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http://www.geerassociation.org

Cover Page Photo Credit: Handout from GOES satellite image provided by NASA, Hurricane Sandy churns off the East Coast on Monday morning, Oct. 29, 2012.

Acknowledgements and Collaborations

Extreme Event Reconnaissance is a challenging activity that requires extremely careful planning and implementation. Safety is always of paramount importance. In many cases, the hazards are not just the result of already existing collapses but are just as likely to be the result of delayed collapse of already weakened infrastructure systems due to ongoing rescue and recovery activities. To ensure that individuals participating in such reconnaissance activities do so with the utmost attention to safety, GEER has developed a culture of safety and collaboration as it plans and implements its activities and considers these two factors to be critical components of their work. The response to the October 2012 Hurricane Sandy event was no exception to this approach and thus GEER is particularly grateful for the collegial interactions and collaborations it had with a variety of organizations in support of the individuals deployed there.

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Executive Summary

Hurricane Sandy, also referred to as super-storm Sandy, was unprecedented in scale and impact on the urban cluster comprised of New York City and the surrounding metro areas in addition to numerous coastal communities along the New Jersey and New York coasts. The storm exposed the fragility of our modern urban infrastructure and highlighted the vulnerability of this infrastructure to a potentially new norm of extreme events. The storm caused severe coastal damage, as well major flooding that disrupted normal life in a number of communities as well the business activities in Lower Manhattan, the financial capital of the world. The flooding, for the first time, affected numerous underground subways and roadways that further amplified the impact of the storm.

The storm has raised awareness of issues associated with climate change, sea level rise and challenges we face as engineers and as a society in enhancing the resiliency of our infrastructure to rapidly recover from such an extreme natural event.

GEER has formed a team co-led by Prof. Youssef Hashash and Dr. Sissy Nikolaou to document damage to the geotechnical infrastructure in the New Jersey and New York regions. A large team of volunteers with the support of a number of agencies worked diligently and under sometimes difficult circumstances to capture the damage caused by the storm in a timely manner. The observations are not intended to be comprehensive, but highlight key types of damage observed. The observations documented in this report provide important case histories that help us in better understanding the response of these infrastructure elements to the storms and will help future researchers and engineers in developing measures to mitigate the adverse effects observed from this extreme event.

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1 INTRODUCTION

Hurricane Sandy, also referred to as super-storm sandy, a slow moving storm, was well documented and tracked. Forecasters were able to reliably identify the path of the storm as well as anticipated wind speeds and storm surge. Communities in potentially affected areas had warning of sometimes over 1-2 days to prepare for the storm. This advance warning was instrumental in saving many lives; however, damage to the physical infrastructure was severe. Coastal communities and their infrastructure were battered by wave action combined with storm surge and high winds. Areas in New York (NY) City experienced extensive and severe flooding that easily overwhelmed the limited defenses that were placed in anticipation of the storm. The storm impacted coastal protection structures, bridges, underground utilities, building basements as well as transit and roadway tunnels. This report documents observed damage to geotechnical infrastructure by the GEER team. Section 2 provides background on the storm. Section 3 lists the areas covered by the GEER team. Section 4 describes the coastal geomorphology and the changes due to the storm. Section 5 describes damage to major infrastructure such as bridges along the New Jersey (NJ) coastline. Section 6 describes damage observed in coastal communities. Section 7 documents damage observed in dense urban areas. The observations in this report are not comprehensive but are intended to highlight key types of damages that were observable by the GEER team.

2 HURRICANE SANDY, THE EVENT TIME LINE AND KEY CHARACTERISTICS

Sandy was a late-season cyclone or hurricane starting in the southwestern Caribbean Sea (Blake et. al. 2013) with its origins off the coast of West Africa. The hurricane moved north along the US east coast Figure 2.1. Blake et. al (2013) provide a detailed description of the storm and its path.

Figure 2.1 Track map of Hurricane Sandy at 6-hour intervals. The color represents the storm's maximum sustained wind speeds as classified in the Saffir-Simpson Hurricane Scale and the shape of the data points represent the nature of the storm. [Ref: Wikipedia.org; Created by Cyclonebiskit with background image from NASA] .

