facilities, assuming that even if all six variables were close to zero, the public would avoid using transport for general economic activity (businesses may be closed) on the day of the storm, and mass transit would largely be reserved for emergency evacuation according to NYC's

emergency plans. For road tunnels the time for accessibility by emergency and essential traffic (repair crews, utilities, etc.) may be shorter than those shown, which are meant to indicate when the facility becomes operational for the general public. In **Table 9.5**, rows 1–4 address the first term, and rows 5–27 the second term of equation 2.

There are large uncertainties with each of these variables, and also for the functional relationships between them. It is possible to devise alternatives to equation 2. **D** is in most cases less than one day, but a stalled nor'easter storm could extend **D** from one to a few tidal cycles (roughly 12 hours apart) to as much as a few days. **E**, electricity restoration time, has been discussed in conjunction with **Figure 9.20**, but could range, for transportation priority customers, between zero and perhaps two days; for certain functions, it can be shortened by the availability of emergency generators. **L** is essentially the time to bring the pumps into place, ready for operation; with proper pre-storm planning it could be almost zero; if no preparations at all have been made, it may easily take a week to get so many pumps from across the nation to New York, especially if adjacent coastal communities have similar demands. **P** and **A** have been discussed above, and **R**, repair time, is highly uncertain and system-specific.

If, for instance in the case of subways, repairs need to be performed on existing relay, signal, and switching gear of older vintage (such as electric controls, pumps, and ventilation systems, which may need to be disassembled, cleaned, dried, reassembled, installed, and operationally tested because replacement by new spares are not an option), **R** may contribute the largest term and associated uncertainty in equation 2. For a new transport system, or a much simpler road tunnel, the **R** time may be shorter than, or comparable to **P**.

All numbers in column 3 are elevations in feet. All numbers in columns 4–6 are time estimates in days. Rows 1–4 are region-wide, generic (not structure-specific) estimations of days, i.e., **D, E, L** contributing to the service outage (except L is coupled to a facility by the operator |>P to whether pumping is needed, P>0; or is not needed (P=0) at any facility listed in Rows 5–27; the |>P operator determines whether L is accounted for when selecting Max{**D,E,L**}. The parentheses {**P,A,R**} in columns 4–6, rows 5–27, contain the days assigned to the delays caused by pumping P, assessing damage A, and repairs R,

respectively. The maximum value of the triplet {**P,A,R**} is then added, for each scenario, to the resulting Max{**D,E,L**|P>0} listed in row 4 (for each scenario, columns 3–5; note that the upper bound is listed; for less complicated transport systems lesser values were chosen). This sum is then entered as the bold number T=... in columns 3–5, rows 5–27. This value T constitutes the estimated T90 (days) for each facility and storm surge/sea level rise scenario. Row 30, columns 3–5 list the range of T90 values obtained. These are assigned to T90min and T90max, respectively, as used for economic estimates in this chapter's case study, Appendix C, and Equation 4 therein.

The color code (see **Table 9.5**, footnote) indicates for which coastal storm surge scenario the respective facility becomes flooded (i.e., red for LCE$\leq Z_i$, orange for LCE$\leq Z_i$+2 feet, green LCE$\leq Z_i$+4 feet); or never becomes flooded (dark grey, LCE>Z_i+4 feet) for the modeled 100-year storms and sea level rise assumptions. The color scheme signals how readily a system/facility floods, from red as most vulnerable to grey as quite safe with orange and green in between.

Table 9.5 displays the results assuming no adaptation or protective measures are undertaken other than those indicated.

In specific cases, adaptation measures can drastically reduce the vulnerability of the systems and facilities. As such, the outage time and resulting economic impact, including fare/toll revenue losses to a system's operator, can be greatly reduced by taking preventative measures. Such protective measures also would avoid some of the damage and limit repair costs.

Economic Impact of the Vulnerability of New York City's Transportation Systems to Sea Level Rise and Coastal Storm Surges: Case Study Results vs. Losses from Hurricane Katrina

The social and economic impacts of a coastal storm with storm-surge flooding can be significant and in some instances long lasting. This has been vividly demonstrated by the extreme case of the effects of Hurricane Katrina on New Orleans in 2005, which cost in excess of $100 billion in losses, social disruptions, and displacements.

However, there are many differences between this ClimAID 100-year storm case study for the New York City metropolitan area and Hurricane Katrina in New Orleans. Portions of New Orleans are as much as 8 feet permanently below the average current sea level. So, once the levees were breached during Katrina, quasi-permanent flooding prevailed. Virtually all of the New York metropolitan area is above, albeit close to, sea level, with the important exception of some underground portions of the transportation and other infrastructure and of some excavated basement structures. Once the lowest critical elevations and/or the pumping capacities are exceeded by the floodwaters, then the physical circumstances simulate those of any inundated below-sea-level community.

Another difference is that Katrina was a hurricane of Saffir-Simpson category 3. As pointed out earlier, the 100-year storm used in this case study is closer to a non-direct but nearby hit of a hurricane of category 1 to 2.

On the other hand, the asset concentration in the New York City metropolitan region (some outside of New York State) is approaching $3 trillion—much larger than that of New Orleans. About half the assets are in buildings and half in infrastructure of all types. The metropolitan region's gross regional product is in excess of $1.466 trillion per year,[43] corresponding to a daily gross metropolitan product (DGMP) of nearly $4 billion per day.[44]

To assess the economic impact of such a storm on New York City, the ClimAID assessment made a number of assumptions. For example, after such an extreme event it is assumed that electricity and the economy come back not suddenly but gradually. The cost of a storm event depends on how quickly the economic activity can be restored. The analysis considers a range of how long this might take under current conditions and the two sea level scenarios, from a minimum restoration time to a maximum. The cost of a storm event must also consider the physical damage to the infrastructure. (For a complete list of assumptions and how the analysis was conducted, see Appendix C).

The procedure, described in Appendix C, yields a "time-integrated economic loss for the entire metropolitan" region (TIELEM), in dollars. Based on this analysis, the economic losses, due to failure of infrastructure systems in the entire New York City metropolitan region, range from $48 billion (current sea

level) to $57 billion (2-foot rise) to $68 billon (4-foot rise). Economic recovery times would range from 1 to 29 days (**Table 9.5**). The results of this economic loss analysis are summarized in **Table 9.7**.

To these time-integrated economic losses (TIELEM), one must add the cost of the direct physical damages resulting from the storm. Then the total costs become even greater (**Table 9.5**). Physical damages alone are valued from $10 billion (current sea level scenario) to $13 billion (2-foot rise) to $16 billion (4-foot rise). For details on how the physical damage losses were derived, see Appendix C. Total losses, including both economic activity and physical damages, range from $58 billion (current), to $70 billion (2-foot rise), to $84 billion (4-foot rise)(**Table 9.8**).

Within these estimates there may be unaccounted for numerous other significant constraints on the ability of the transportation systems to recover from climate change-induced incidents. Such constraints include the age of equipment, the availability of replacement parts/equipment, and the need for these in appropriate quantities. These and other currently unknown and/or not-quantified factors could significantly increase climate change impacts in time, labor, and dollars.

Scenario	T90min (days)	T90max (days)	TIELEM ($Billion)
S1 (current sea level)	1	21	48
S2 (2-foot rise in sea level)	1	25	57
S3 (4-foot rise in sea level)	2	29	68

Note: T90min is the minimum amount of time (number of days) needed for the transportation system to regain 90 percent of its pre-storm functional capacity. T90max is maximum amount of time (number of days) needed for the transportation system to regain 90 percent of its pre-storm functional capacity. TIELEM is the time-integrated economic loss for the entire metropolitan region. 2010 assets and 2010-dollar valuation

Table 9.7 Economic losses for the New York City metropolitan region due to current 1/100 year coastal storms and future 1/100 year storms with 2 and 4 feet sea level rise

Scenario	Combined Economic ($ billion)	Physical Damage ($ billion)	Total Loss ($ billion)
S1 (current sea level)	48	10	$58
S2 (2-foot rise in sea level)	57	13	$70
S3 (4-foot rise in sea level)	68	16	$84

Note: 2010 assets and 2010-dollar valuation

Table 9.8 Combined economic and physical damage losses for the New York City metropolitan region for a 100-year storm surge under current conditions and two sea level rise scenarios

The losses summarized in **Table 9.8** do not include any monetary value for any lives lost. There are several reasons for excluding them: 1) it is very difficult to forecast loss of lives since such losses depend on the quality of storm forecasts, emergency planning, warnings, and readiness of the population to follow evacuation instructions and other behavior; 2) given that the New York City Office of Emergency Management and emergency services in the nearby counties in coordination with the New York State Emergency Management Office have extensive coastal storm evacuation plans in place, the loss of lives should be modest; and 3) it is difficult to assess the value of a human life.

The economic losses of Hurricane Katrina on New Orleans illustrate the significant economic impacts a coastal storm and associated storm surge can have. The economic impacts from the storm surge and sea level rise scenarios analyzed in this case study for the New York City area would be comparable with significant impacts and losses to transportation infrastructure.

Vulnerability and Social Equity

The social and economic effects of a 100-year storm would not be distributed evenly. Certain regions would be more likely to cope and recover quickly, while other regions might suffer to a greater degree and over a longer period of time. In general, underlying differences in patterns of poverty, income, levels of housing ownership, and demographics can give some indication of the resilience of an area. These effects are explored in more detail in the Chapter 5, "Coastal Zones", case study. This section builds upon that analysis by delving more deeply into the role of transportation access in mediating the effects of a storm along New York City and Long Island, both in the evacuation prior to landfall and during the resulting stages of relief and recovery.

This analysis illustrates existing transport disadvantages and the types of vulnerabilities that could be experienced with a storm event of this magnitude. It is important to note that, compared to other cities across the country, New York City has addressed these issues extensively as part of comprehensive evacuation plans. The New York City Office of Emergency Management and the MTA have incorporated income statistics and private-vehicle access into estimates of people who would need evacuation. Public information on the

evacuation plans has been distributed in 11 different languages (Milligan, 2007).

Nevertheless, evacuation planning in the New York metropolitan region is very much a work in progress as it relates to transport-disadvantaged and special-needs populations (TRB, 2008b). To some degree, this is a result of intrinsic difficulties in managing an urban area as complicated as the New York metropolitan area, with three states and numerous agencies. While the Department of Homeland Security has been forthcoming with emergency planning funds, it has been less so for funding regional evacuation plans. These efforts are evolving slowly (TRB, 2008b).

Fully addressing transport disadvantage is also hampered by the structure of existing service delivery and the nature of the evacuation plans. The New York City Office of Emergency Management has conducted basic mapping of special-needs populations and made this information publicly available, but it does not have a complete picture of the location or needs of these populations and the resources available to them (TRB, 2008b). Furthermore, strategies that have worked well in places like Tampa, Florida, such as a special-needs registry, have not been attempted in New York City, largely because of the size and complexity of the city. The dominant strategy, therefore, is communicating preparedness through social networks, community groups, and community emergency-response teams, an approach that will not reach the many special-needs individuals who are isolated from consistent outreach services (Renne et al., 2009). As a last-resort option for those unable to arrange their own transport, the city offers "311" emergency services that would link individuals with the city's paratransport vehicles or, in critical situations, with fire and police. Still, there are lingering concerns that the paratransport fleet may be too small during any large evacuation (Renne et al., 2009) and that private-sector drivers might not report to work (TRB, 2008b). Further complicating the approach, there may be a conflict of priorities as public services (e.g., emergency personnel, buses) could be pulled away from the epicenter of evacuation to serve piecemeal needs.

The following section describes the broad climate change impacts, transport disadvantages, and transport resiliencies that extend along the coast of New York City and Long Island. Based on estimates generated for the ClimAID case study (and for current sea level), 90-percent-recovery times for specific parts of the New York City metropolitan transport system would vary from a few days to almost a month. This range in recovery would condition the relative regional severity of indirect economic impacts of a coastal storm surge. Those populations and areas dependent on less-resilient parts of the transport system would more likely suffer extended periods of lost wages and curtailed commercial operations. Some of those hardest hit by systemic failures would likely include populations dependent on the New York subway and those commuting to Manhattan by rail from New Jersey (via NJ TRANSIT) and Long Island (via LIRR), and the commuters of the northern suburbs relying on Metro-North Railroad (MNR).

In general, populations and regions with diverse and redundant transport options would more easily cope and recover from transport systems failure. Further hardship would confront transport-disadvantaged populations and regions, including communities constrained by geography to limited transport options, low-income households dependent on public transport, and individuals with limited mobility.

A recent study of environmental inequalities in Tampa Bay, Florida, suggests three census variables as proxies for transport disadvantage: households with no car, households with disabled residents, and households with residents 65 years or older (Chakraborty, 2009). The ClimAID analysis examines the distribution of these variables across the 100-year floodplain of New York City and Long Island to evaluate vulnerabilities and equity effects in the case of a 100-year storm. **Table 9.9** presents a regional comparison of these indicators.

|	In Floodplain	Out of Floodplain
New York Coastal Zone		
% older than 65	14.3	11.9
% physically disabled, age 16-64	5.2	5.9
% households without a car	16.3	10.1
New York City		
% older than 65	13.1	11.1
% physically disabled, age 16-64	6.8	6.7
% households without a car	20.8	23.2
Long Island		
% older than 65	15.2	13.6
% physically disabled, age 16-64	4.1	4.4
% households without a car	2.4	2.1

Source U.S. Census 2000; authors' calculations

Table 9.9 Characteristics of transport-disadvantaged populations living in census block groups: New York Coastal Zone and the case study area

	In Floodplain	Out of Floodplain
New York Coastal Zone		
total workers using public transport	63,819	1,764250
total workers using public transport – bus	14,989	372,028
New York City		
total workers using public transport	48,943	1,635,907
total workers using public transport – bus	13,473	350,935
Long Island		
total workers using public transport	14,875	128,344
total workers using public transport – bus	1,515	21,094

Source U.S. Census 2000; authors' calculations

Table 9.10 Total workers living in New York Coastal Zone and using public transport as primary means of getting to work

	In Floodplain	Out of Floodplain
New York Coastal Zone		
% workers using public transport	27.8	42.1
% workers using public transport - bus	6.4	8.9
New York City		
% workers using public transport	44.9	52.7
% workers using public transport - bus	11.8	11.5
Long Island		
% workers using public transport	11.8	11.7
% workers using public transport - bus	1.3	1.8

Source U.S. Census 2000; authors' calculations

Table 9.11 Characteristics of transport-disadvantaged populations living in census block groups: New York Coastal Zone

Mirroring the statewide disparity in vehicle ownership between urban and rural areas, car access in ClimAID Region 4 (Chapter 1, "Climate Risks") heavily favors suburban areas of Long Island (**Figure 9.21**). In the urban centers of New York, rates of households with no car are nearly double those for the state as whole, a fact that would condition evacuation before and during a storm. Lower rates of car ownership partly reflect better access to public transportation (such as the New York subway and other trains). On average, working residents in floodplains in New York City are four times more likely than those on Long Island to use public transportation as their primary means of commuting.

In total, nearly 50,000 people live in the floodplain in New York City (**Tables 9.10** and **9.11**).

Evacuation from Long Island, on the other hand, would benefit from the flexibility offered by high vehicle access, but over-reliance could trigger potential delays and disruption from the clogging of highway systems. Despite a more equitable attempt at evacuation for Hurricane Rita following Hurricane Katrina later in 2005, the over-reliance on evacuation by car created a 100-mile long traffic jam, which generated its own vulnerabilities (Litman, 2005). The most critically vulnerable car-dependent populations include those with limited vehicle exit routes for evacuation, such as some populations along choke points in Suffolk County or those in Manhattan who depend on tunnel or bridge access to leave the city.
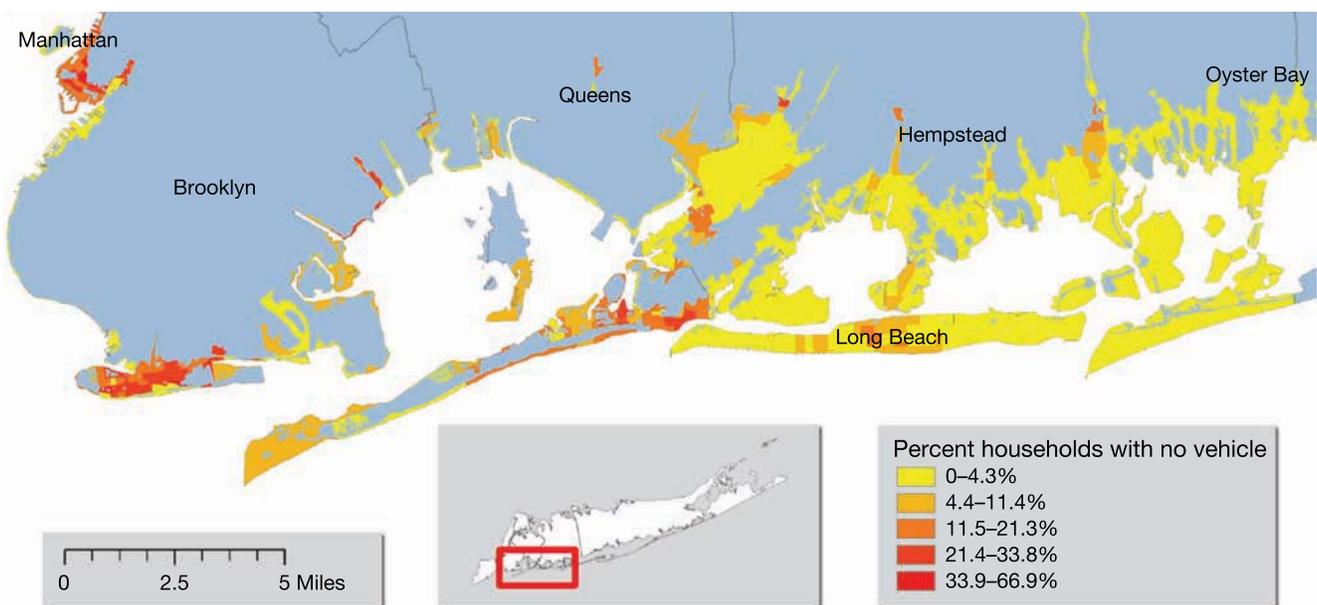
Source: US Census Data 2000, FEMA FIRM base map, with authors' computations and GIS graphics