Hurricane Sandy was unusual in that it was very slow moving; essentially a combination of several weather fronts that resulted in the eye of the storm moving northeasterly along the coast and turning abruptly to the west, making landfall near Brigantine, N.J. (Blake et. al 2013) on October 29, 2012. As the storm approached, the counter-clockwise wind currents caused the predominant high velocity wind direction over Long Island (LI) and New York City to be from the east. This drove devastating storm surges into coastal areas of western LI, Staten Island, Queens, Brooklyn, Manhattan and New Jersey. The slow movement of the storm coincided with the astronomical high tide causing flooding of densely populated urban centers at an unprecedented scale. In Battery Park in lower Manhattan, the storm tide (storm surge added to tide at the time) reached nearly 14 feet above Mean Lower Low Water (MLLW) (see Figure 2.2), resulting in estimated inundation of 5.5 to 6.5 feet above ground surface, while in Staten Island the Storm tide exceeded 14.5 ft (Blake et. al 2013).

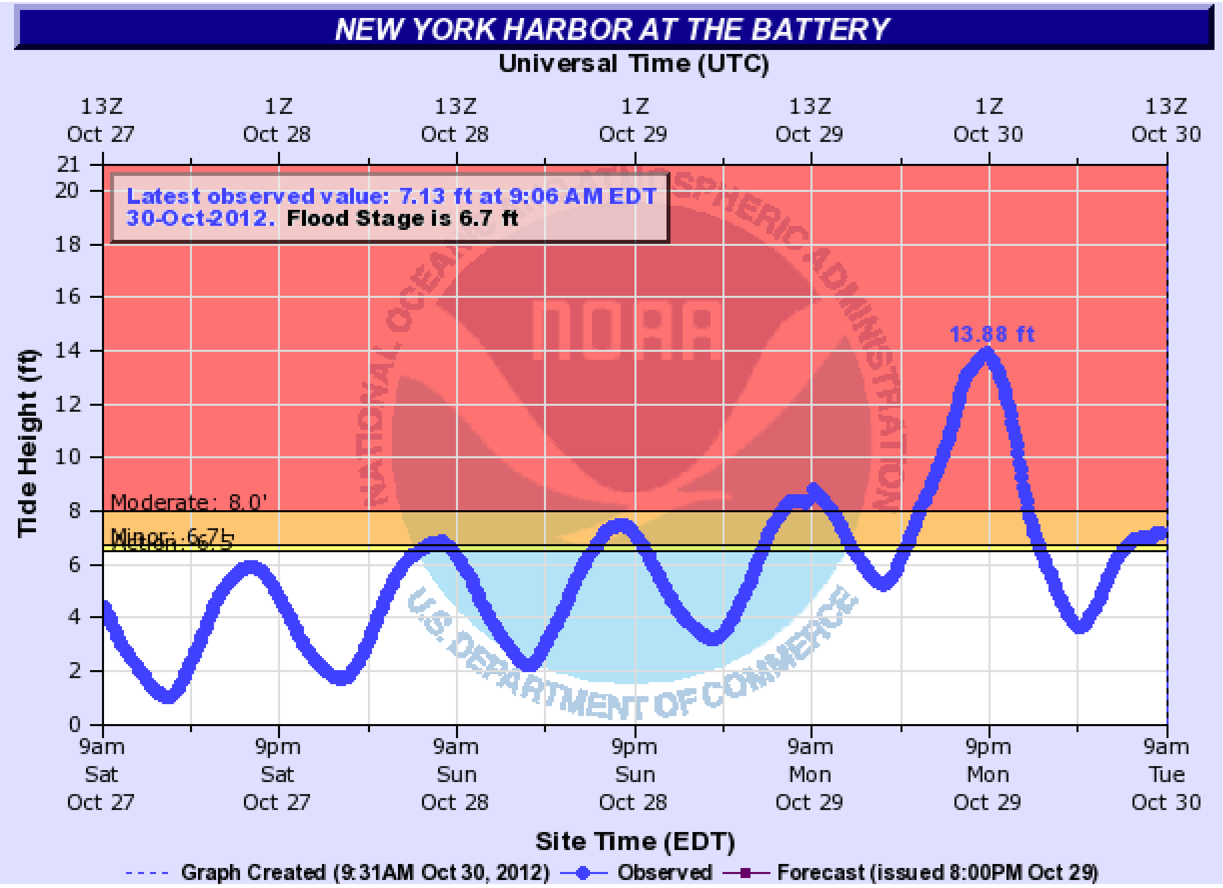


Figure 2.2 Hurricane Sandy surge at the NYC Battery (NOAA; provided by T.D. O'Rourke).