Figure 9.21 Variations in access to a vehicle within the 100-year floodplain

Across census block groups, the percentage of people with access to a car ranges from less than 5 percent to more than 60 percent. Despite generally high rates of car ownership on Long Island, small pockets of low ownership are interspersed largely within Nassau County. A look at the demographic and socioeconomic makeup of a few of these census block groups underscores that car ownership is partly a function of underlying socioeconomic conditions. For example, a few such areas in Hempstead also have higher rates of poverty and lower average educational attainment compared to regional means. These conditions would act together as a group of stresses during a storm event, reinforcing the vulnerability of a person with no car. Put simply, not having vehicle access is a problem for anyone when it is time to prepare for a storm or evacuate, but if that person is elderly with existing mobility challenges or is living below the poverty line as a single mother with two children, then having no car can have a multiplier effect.

The mapping analysis builds on the basic methods used by New York City and Long Island transportation agencies as part of their compliance with requirements set out by Federal Executive Order 12898 on Environmental Justice. For example, the New York Metropolitan Transportation Council identifies the communities in **Table 9.12** as "communities of concern" on Long Island based on socioeconomic and racial status.

Social Justice and Adaptation

Securing transport systems for regional connectivity and mass commuter patterns are critical foci of hazards and adaptation planning. At the same time, successfully integrating equity into system-wide adaptations will require taking seriously the wide range of transport capacities mentioned in the previous section, including constraints on physical mobility, limited access to transportation options, and localized transport dependencies.

A frequently considered short-term adaptation is the selective "hardening" (i.e., protective measures such as buildings seawalls, raising road beds, and improving drainage) of transport infrastructure, but an important question remains: Hardening for whom? Will certain populations and regions benefit from secured commuting and mobility while others do not? For example, in and around New York City, populations reliant on specific local bus routes for commuting—often lower income—may be at a relative disadvantage
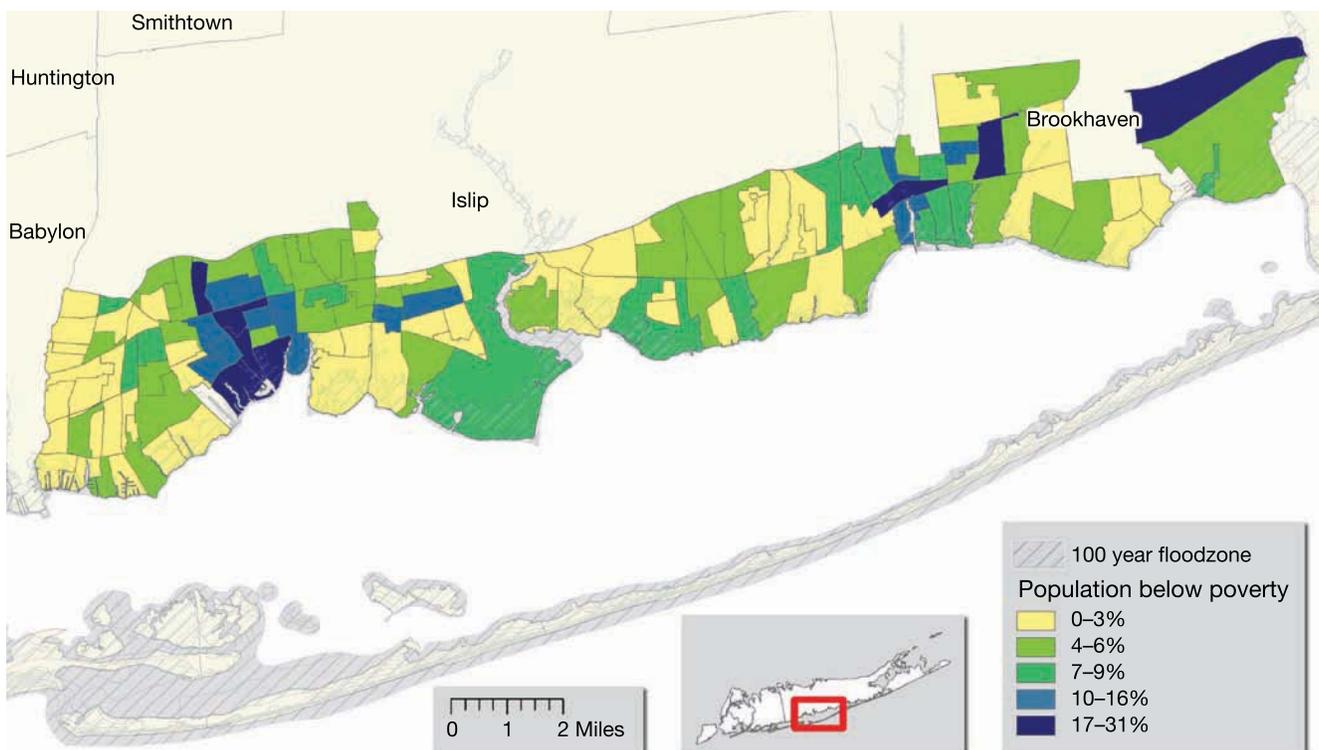
Source: US Census Data 2000, FEMA FIRM, and authors' computations and GIS graphics

Figure 9.22 Clustered poverty along the Long Island coast (Great South Bay)

Nassau County		Suffolk County	
Town	Village/Hamlet	Town	Village/Hamlet
Glen Cove	Glen Cove	Huntington	Huntington Station
Hempstead	East Garden City		Wyandanch
	Uniondale		Wheatley Heights
	Hempstead		N. Amityville
	Roosevelt		Copiague
	Freeport	Islip	Brentwood
	Elmont		Central Islip
	Inwood		Oakdale
	N. Valley Stream	Islip/Brookhaven	Holbrook
	Valley Stream		Holtsville
North Hempstead	New Cassel	Brookhaven	Patchogue
	Westbury		Stony Brook
Oyster Bay	East Massapequa		Centereach
			Selden
			Coram
			Middle Island

Source: NYMTC 2007

Table 9.12 Environmental justice communities of concern on Long Island

if hardening infrastructure is aimed at the short-term protection of arterial commuter rail lines and regional business connectivity to Manhattan. In New York City, bus commuters constitute 11.8 percent of the population in the floodplain (**Table 9.11**), many of whom are commuting within boroughs. On the other hand, bus systems are less vulnerable to storm surge flooding, since they generally can resume their function shortly after the floods retreat. Fixed rail lines, and especially those depending on tunnels, may require much longer recovery times after a storm as described in this case study.

A longer-term adaptation strategy is managed retreat, consisting of coastal buyout and relocations. Low-income regions and populations could be particularly sensitive to indirect effects of such interventions. For example, a protracted program could incrementally change land use and regional perception in ways that devalue communities prior to buyouts. There is also a risk that social support and monetary compensation are inadequate for successfully moving and reintegrating migrants. As **Figure 9.22** suggests, wealth and poverty tend to cluster in localized areas along the coast of Long Island and New York City. This uneven distribution would condition the response and sensitivity of different communities to a buyout program. Transport-specific issues include the exacerbation of spatial mismatches between jobs and housing centers as migrants put new pressures on local

job and housing markets. This is a recurring challenge for planners on Long Island, where New York City's gravitational pull on the transport system exacerbates a mobility gap for those trying to commute north to south across the island rather than east to west (see, for example, http://www.longislandindex.org/).

Coastal Storm Surge Adaptation Options, Strategies, and Policy Implications

Options and time scales for adaptation measures vary over the short, medium, and long terms:

1) *Short-term Measures (over the next 5 to 20 years)*
   - Short-term measures (individual floodgates, berms, local levees, pumps, etc.) can be effective for a few decades for high-to-moderate probability events, i.e., surges with annual probabilities with low-to-moderate recurrence periods of 100 years or less (storms up to or weaker than the 100-year storm). These "concrete and steel" or "hard" engineering measures may be preceded by or combined with interim measures that improve a system's operational resiliency (e.g., those mentioned for the Lincoln and Holland Tunnel ventilation shaft doors, see footnotes to **Table 9.5** and **Table 9.4**). MTA NYCT is currently undertaking one such short-term measure by raising floodwalls at its 148th Street Yard along the Harlem River. This measure avoids the repeat of flooding already experienced in the past.