2.1 Historical Severe Storms/Hurricanes in the New York City (NYC) Area

The storms discussed herein are limited to those causing damage within the five boroughs of NYC, Long Island and along the coast of New Jersey. A number of tropical storms often originating in the Atlantic Ocean east of the Caribbean occur every year particularly in late summer and the fall. Some become hurricanes and travel east into the Gulf of Mexico and strike coastal areas in that area. Others travel up the East Coast, sometimes developing into hurricanes, decreasing in wind speed as they make landfall and travel inland. Some of these storms move northeasterly and never make landfall but the resulting winds are felt along the coast. These storms often result in large amounts of rainfall that cause flooding and inland rivers to swell and overflow their banks.

In coastal areas, these storms cause surges in the ocean level that extend above the normal tide level resulting in flooding. The shape of the coastline and the direction of the winds affect the height of the surge. Areas like the mouth of the NY Harbor and the west end of LI Sound can constrict a surge flow and result in higher flood levels. Sustained winds can cause surges in water level behind the barrier beaches particularly when the wind is parallel to the direction of the barrier beach.

Hurricanes often travel rapidly through an area and the high velocity winds cause surges in the water level that are superimposed on the normal astronomical tidal fluctuations. Commonly, these surges occur at times other than astronomical high tide. Nor’easter storms are often more sustained causing high wind and rain that extend through much of a tide cycle thus causing more sustained rainfall and surges superimposed on high tides.

A review of the principal previous hurricanes and large storms that have impacted the coastal areas of the NYC area (Table 2.1) indicates that in the last 100 years, principal storms have occurred about once every 6 years. However, in the last 21 years storm frequency has averaged once every 3.5 years. The record identifies only one storm about every 14 years in the nineteenth century. Part of the reason for the fewer recorded severe storms in the nineteenth century may be differences in record keeping and communications. These storms have made landfall and impacted widely varying areas with somewhat more storms having impacted Suffolk County (1938 Hurricane) than other areas. Records of severe storm surges indicate heights of 3 to 18 ft; fortunately some of the highest ones occurred close to astronomical low tide. Extreme wind gusts varied from 52 to 113 mph. The most extreme hurricanes varied from Category 1 to 3.

Table 2.1 Summary of Principal Storms in the New York City Area

DATE	STORM SURGE FT	WIND MPH	GUST MPH	DAMAGE	LOCATION	CATEGORY
1278-1438				major hurricane	NY/NJ	
10/29/1693	coast changing			severe damage/Fire Island Cut created	Long Island	
8/19/1788				severe flooding and damage at Battery	Manhattan	
9/23/1815	6(SH)11-12(Nar.B)			Created Long Beach/Rockaway beach cut	Sag Harbor	3
9/3/1821	13	high		ship crash on LI, 17 people killed	Long Island	
6/4/1825				several ship wrecks, 7 people killled	NJ/SE of NY	
10/4/1841		Gale		$41 m (in 2007$)	NY	
10/6/1849				severe structural damage	NY/LI	
8/24/1893		56 (Manhattan)			W. end of Rockaway	1
10/10/1894				building,telegraph lines,trees & boats	NYC/LI	1
9/17/1903			65	3" rain		
9/20/1936	strong			flood much of LBI,severe beach erosion	Long Beach Island, NJ	
9/21/1938	18		125	8900 hses destr., 60 deaths	Suffolk Co	3
9/14/1944			>100(NYC)	117 hses destr., 1000 business destr.	LI/NYC	1
1954			113		Battery Park	
8/31/1954			120(Montauk)	$460 m damage(1954USD)	Eastern LI	
9/11/1960	6	100 ELI/70 WLI		beach erosion/several homes destroy	LI	2
9/21/1961			108	coastal flooding, 260,000 hses w/o power	Suffolk Co	
8/28/1971				8" rain, NYC subways flooded/upstate floods	NYC/Upstate NY	
6/22/1972	3.1		55	12" rain caused severe river flooding	NYC	
8/11/1976	7.2		70	6" rain, $980 m (2007USD) damage	LI	1
9/27/1985			100	3.4" rain, $591 m (2007USD) damage, 48 homes	LI	2
8/28/1991	6		high	7" rain, $117 m (1991USD) damage	Eastern LI	2
9/16/1999			60	Severe flooding,$18 m (2007USD) damage	SE NY	
9/21/2003			high	power outage/$98 m (2006USD) damage	NYC	
9/6/2008			52	downed trees	LI	
8/27-28/2011		70(NYC)	91(Sayville,LI)	2 tornadoes,power outages/trees down	Coney Island	1
				flooding of lower Manhattan		
10/28-29/2012	13.7		85	flooding of lower Manhattan, Rockaways,	LI, NYC, NJ coast	
				Long Beach, NY, Staten Island,NJ coast		