2) *Medium-term Engineering Hard Measures (over the next 30 to 100 years)*
   - System or site-specific (i.e., each station, rail track segment, substation, etc.) measures are needed to protect each site individually, such as by raising some structures or track segments.
   - Region-wide protective measures, such as constructing estuary-wide storm barriers, have been proposed (Aerts et al., 2009). These have been discussed in NPCC 2010.

3) *Long-term Sustainable Strategies (any time from now to beyond 100 years)*
   - Long-term measures include changing land use and providing more retreat options. These measures can be combined with the short- and

medium-term strategies indicated above. When sea level rise combined with coastal storm surges exceeds the design elevations of barriers and levees, these long-term strategies require comprehensive, sustainable plans that include time-dependent decision paths and "exit strategies."

To determine the optimal climate change adaptation for the transportation system in the coastal zone of New York State with the highest benefit-cost ratios, the time-dependent assessments listed below for current and projected future conditions need to be performed. Depending on the structure or system, these assessments may need to be projected out 100 or 150 years:

• Make probabilistic time- and sea level rise-dependent coastal storm surge hazard projections on a regular basis.
• Conduct a vulnerability assessment of transportation infrastructure systems given the hazard projections.
• Develop time-dependent transportation infrastructure asset-value estimation methodology and databases.
• Combine the above three items into regular time-dependent risk (loss) assessments.
• Assess costs and benefits of various adaptation options as a function of time.
• Conduct policy and finance assessments.
• Develop decision making and implementation strategies based on all of the items above.

Case Study Knowledge Gaps

The following major knowledge gaps for the transportation sector of the New York State Coastal Zone have been identified from the case study:

• High-resolution digital elevation models for terrains with infrastructure
• The as-built infrastructure elevations, geometry and volumes of the above- and below-grade structures, openings, hydrodynamics, flow rates, filling times
• Vulnerabilities (fragility curves) for coastal storm surge hazards for items listed in the prior bullet, especially when saltwater comes in contact with sensitive equipment

• Realistic estimation techniques for outage times, costs, and reduced losses versus benefits from adaptation measures
• Better economic models for the relationship of transport system outage to over-all economic losses
• Institutional and policy issues related to: How to foster strategic long-term planning at agencies? What is the legal/regulatory framework, and how can professional codes (engineering codes, FEMA's National Flood Insurance Program regulations, enforcement, etc.) be updated to take projected sea level rise and increased coastal storm damage into account ?

Case Study Conclusions

This detailed case study of 100-year coastal storm surges for current sea level and two sea level rise scenarios has provided insights into the technical, economic, and social consequences of climate change. They demonstrate, by example, the potential severity of climate change impacts on the state's transportation sector. Timing of adaptation paths, institutional transformations needed to embed adaptation measures into decision making, and allocation of funding present serious challenges. There is a broad range of policy options and measures that can be implemented to avoid future climate-related losses and to provide the state with a sustainable, climate-resilient transportation system.

Hazards, risks, and potential future losses from climate change—and especially sea level rise—to the region's transportation systems and general economy are increasing steadily. Costs, when annualized, may amount initially to an average of only about $1 billion per year over the next decade. By the end of the century, these costs will probably rise to tens of billions of dollars per year, on average. Note that these are long-term annualized averages. Individual storms may cost much more, as described above in the ClimAID scenario analysis.

Benefits versus Costs

Several thorough studies have shown, based on empirical data from the last 30 years, that there is an approximate 4-to-1 benefit-to-cost ratio of investing in protective measures to keep losses from disasters low

(MMC, 2005; CBO, 2007; GAO, 2007). If the 4-to-1 benefit-cost ratio for protective and other mitigation actions applies, then up to one-quarter of the expected annual losses should be invested every year. This approach provides rough guidance for the needed investments towards protective measures that can be considered cost-beneficial, if based on sound engineering and planning.

Based on the loss estimates given in **Table 9.8** for the 100-year storm,[45] this implies that hundreds of million dollars per year initially may be needed for protective adaptation measures, rising to billions per year at latest by mid-century. Such investment be needed by mid-century because of the long lead-times for infrastructure projects, and to ensure that adequate protections are in place before the end of century. Institutions must plan for the long term, sometimes as much as one to two centuries into the future, for instance when considering right-of-way and land-use decisions, especially in coastal areas. Such major climate change adaptation measures need to be integrated into the overall infrastructure upgrade and rejuvenation projects during the coming decades.

It is important to act before systems become inundated and damaged beyond easy repair.

Long-term Sea Level Rise

Decision-makers need to engage with scientists to monitor the Greenland Icesheet and the West Antarctic Ice Shield, which have the potential to contribute multiple feet to sea level rise this century. These impacts may need to be considered even when planning short- or medium-term adaptation strategies, in order to ensure their long-term sustainability.

In Europe, researchers have analyzed what to do under a scenario in which sea level rose by about 15 feet over the course of one century. The desktop exercise, named *Atlantis* (Tol et al., 2005), has been performed for three regions in Europe. The study areas included the Thames Estuary/London, the Rhine Delta/Netherlands/Rotterdam, and the Rhone Delta/South France. While the hypothetical scenario has a low probability, its high consequences put the larger societal issues into perspective for what, in reality, may turn out to be incremental solutions that are socially acceptable.

Indicators and Monitoring

The establishment of a climate indicators and monitoring network will enable the tracking of climate change science and impacts. Recording the changes in the physical climate (sea level rise), climate change impacts (flood events), and adaptation actions can provide critical information to decision-makers (Jacob et al., 2010).

References

Aerts, J., D.C. Major, M.J. Bowman, P. Dircke, and M.A. Marfai. 2009. Connecting Delta Cities. Coastal Cities, Flood Risk Management and Adaptation to Climate Change. VU University Press.

Bowman, M.J., B. Colle, R. Flood, D. Hill, R.E. Wilson, F. Buonaiuto, P. Cheng and Y. Zheng. 2005. "Hydrologic Feasibility of Storm Surge Barriers to Protect the Metropolitan New York - New Jersey Region, Final Report. Marine Sciences Research Center Technical Report." New York: Stony Brook University, March 2005.http://stormy.msrc.sunysb.edu/phase1/Phase%20I%20final%20Report%20Main%20Text.pdf

Bowman, M.J., D. Hill, F. Buonaiuto, B. Colle, R. Flood, R. Wilson, R. Hunter and J. Wang. 2008. "Threats and Responses Associated with Rapid Climate Change in Metropolitan New York." In *Sudden and Disruptive Climate Change*, edited by M. MacCracken, F. Moore and J.C. Topping, 327. London: Earthscan.

Bullard, R.D., ed. 2007. *Growing Smarter: Achieving Livable Communities, Environmental Justice, and Regional Equity*. Cambridge, MA: MIT Press.

Byron, J. 2008. "Bus Rapid Transit for New York?" *Gotham Gazette*, April 21. http://www.gothamgazette.com/article/sustain/20080421/210/2498

Chakraborty, J. 2009. "Automobiles, Air Toxics, and Adverse Health Risks: Environmental Inequities in Tampa Bay, Florida." *Annals of the Association of American Geographers* 99(4): 674-697.

Chen, D. 2007. "Linking Transportation Equity and Environmental Justice with Smart Growth." In *Growing Smarter: Achieving Livable Communities, Environmental Justice, and Regional Equity*, edited by R.D. Bullard. Cambridge, MA: MIT Press.

City of New York. 2011. PlaNYC: A green, greater New York. Update April 2011. Office of the Mayor, http://www.nyc.gov/html/planyc2030/

Colle, B.A., F. Buonaiuto, M.J. Bowman, R.E. Wilson, R. Flood, R. Hunter, A. Mintz and D. Hill. 2008. "New York City's Vulnerability to Coastal Flooding: Storm Surge Modeling of Past Cyclones." *Bulletin of the American Meteorological Society* 89(6):829-841.

DeGaetano, A.T. 2000. "Climatic perspective and impacts of the 1998 northern New York and New England ice storm." *Bulletin of the American Meteorological Society* 81:237–254.

Freed, A. 2009. New York City Office of Long-Term Planning and Sustainability, personal communication.

Godschalk, D.R., T. Beatley, P. Berke, D.J. Brower and E.J. Kaiser. 1999. *Natural hazard mitigation*. Washington D.C.: Island Press.

Hansen, J.E. 2007. "Scientific reticence and sea level rise." *Open Access E-Prints in Physics, Mathematics, Computer Science, Quantitative Biology and Statistics*, Cornell University. http://arxiv.org/pdf/physics/0703220v1.

Hess, D.B. and J.C. Gotham 2007. "Multi-Modal Mass Evacuation in Upstate New York: A Review of Disaster Plans." *Journal of Homeland Security and Emergency Management* 4(3): Article 11. http://www.bepress.com/jhsem/vol4/iss3/11.

Hill, D. 2008. "Must New York City Have Its Own Katrina?" American Society of Civil Engineers *Journal of Leadership and Management in Engineering* 8(3):132-138.

Horton, R., C. Herweijer, C. Rosenzweig, J.P. Liu, V. Gornitz and A.C. Ruane. 2008. "Sea level rise projections for current generation CGCMs based on the semi-empirical method." *Geophysical Research Letters* 35:L02715.