3 THE GEER TEAM AND AREAS COVERED

3.1 GEER New York City Team

On Friday, November 2nd, an organizational meeting was held at the office of Mueser Rutledge Consulting Engineers (MRCE) in Manhattan. At that time, partial service had been restored to some New York City subway and bus lines, but significant portions of the subway, road, and commuter rail network remained disabled (refer to MTA November 1, 2012 subway recovery map, Figure 7.18). At the meeting, attended by about 15 engineers, data collection procedures were reviewed (based on the "Manual for GEER Reconnaissance Teams"), areas of the city identified for field visits, and teams of two or three engineers assigned to each area. A primary goal of the initial reconnaissance effort was to visit accessible areas to collect perishable data, which could later be supplemented with background information.

Over the next two days (November 3rd and 4th, 2012), the GEER New York City team visited the locations listed in Table 3.1. A standard form for recording field observations was employed. A brief summary of the damage observed in each visit is included in Table 3.1; detailed inspection findings are described later in this report.

Table 3.1 Summary of GEER New York City Site Visits

Date	Location	Volunteers	Remarks *(see text for detailed inspection findings)*
11/1/12-11/2/12	Manhattan Lower West Side and Battery Park City Waterfront, Manhattan	AK, RC	Minimal damage to waterfront structures
11/3/12	Lower Manhattan Waterfront	RC, MU	Minor damage to waterfront structures.
11/3/12	Manhattan Lower East Side Waterfront	AMD, ALS	Minor damage to waterfront structures. A few ground loss / washout features.
11/4/12	Lower Manhattan	RG, SN, YH	Primary damage due to flood inundation.
11/4/12	Staten Island	SN, YH, RG, KR	Significant damage to beachfront homes. Severe soil erosion and sinkholes. Prevalent flood damage.
11/4/12	Red Hook & Brooklyn Bridge Park, Brooklyn	DJG, JJA	Minor damage to waterfront structures. A few ground loss / washout features.
11/4/12	The Rockaways, Long Beach, and Broad Channel, Queens	RC, MU, HSL	Significant damage to beachfront boardwalk and timber-frame homes. Flooding of first floor destroyed contents and interior walls of most buildings. Lesser damage to high-rise buildings.

AK: Aleksandr Krutovskiy; RC: Raj Chinthamani; MU: Mariusz Ukowski; AMD: Adam M. Dyer; ALS: Aaron L. Sacks; RG: Ramon Gilsanz (GMS); SN: Sissy Nikolaou; YH: Youssef Hashash; KR: Karl Rubenacker (GMS); DJG: Daniel J. George; JJA: Jabber Al-Bihani; HSL: Hugh S. Lacy;

Additional general observations were made by MRCE in collaboration with the New York City Department of Buildings during the subsequent weeks.

It should be noted that owner sensitivity regarding the release of information pertaining to property damage was encountered frequently in our New York City reconnaissance work. This is understandable because most owners (both private owners and public utilities) had re-occupancy approval, insurance claims, and in some cases lawsuits hinging on the outcome of property condition assessments. It is perhaps not a new observation that economic forces can at times run counter to the engineering desire to understand performance across a variety of sites and structures, especially in highly developed urban areas such as New York City.