Horton, R., and C. Rosenzweig, 2010: Climate Risk Information. Climate change adaptation in New York City: Building a Risk Management Response, C. Rosenzweig, and W. Solecki, Eds., New York Academy of Sciences.

Jacob, K.H., N. Edelblum, and J. Arnold. 2000. Risk increase to infrastructure due to sea level rise. http://metroeast_climate.ciesin.columbia.edu/reports/infrastructure.pdf. Last accessed March 9, 2011. An abbreviated version, Jacob et al. (2001), is included as Chapter 4 in Rosenzweig and Solecki (2001).

Jacob, K.H., V. Gornitz and C. Rosenzweig. 2007. "Vulnerability of the New York City Metropolitan Area to Coastal Hazards, Including Sea level rise - Inferences for Urban Coastal Risk Management and Adaptation Policies." In *Managing Coastal Vulnerability: Global, Regional, Local*, edited by L. McFadden, R.J. Nicholls and E. Penning-Rowsell, 141-158. Amsterdam, London, New York: Elsevier.

Jacob, K.H., et al. 2008. "Climate Change Adaptation - a Categorical Imperative." New York Metropolitan Transportation Authority (MTA) White Paper. http://www.mta.info/sustainability/pdf/Jacob_et%20al_MTA_Adaptation_Final_0309.pdf

Jacob, K.H. 2009." Metropolitan Transportation Authority (MTA) Blue Ribbon Commission on Sustainability." In *Adaptation to Climate Change*.

Jacob, K., R. Blake, R. Horton, D. Bader, and M. O'Grady. 2010. Indicators and monitoring. Annals of the New York Academy of Sciences, 1196: 127–142. doi: 10.1111/j.1749-6632.2009.05321.x

Jones, K.F. and N.D. Mulherin. 1998. "An Evaluation of the Severity of the January 1998 Ice Storm in Northern New England." USA CoE Report for FEMA Region 1. http://www.crrel.usace.army.mil/techpub/CRREL_Reports/reports/IceStorm98.pdf.

Litman, T. 2005. *Lessons From Katrina and Rita: What Major Disasters Can Teach Transportation Planners*. Victoria Transportation Policy Institute (VTPI).

McGuire, R.K. 2004. "Seismic Hazard and Risk Analysis." Earthquake Engineering Research Institute. Monograph EERI-MNO-10. ISBN #0-943198-01-1.

Metropolitan Transportation Authority (MTA). 2007. "August 8, 2007 Storm Report." September 20. http://www.mta.info/mta/pdf/storm_report_2007.pdf.

Metropolitan Transportation Authority (MTA). 2008a. "Greening Mass Transit & Metro Regions: The Final Report of the Blue Ribbon Commission on Sustainability and the MTA." http://www.mta.info/sustainability/pdf/SustRptFinal.pdf.

Metropolitan Transportation Authority (MTA). 2008b. "MTA Adaptations to Climate Change: A Categorical Imperative." http://www.mta.info/sustainability/pdf/Jacob_et%20al_MTA_Adaptation_Final_0309.pdf.

Metropolitan Transportation Authority (MTA). 2009. http://www.mta.info/sustainability/pdf/SustRptFinal.pdf.

Metropolitan Transportation Authority (MTA). 2009. "Greening Mass Transit & Metro Regions." Blue Ribbon Commission on Sustainability. http://www.mta.info/sustainability/pdf/SustRptFinal.pdf.

Mileti, D.S. 1999. *Disasters by design*. Washington D.C.: Joseph Henry Press.

Millerd, F. 2007. *Global Climate Change and Great Lakes International Shipping*. Transportation Research Board (TRB) Special Report 291. 2007. http://onlinepubs.trb.org/onlinepubs/sr/sr291_millerd.pdf.

Milligan and Company. 2007. *Transportation Equity in Emergencies: A Review of the Practices of State Departments of Transportation, Metropolitan Planning Organizations, and Transit Agencies in 20 Metropolitan Areas*. Washington D.C.: Federal Transit Administration.

Morrow, B. H. 1999. "Identifying and Mapping Community Vulnerability." *Disasters 23(1):1-18.*

Multihazard Mitigation Council (MMC). 2005. *Mitigation Saves.* National Institute of Building Sciences. http://www.nibs.org/index.php/mmc/projects/nhms.

National Infrastructure Simulation and Analysis Center (NISAC). 2006. *Hurricane Scenario Analysis for the New York City Area.* National Infrastructure Simulation and Analysis Center at Sandia National Laboratory of the Department of Homeland Security. Draft dated June 16.

National Oceanic and Atmospheric Administration (NOAA). 2004. "Aviation Climate Assessment Report." http://www.srh.noaa.gov/abq/avclimate/docs/Aviation_Climatology_Assessment_Report.pdf.

New York City Office of Emergency Management (NYC OEM). 2006. "Coastal Storm Plan. Version 2006." http://www.nyc-arecs.org/CoastalStormPlan_summary_06.pdf.

New York City Office of Emergency Management (NYC OEM). 2009. "Natural Hazard Mitigation Plan." http://nyc.gov/html/oem/html/about/planning_hazard_mitigation.shtml.

New York City Panel on Climate Change (NPCC). 2010. *Climate Change Adaptation in New York City: Building a Risk Management Response*. C. Rosenzweig and W. Solecki, Eds. Prepared for use by the New York City Climate Change Adaptation Task Force. *Annals of the New York Academy of Sciences* 1196. New York, NY.

New York Metropolitan Transportation Council (NYMTC). 2007. *Access to Transportation on Long Island: A Technical Report*. Accessed February 18, 2010. http://www.nymtc.org/project/LIS_access/documents/Final_TechRpt.pdf

New York Metropolitan Transportation Council (NYMTC). 2009. *A Coordinated Public Transit-Human Services Transportation Plan*. Accessed February 19, 2010. http://www.nymtc.org/project/PTHSP/PTHSP_documents.html.

New York State Emergency Management Office (NYSEMO). 2006. *SLOSH Model Hurricane Inundation Zones Revised*. Polygon Coverage. UTM NAD83. http://www.nysgis.state.ny.us/gisdata/inventories/details.cfm?DSID=1043

New York State Sea Level Rise Task Force (NYS SLRTF). 2010. http://www.dec.ny.gov/energy/45202.html.

Northeast Climate Impacts Assessment (NECIA). 2006. *Climate Change in the U.S. Northeast.* http://www.climatechoices.org/assets/documents/climatechoices/NECIA_climate_report_final.pdf

Northeast Climate Impacts Assessment (NECIA). 2007. *Confronting Climate Change in the U.S. Northeast.* http://www.climatechoices.org/assets/documents/climatechoices/confronting-climate-change-in-the-u-s-northeast.pdf.

Port Authority of New York and New Jersey (PANYNJ). 2008. "The Port Authority 2008 Annual Report." http://www.panynj.gov/corporate-information/pdf/annual-report-2008.pdf.

Press, E. 2007. "The new suburban poverty." *The Nation*, April 23. 18–24.

Pucher, J. and J.L. Renne. 2003. "Socioeconomics of Urban Travel: Evidence from the 2001 NHTS." *Transportation Quarterly* 57(3).

Renne, J.L., T.W. Sanchez, P. Jenkins and R. Peterson. 2009. "Challenge of Evacuating the Carless in Five Major U.S. Cities." *Transportation Research Record* 2119:36-44.

Rahmstorf, S. 2007. "A semi-empirical approach to projecting future sea level rise." *Science* 315:368-70. http://assets.panda.org/downloads/final_climateimpact_22apr08.pdf.

Root, A., L. Schintler and Button, K.J. 2000. "Women, travel and the idea of 'sustainable transport'." *Transport Reviews* 20(3):369-383.

Rosenzweig, C., R. Horton, D.C. Major, V. Gornitz and K. Jacob. 2007a. "Appendix 2: Climate." In "August 8, 2007 Storm Report." New York City Metropolitan Transportation Authority (MTA). September 20. http://www.mta.info/mta/pdf/storm_report_2007.pdf.

Rosenzweig, C. and W. Solecki, eds. 2001. *Climate Change and Global City: The Potential Consequences of Climate Variability and Change — Metro East Coast.* Report for the U.S. Global Change Research Program, National Assessment of the Potential Consequences of Climate Variability and Change for the United States. New York: Columbia Earth Institute.

Sanchez, T., R. Stolz and J. Ma. 2004. "Inequitable Effects of Transportation Policies on Minorities." *Transportation Research Record* 1885:104–110

Sanderson, A. August 2009. NYS Department of Transportation, personal communication.

Stedinger, J. 2010. State University of New York, Stony Brook. http://stormy.msrc.sunysb.edu.

Suro, R. and A. Singer. 2002 "Latino Growth in Metropolitan America: Changing Patterns, New Locations" *Census 2000 Survey Series.* Washington DC: The Brookings Institution.

Sze, J., and J.K. London. 2008. "Environmental justice at the crossroads." *Sociology Compass* 2(4):1331-1354.

Tol, X., et al. 2006. "Adaptation to 5 meters of sea level rise." *Journal of Risk Research* 9(5): 467–482.

Transportation Research Board (TRB). 2008a. "Potential Impacts of Climate Change on U.S. Transportation." *Special Report* 290. *National Research Council.*

Transportation Research Board (TRB). 2008b. "The Role of Transit in Emergency Evacuation." *Special Report* 294. *National Research Council.*

URS Corporation. 2008. "Appendix E: History and Projection of Traffic, Toll Revenues and Expenses. and Review of Physical Conditions of the Facilities of the Triborough Bridge and Tunnel Authority." http://www.mta.info/mta/investor/pdf/2008/TBTAReport2008Final.pdf.

United States Army Corps of Engineers, et al. 1995. *Metro New York Hurricane Transportation Study*. Interim Technical Data Report.

United States Bureau of Labor Statistics. 2010. Consumer Expenditure Survey.

United States Congressional Budget Office (CBO). 2007. *Potential Cost Savings from the Pre-Disaster Mitigation Program.* http://cbo.gov/ftpdocs/86xx/doc8653/09-28-Disaster.pdf.

United States Climate Change Science Program (CCSP). 2008a. "Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I." A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, edited by M.J. Savonis, V.R. Burkett and J.R. Potter. Department of Transportation, Washington, DC. http://www.climatescience.gov/ Library/sap/sap4-7/final-report/.

United States Climate Change Science Program (CCSP). 2008b. "Final Synthesis and Assessment Report 3-4: Abrupt Climate Change." http://www.climatescience.gov/Library/sap/sap3-4/final-report/default.htm#finalreport.

Untied States Government Accounting Office (GAO). 2007. *Natural Hazard Mitigation*. August. http://www.gao.gov/new.items/d07403.pdf.

Viscusi, W.K. and J.E. Aldy. 2002. "The value of a statistical life: a critical review of market estimates throughout the world." *Discussion Paper 392*. Harvard Law School. ISSN 1045-6333. http://www.law.harvard.edu/programs/olin_center/papers/pdf/392.pdf.

Appendix A. Stakeholder Interactions

Stakeholders of the New York State Transportation Sector cannot be easily differentiated by modes of transportation (air, water, ground), but are more readily described by their public, semi-public, and private institutional status, with considerable overlap across modes in these three classes of ownership.

The New York State Department of Transportation (NYSDOT) has the broadest statewide oversight function, in close coordination with U.S. federal transportation programs and guidelines. On a regional basis, government-established transportation authorities with a quasi-corporate administrative structure have the mandate to serve the public's transportation needs (examples include Metropolitan Transportation Authority (MTA), Port Authority of New York and New Jersey (Port Authority), New York State Thruway Authority, New York State Bridge Authority, etc.). In addition, there are many private transportation operators, including airlines, ferries, maritime and river barge operators, bus companies, rail freight companies, individual trucking operators and—last but not least—private truck and car owners, cyclists, and pedestrians. The ClimAID stakeholder process focused primarily on ground transportation, and on the public and semi-public transportation sector. Stakeholders of the ClimAID transportation sector thus included NYSDOT, MTA, the Port Authority of New York/New Jersey, Amtrak, CSX, New Jersey Transit, and others.

Stakeholders were invited to ClimAID meetings at the beginning of the project. Survey forms were sent to stakeholders early in the project asking for information related to a self-assessment of their vulnerabilities to climate change. In the New York City metropolitan area, ClimAID greatly benefited from the process that the NYC Climate Change Adaptation Task Force had

undertaken to collect climate change vulnerability information and systematically order it in a risk matrix for importance/severity and adaptation feasibility (Adam Freed, personal communication, 2009; NPCC, 2010). The ClimAID stakeholder process also benefited greatly from close cooperation and coordination with the New York State Sea Level Rise Task Force on all matters related to sea level rise.

ClimAID transportation focus group meetings were held with individual agencies (MTA, the Port Authority of New York/New Jersey, and others) and by numerous conference-call working sessions to clarify survey questions and address security issues. The focus was previously on detailed technical issues regarding climate change vulnerabilities and protective measures.

Contributions to the chapter topics were solicited from the stakeholders. A total of at least three drafts of the chapter at various stages, and for some stakeholders several more, were provided for comment and input. Numerous comments, corrections, and improvements were received. This extensive iterative process led to the final version, which incorporated as many of these improvements as possible. But the responsibility for the final version rests with the ClimAID transportation sector research team.

Stakeholder Participants

- Amtrak
- CSX
- Federal Highway Administration
- Florida State University
- Long Island Railroad
- Metropolitan Transportation Authority
- New Jersey Transit
- New York City Office of Emergency Management
- New York City Office of Long-Term Planning and Sustainability
- New York City Transit
- New York State Department of Environmental Conservation
- New York State Department of Transportation
- New York State Office of Emergency Management
- New York University
- Port Authority of New York and New Jersey
- US Department of Homeland Security
- US Geological Survey

Appendix B. Method of Computation of Area-Weighted Average Flood Elevations for Nine Distinct Waterways in New York City

As stated in the main body of this chapter, the 2- and 4-foot sea level rise values are similar to the rapid ice-melt sea level rise scenario forecasts for the 2050s (2 feet) and 2080s (4 feet), described in Chapter 1, "Climate Risks," and by the New York City Panel on Climate Change (NPCC, 2010). Both sources provide more highly resolved sea level rise ranges: 19 to 29 inches by the 2050s and 41 to 59 inches by the 2080s, with central values of 24 inches and 50 inches. Within the integer-foot resolution (rounded whole number values) adopted for this case study, the investigators have approximated these two measures as 2 feet (2050s) and 4 feet (2080s). When in the course of this case study any maps or tables refer to 2-foot and 4-foot sea level rise, then this represents an approximation of the more precise sea level rise estimates and their range of uncertainties as given originally in the New York City Panel on Climate Change study for the rapid ice-melt model.

To analyze the risk that flooding poses to transportation infrastructure, the elevations of the structures relative to the elevation of the floodwaters according to FEMA's 100-year flood maps are analyzed. New flood zones that account for the anticipated 2- and 4-foot sea level rise are then also analyzed with respect to their impact on transportation structures.

When the effects of flooding on extended transportation networks are analyzed, then the relative elevation of the floodwaters to the transport system's critical elevations must be measured at many locations along the transport network's geographical extent. To achieve this task within the timeframe and resources available for this study, the ClimAID team used an approximation. FEMA's Flood Insurance Rate Maps (FIRMs) provide 100-year base flood elevations at a finite number of points along a waterway. The actual base flood elevations vary slightly from location to location within the flood zones mapped by FEMA that are shown, without alteration, as the red zones in **Figure 9.7**. The variations in flood elevations occur for hydrodynamic reasons related to bathymetry, topography, wave and wind exposure, etc.

When adding 2 and 4 feet of sea level rise, new flood zones of an indeterminate shape on their landward side

result. That shape does not exactly follow terrain contours of constant elevations, just as the flood zone boundaries of FEMA's 100-year base flood elevations cross contours of constant elevations, according to hydrodynamic factors. To minimize the effort to determine the relative height of a transportation system versus flood elevations that vary slightly from location to location, the entire New York City water and land area was subdivided into nine waterways, based on their tidal and coastal storm surge characteristics (**Figure 9.8**).

Using the discrete FEMA-provided 100-year base flood elevation control points along the shores of each waterway, averaged base flood elevation control heights were computed for each of the nine zones. The arithmetic mean (simple average; **Table 9.13**, column 3) of the base flood elevation control points for each zone was, however, *not* applied. Instead, an area-weighted mean (Z_i, or area-weighted base flood elevation, column 4) was used. The weights were assigned proportional to the areas that the control points represent along the shorelines of each waterway. This weighting minimizes the undue influence of shore segments with unusually high density of control points that may skew the average base flood elevation for each waterway. **Table 9.13** (column 6) shows the number of control points for each zone (waterway) and the standard deviation (column 5) around the weighted mean for each area-weighted mean value.

Note that the original base flood elevations from FEMA's Flood Insurance Rate Maps are generally (at least for New York) referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929). The investigators, however, chose the new, averaged sea level rise-dependent flood zone elevations to reference

to the more recent, and now generally more commonly used, North American Vertical Datum (NAVD 1988). Note that in contrast to FEMA maps in New York, FEMA maps for New Jersey use the NAVD 1988 datum. A constant difference of 1.1 feet between the two datums was used throughout the New York City area such that the numerical elevations above the two vertical datums relate to each other by Equation 3:

Equation 3. Elevation(ft) above NAVD'88 = Elevation(ft) above NGVD'29 - 1.1 ft

The so-derived, area-weighted average base flood elevations or area-weighted average (in the NAVD'88 reference frame) are rounded to the nearest integer foot for assessing the flood and sea level rise impact on transport in the region.