3.2 GEER New Jersey Team

On Saturday, November 3, the New Jersey team convened at the Sheraton Hotel, Atlantic City to determine the plan for site visits moving forward. The New Jersey team was comprised of 5 engineers, three of whom were academics, one a practicing engineer from GEI and another from MRCE. Areas of the New Jersey coastline were identified for review. Soon after the initial meeting, the team headed to Brigantine for a site visit. Based on the initial reconnaissance and a conference call with the New York City team, it was decided that major infrastructure such as bridges would be surveyed. Over the next day, an assessment of some of the bridges along the New Jersey coastline was completed but several were inaccessible due to storm damage and travel restrictions. Team members who had travelled from Rhode Island and Boston returned to their home base and the rest of the assessment was done over a period of a month and a half by Rowan University faculty and students and NJ Department of Environmental Protection personnel. To obtain access to several of the communities that had serious damage, Senator Menendez's office had to intervene on the GEER team's behalf to obtain access to these communities. Table 3.2 provides a summary of the New Jersey Team GEER site visits.

Table 3.2 Summary of GEER New Jersey Site Visits

Date	Location	GEER Volunteers	Remarks
11/3/12 – 11/4/12	New Jersey Coast from Brigantine to Belmar	AB, CB, BS, LW, MAQ	Minimal damage to bridges. A few ground loss /washout features.
11/6/12	Atlantic City	BS and RU students	Damage to waterfront structures in isolated areas.
11/11/12	Atlantic City, Ocean City, Longport	BS	Minimal damage to waterfront structures.
11/27/12	Ship Bottom and Long Beach Island	BS, MB	Widespread flooding damage and some damage to waterfront structures.
12/3/12	Seaside Heights, Lavalette, Ortley	BS, RU Students, MB	Severe damage to waterfront structures.

AB: Aaron Bradshaw; CB: Chris Baxter; BS: Beena Sukumaran; LW: Lee Wooten; MAQ: Michael A. Quasarano; MB: Michael Burlingame

A complete map of New York City and New Jersey locations observed is provided in Figure 3.1.

Figure 3.1 GEER observation locations, including site visits in the days following the storm, and information gained through collaboration with city and state agencies over the subsequent weeks.

4 COASTAL GEOMORPHOLOGY AND IMPACTS ON THE NATURAL COAST LINE

The shoreline affected by Hurricane Sandy is primarily made up of eroding headlands and a series of barrier islands that run roughly parallel to the mainland. As the name implies, natural barrier islands serve as a buffer to protect the mainland and the back-bay from storm and wave action coming from the ocean. Barrier islands are composed of loose sediment held in place only by gravity and roots. Ocean waves expend energy by moving the beach sand around and building up the island, thus limiting the ocean's effect on the mainland. Over time as sea-level rises and the shoreline moves inland, wave action helps the barrier island migrate landward with the shift.

Figure 4.1 shows a typical cross-section of the depositional environments encountered across a barrier island from the bayside to the ocean. Several geologic processes are responsible for maintaining the beaches. When waves are gentle, off-shore sand, often placed there by storms, is pushed up onto the beach. Wind helps to build up sand dunes and vegetation helps to anchor and stabilize the dunes. Marshes often build up in the back-bay, extending the base of the barrier island landward.

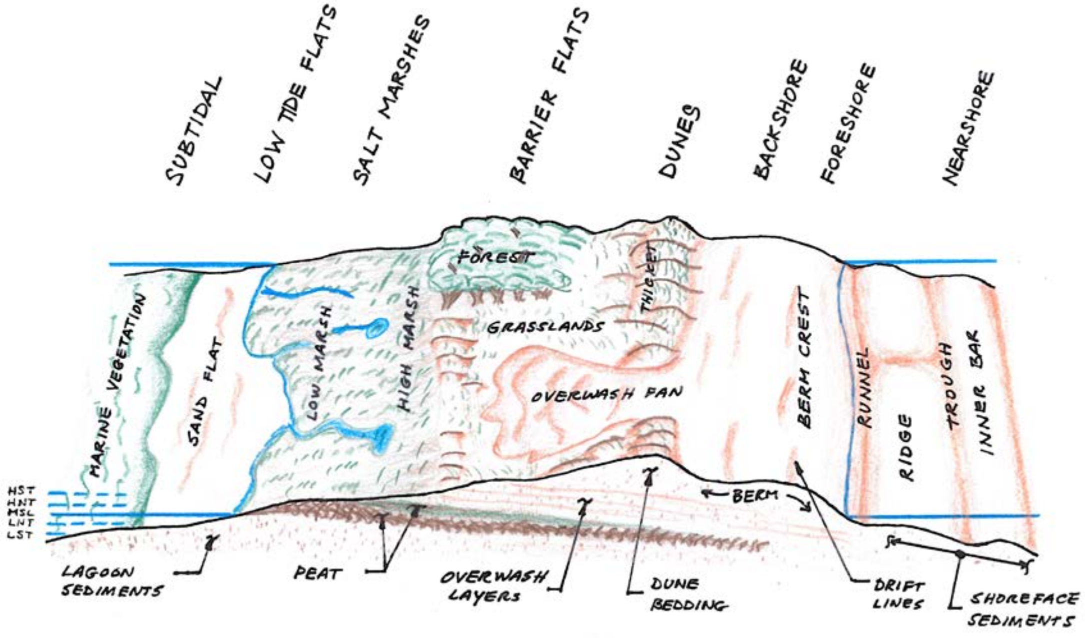
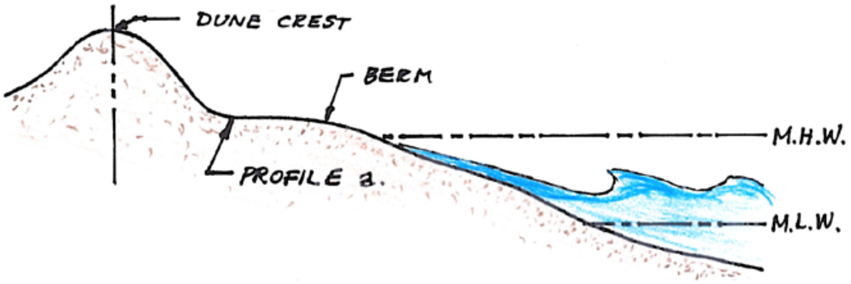
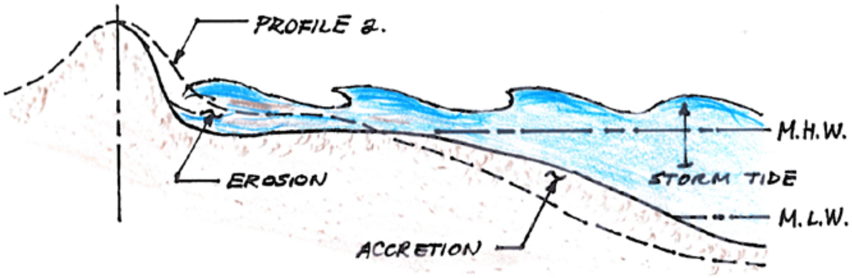


Figure 4.1 Barrier environments (modified by A. Dyer from Leatherman, S.P., 1979; original in Godfrey, 1976).

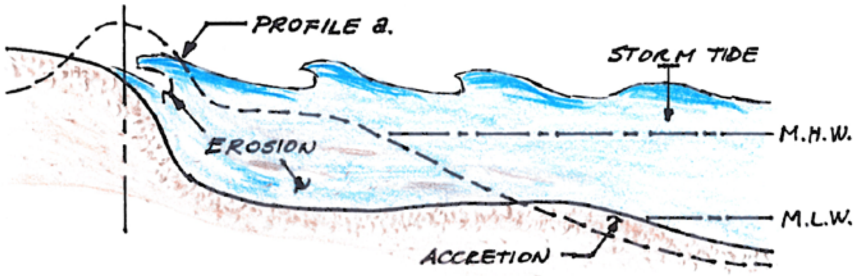
During a storm the higher and stronger ocean waves pick up the sand on the beach and move it offshore, eroding and steepening the beach (Figure 4.2). Waves then start to erode away the dune line. If the dune line is overtopped or breached, then the waves are able to push sand from the beach and dunes landward over the marshes and even into the back-bay. These washovers build the bay-side of the barrier island upward and landward, helping to maintain a barrier island between the open ocean and the mainland (Figure 4.3).