Once the area-weighted and integer-rounded average base flood elevations (or area-weighted averages) were obtained for the nine waterways, the 2- and 4-foot sea level rise estimates were added to these values. This allows the elevations of transport structures to be easily compared to the flood zone elevations.

In the regions outside New York City, including Long Island (Nassau and Suffolk counties), Westchester County, and the Lower Hudson Valley, much cruder approaches were used for a number of reasons. First, no high-resolution digital elevation model with a 1-foot vertical resolution was uniformly available for these regions outside of New York City. Additionally, for these areas, the lowest critical elevations are not known for many of the transportation systems and related structures as well as they are known within New York City. The New York City estimates were largely obtained from the

Zone (i)	Waterway	Rounded, Average Base Flood Elevation (feet) NGVD 88	Rounded, Area-Weighted Average Base Flood Elevation in NGVD 88, Z_i (feet)	Standard Deviation (feet)	Number of Points on FEMA Flood Map per Zone (n)	Relevant Boroughs
1	Long Island Sound	14	14	1.45	31	Bx, Q
2	East River	13	11	1.06	53	Bx, Q, M
3	Harlem River	9	9	1	3	Bx, M
4	Hudson River	8	8	0.71	2	Bx, M
5	Inner harbor	9	9	0.97	13	M, Bk, SI, (Q)
5A	Kill Van Kull	8	8	0.63	6	SI
6	Outer Harbor	10	10	1.20	48	SI, Bk
7	Jamaica Bay	7	8	0.72	32	Bk, Q
8	Rockaway (Atlantic and Jamaica Bay)	8	9	1.13	22	Q

Note: Bk=Brooklyn, Bx=Bronx, M=Manhattan, Q=Queens, SI=Staten Island

Table 9.13 New York City waterway zones and their rounded average values for obtained area-weighted base flood elevations

Hurricane Transportation Study (USACE, 1995), and the metropolitan east coast (MEC) climate change infrastructure study (Jacob et al., 2000 and 2007).[46]

This lack of elevation information points to the need for accurate, accessible digital elevation models in the storm-surge-prone coastal zones of New York State. These models need vertical resolutions of less than 1 foot. There is also a need for accurate as-built elevations of the transport structures. The digital elevation model resolution is technically achievable with carefully executed remote sensing technology (LIDAR surveys) and careful post-processing after acquiring the raw data. Some coverage with this technology exists in New York State, but needs to be undertaken systematically, at least for all flood-prone zones across the state that are affected by sea level rise and coastal storm surges. The collection of reliable elevations of transport structures in these critical areas is in the best interest of the operating agencies, but needs to be performed in the public interest as part of a concerted statewide flood-risk management plan.

Appendix C. Method to Compute Economic Losses (Appended to Case Study A, 100-Year Coastal Storm Surge with Sea Level Rise)

To estimate the economic losses from the ClimAID case study storm scenario, using the values summarized in **Table 9.5**, these assumptions were made:

- The economic activity is essentially zero from day zero to the lowest value of T90, for each scenario, listed in Row 30 of **Table 9.5**.
- The economic activity recovers gradually (assuming a linear relation) from day T90min to T90max, where the latter is the upper bound of the T90 value (in days) listed in Row 30 of **Table 9.5**, for each scenario.
- The recovery from 90 percent functionality to 100 percent functionality (on day T100) occurs with the same slope as between 0 and 90 percent functionality.

This concept of a gradual recovery of the economy (rather than coming to a total halt and then suddenly jumping back into full gear) is important for fully appreciating how the information in **Table 9.5** is used.

TheT90 values in row 30, columns 3, 4, and 5, are not the times by which the economy is assumed to start recovering; these values are intended to mark the times by which the economy has recovered to 90 percent of its pre-disaster level, i.e., they mark the time by which the recovery has come almost to an end, and had made progress for the entire period in the days between T90min and T90max after the onset of the disaster.

All of these assumptions and approximations are highly uncertain, but can be justified by comparing them to the electric grid recovery curve shown in **Figure 9.20**, except the slightly upward convex curve of this figure is replaced with a linear relation. The basic concept is that electricity and economy come back not suddenly but gradually after such an event. Even if some transport modes do not work, commuters may find a way to substitute, work at home, or pay for and/or share a taxi (for caveats, see Vulnerability and Social Justice sections of the case study).

With these assumptions, the time-integrated economic losses for the entire metropolitan region (TIELEM) from the 100-year storm of the case study can be computed by integrating (summing up) over time the gradually (i.e., with time linearly) decreasing daily economic productivity losses from day zero to day T100. Using this concept of decreasing daily losses and increasing recovery of the economy yields Equation 4:

Equation 4: TIELEM = DGMP [T90min + ½ (T90max − T90min) 100/90]

Using the daily gross metropolitan product, DGMP = $4 billion/day and the T90min and T90max values of **Table 9.5** for the three SLR scenarios S1 to S3, yields the TIELEM values summarized in **Table 9.7**.

Forward-Projection of Losses to 2050 and 2090

Note it has been assumed that all three SLR scenarios are applied to the 2010-DGMP. But the three scenarios require time for sea level to rise. The study assumes that the three scenarios occur in S1=2010, and that S2 occurs in the 2050s and S3 before 2090. Therefore, the study must account for what the economic trends for the next 40 and 80 years could be (a) by accounting for inflation and/or discount rates; and (b) by accounting for economic growth, expressed by increasing DGPM and/or increasing asset values. These trends can be

formally treated in the same way as compounding
interest for an interest rate of **r** % (say for inflation or
economic growth rate), while adding a certain *fixed
amount* of dollars **p** to every 100 dollars of built assets,
say, *at the end of each year* (note that this means a
steadily *decreasing percentage* addition of assets, since the
dollar amount **p** stays constant while the initial asset
value increases by compounding in relation to **r**).

Using, for example, the assumption that scenario S2
occurs around 2050, i.e., 40 years from now, and that
scenario S3 occurs 80 years from now; and that for
every $1 trillion/year in economic activity, another
(constant) $20 billion per year (i.e., **p=2**) is added over
the next 40 years or 80 years, respectively, then the
multipliers for the S2-TIELEM of $57 billion, and for
the S3-TIELEM of $68 billion, respectively, as a
function of an effective economic growth rate **r** will be
as indicated in **Table 9.14**.

Added to the economic losses (TIELEM) must be the
direct *physical damage* **D** ($), incurred by the affected
infrastructure during the storm. Since no vulnerability
or fragility curves for the transportation systems, nor a
realistic aggregate asset value of the transportation
infrastructure, are known with any degree of accuracy
or confidence at this time, proxies are used with
uncertain validity. For a first-order approximation, we
make the following working assumptions for estimating
the direct damage **D** for this case study, and using
several different approaches:

a) The regional combined transportation assets are on
    the order of $1 trillion (2010 dollars). The physical
    damage rates, based on typical flood scenario
    computation with the tool HAZUS-MH, are taken
    to be on the order on the order of 1.00, 1.25, and
    1.50 percent of the asset values, respectively, for the
    three scenarios S1 to S3, respectively. This yields
    direct physical damage losses of **D=$10, $12.5,
    and $15 billion** (for 2010 assets) for the three
    scenarios, assuming they all were to occur in the
    year 2010. Since they do not, multipliers shown in
    Table 9.14 would apply for S2 and S3 occurring in

Effective Economic Growth Rate *r* (%/year)	0	1.5	1.75	2.0
S2-TIELEM Multiplier for 40 Years:	1.8	2.91	3.16	3.44
S3-TIELEM Multiplier for 80 Years:	2.6	6.39	7.50	8.83

Table 9.14 Multipliers for 40- and 80-year time horizons as
a function of growth rate *r* when p=2

2050 and before 2090, respectively, and assuming
all other conditions would apply when the **Table
9.14** multipliers were computed (i.e., constant **p=2**
or **$20 billion** annual infrastructure asset additions
to the initial [2010] $1 trillion assets).

b) Based on limited observations, a finding is that
    losses for infrastructure assets during natural
    disasters in urban settings are typically of the same
    order of magnitude as for the building-related losses
    in the same area (e.g., Jacob et al., 2000). NYSEMO
    periodically computes losses (using the FEMA-
    sponsored HAZUS-MH software) associated with
    various storm scenarios for emergency exercises.
    One of these is a storm scenario in which a category
    3 hurricane named "Eli" traverses Long Island
    making landfall near the boundary between Nassau
    and Suffolk county (D. O'Brien, NYSEMO,
    personal communication, October 2009). While
    this scenario is excessive for Nassau and Suffolk, it
    produced wind speeds and coastal storm surges for
    the five NYC boroughs and for Westchester County
    that are comparable to our 100-year storm
    scenarios. The building-related losses from the
    storm surge flooding in the five boroughs amounted
    to slightly over $20 billion, while in Westchester
    County it was just below $0.6 billion (for
    comparison, the wind damage in the five boroughs
    was only about $110 million and in Westchester
    $16 million). Moreover, an interesting observation
    is that the ratio of storm-surge flood- to wind-
    related losses was 3 to 1 for all counties in New York
    State affected by scenario "Eli."

If the results from the two approaches are combined,
the conclusion is that the physical losses for all
infrastructure systems for the entire scenario region due
to coastal storm surge flooding is on the order of a few
tens of billions of dollars; i.e., in the range of $10 to $20
billion. How much of it is attributable to damage to
transportation versus other infrastructure? While at the
moment there are no hard data to affirm this, the
ClimAID Transportation study suggests, largely because
so much of the transportation infrastructure assets are
located at or below sea level and are therefore the most
vulnerable, that at least half and perhaps as much as
three-quarters of this total amount is attributable to
damage to the transportation infrastructure.

If the physical damage and the economic losses are
compared from the scenario event that are, directly or
indirectly by its effect on the general economy,

attributable to losses of functionality of the transportation infrastructure, then first-order approximation estimates of total losses from the three storm scenarios (all in 2010 dollars and for 2010 assets) can be obtained and are summarized in **Table 9.5** of the case study.

When reviewing these estimates, the ClimAID team again caution (as stated in the Case Study, in the paragraphs near equation 2) that there may be numerous other significant constraints on the ability of the transportation systems to recover from climate change-induced incidents. Such may include, for example, the age of equipment, the availability of replacement parts/equipment, and the need for such in appropriate quantities. These and other currently unknown and/or not quantified factors could significantly increase climate change impacts in time, labor, and dollars.

Note that **Table 9.14** multipliers for the losses associated with the scenarios S2 and S3 are applicable throughout to modify all losses; they transform them from their current 2010 time base to what they may be during the 2050s and the end-of-2080s, respectively, for the different economic projections and other assumptions stated.

---

[1] http://www.bts.gov/publications/freight_shipments_in_america/html/table_03.html.

[2] https://www.nysdot.gov/about-nysdot/history/past-present.

[3] https://www.nysdot.gov/about-nysdot/responsibilities-and-functions.

[4] https://www.nysdot.gov/about-nysdot/history/past-present.

[5] http://www.nysba.state.ny.us/Index.html.

[6] http://www.countyhwys.org/.

[7] https://www.nysdot.gov/divisions/operating/opdm/passenger-rail/freight-rail-service-in-new-york-state.

[8] http://www.aar.org/Homepage.aspx and foot note above.

[9] Class I railroads are those with operating revenue of at least $272 million in 2002. http://www.nationalatlas.gov/articles/transportation/a_freightrr.html.

[10] http://www.guardian.co.uk/environment/2006/nov/01/society.climatechange/print.

[11] MEC infrastructure report (Jacob et al. 2000, 2001); FEMA FIRM flood zone maps; and http://www2.sunysuffolk.edu/mandias/38hurricane/.

[12] MEC infrastructure report (Jacob et al. 2000, 2001); NPCC-CRI (2010).

[13] See Chapter 1: "Climate Risks"; and New York City Panel on Climate Change "Climate Risk Information" (2010).

[14] TRB (2008a).

[15] CCSP, 2008a: Gulf Coast Study, Phase I. http://www.climatescience.gov/Library/sap/sap4-7/final-report/.

[16] USACE, 1995; MEC, 2001; and MTA, 2007. The 08/08/07 Storm Report; NPCC, 2009, 2010 and NYCCATF (in preparation).

[17] CCSP, 2008b; http://www.pogo.org/investigations/contract-oversight/katrina/katrina-gao.html.

[18] DeGaetano 2000; Jones and Mulherin 1998.

[19] The Tappan Zee Bridge is expected to be replaced with a new structure, but timing is uncertain.

[20] Stedinger (2010).

[21] TRB (2008a).

[22] The New York State Constitution provides for democratically elected legislative bodies for counties, cities, towns and villages. These legislative bodies are granted the power to enact local laws as needed in order to provide services to their citizens and fulfill their various obligations.

[23] E.g., for MTA see Jacob et al. 2009; Jacob, 2009; NYS SLRTF, 2010; NYC CCATF, 2010; NPCC-CRI, 2009; NYS CAC, 2010; and stakeholder cooperation with this ClimAID project.

[24] http://www.dec.ny.gov/energy/45202.html.

[25] http://www.nyc.gov/html/oem/html/hazards/storms_hurricaneevac.shtml.

[26] *New York Times*, January 28, 2010: "S.E.C. Adds Climate Risk to Disclosure List" http://www.nytimes.com/2010/01/28/business/28sec.html?sq=sec&st=cse&scp=2&pagewanted=p.

[27] http://www.fta.dot.gov/about/offices/about_FTA_927.html#Mission and file:///Downloads/Post%209_11regional_offices_4154.html.

[28] http://www.gothamgazette.com/graphics/2008/04/DotDensityLowIncomeCommute.jpg.

[29] For a purely random occurrence of storms in time, statistics indicate that the probability that a 100-year storm does occur within the 100-year time period is only 63 percent. This is because the 100-year period is an average; thus, there are periods between such storm events that are longer than 100 years. These longer periods make up for occasional shorter recurrence intervals.

[30] Based on the Poisson Distribution, the probability for an event with average recurrence period T to occur in the time interval t is: $p = 1 - e^{-(t/T)}$. When t equals T, in this case 100 years, the result turns out to be ~63%.

[31] The technical term of the average flood elevations for the waterways is: "area-weighted base flood elevations (AW BFE). These are later labeled, for simplicity, the Z_i values. For details and listing of the Z_i values in Table 9.13, see Appendix B.

[32] More could be added when maps of Long Island (Suffolk and Nassau County) for base flood elevations (BFE) of 1% per year and 2 and 4-ft sea level rise become available.

[33] The numbers in this figure were derived using a standard GIS intersection operation applied to the New York City street grid and to the three flood zones shown in Figure 9.7.

[34] A nearly complete and more detailed listing of lowest critical elevations of transportation systems in the New York City metropolitan region can be found in USACE (1995), with the caveats that (i) the lowest critical elevations in that reference are given with respect to NGVD, 1929; and (ii) that some modifications to structures or the terrain may have been made since the 1995 report was issued. Where we provide new information not contained in USACE (1995), the source is indicated where identifiable.

[35] MTA, 2006, courtesy A. Cabrera; communication of December 2009.

[36] The Port Authority has an emergency operational plan for Holland and Lincoln Tunnel and for part of its PATH system that will be activated prior to the arrival of a storm. LCE without such measures would be lower (e.g., Holland Tunnel vent shaft: LCE=7.6 feet; and Lincoln Tunnel vent shaft: LCE=10.6 feet).

[37] The ARC project was put on halt in 2010 to explore less costly options.

[38] Each step in this procedure is associated with large uncertainties. The procedure outlined here is site- and system-dependent, especially in the absence of a complete engineering risk and vulnerability assessment. Such an assessment is urgently needed to perform this task rigorously. The stakeholders provided physical data regarding tunnel volumes and pumping capacity of the most essential transport systems, but were unable to provide estimates of system vulnerability, repair, and restoration times and/or associated costs because there are too many unknown variables. Another large uncertainty is whether grid power will remain uninterrupted and, if interrupted, how long it will take power providers to restore it.

[39] ClimAID uses the hydraulic calculations for estimating the total floodwater volume in the tunnels.

[40] These numbers are preliminary and may change subject to more detailed engineering analyses.

[41] In contrast, the pumps installed in the NYCT subway tunnels are of older vintage and their purpose is not pumping out a flooded tunnel but draining the tunnels under normal operational conditions. NYCT's more than 750 pumps in 300 pump stations drain about 8 to 13 million gallons of water per day from the subway system, depending on whether it is a dry or wet day. Using 13 million gallons per day and 750 pumps yields 17,000 gallons/pump/day or just 12 gallons per pump per minute. If the total available pumping capacity after the scenario storm were 17,000 gallons per day (though the actual capacity is higher), it would take nearly 80 days to drain the system. However, not all of the 750 pumps are installed in the sections that would be flooded and, therefore, the process could take even longer. Note that the 12 gallons per minute value does not constitute the pumping capacity available during an extreme event. It is the pumping capacity used during a typical rainy day.

[42] If N is the number of pumps working in parallel at any given time, then the time required would be 1 week x (100/N).

[43] Based on Price Waterhouse Cooper (PWC) data for 2008.

[44] This daily gross regional product for the metropolitan region (DGMP), when used with the outage times listed in Table 9.5, allows the study to estimate the order of magnitude of the economic impact of outages. While the focus of this chapter is on transportation, the highly simplified assumption is used that the economic productivity is a direct function of the operational functionality of the transportation sector. In reality it reflects the functionality of all types of infrastructure (electricity, gas, water, waste, communication, etc.). But because most of these systems are so tightly coupled, the time estimates for transportation (Table 9.5) are, to a first-order approximation, a seemingly rational choice for a proxy for the functioning of all economic activity.

[45] And forward-projected to 2050 and 2090 by the multipliers of Table 9.14 in Appendix C.

[46] More could be added when maps of Long Island (Suffolk and Nassau County) for BFE of 1% per year and 2 and 4-ft sea level rise will become available.