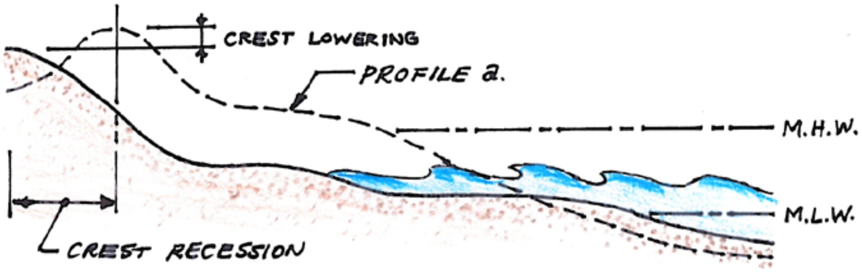
PROFILE a. NORMAL WAVE ACTION



PROFILE b. INITIAL ATTACK OF STORM WAVES



PROFILE c. STORM WAVE ATTACK AT FOREDUNE



PROFILE d. AFTER STORM WAVE ATTACK, NORMAL

Figure 4.2 Beach profile changes in response to a coastal storm (adapted by A. Dyer from U.S. Army Corps of Engineers, 1974).

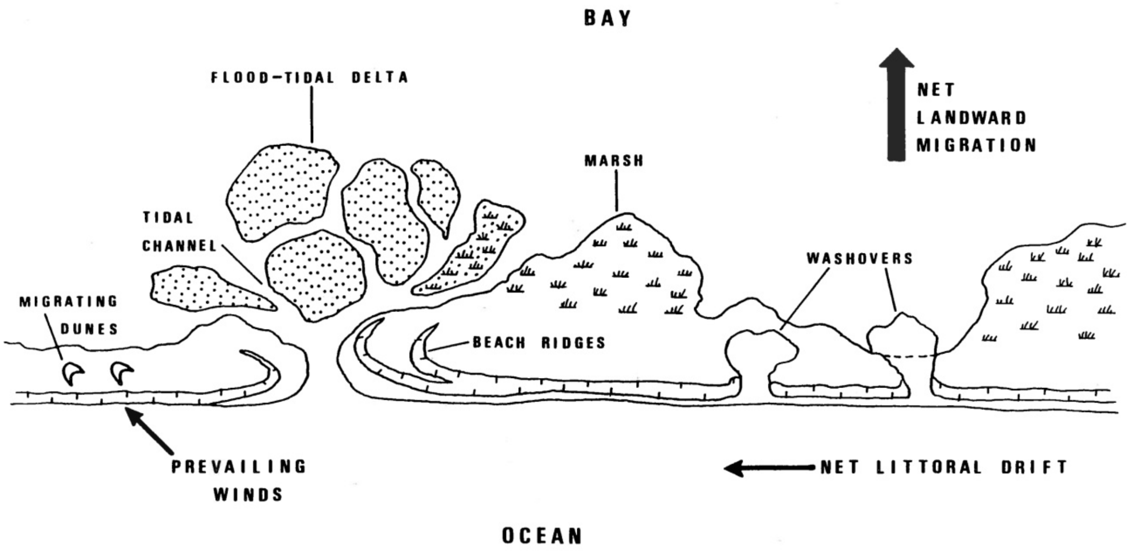


Figure 4.3 Barrier Island formation and migration: Geologic processes responsible for building up a barrier island and allowing it to migrate landward with sea-level rise. (Johnson, AKA Moss, 1982).

In some cases the barrier is completely breached and a new inlet is opened between the ocean and the bay. During high tide sediment is carried through the inlet into the bay, helping to further build up the bay marshes. Longshore drift also carries sediment moving along the beaches into the inlets, building up the beach and dunes on the up-drift side of the inlet, while eroding away the down-drift side of the inlet. Over time inlet migration following the longshore drift can build up the barriers significantly. Longshore drift, washovers and migrating inlets are key processes in maintaining the health of barrier islands. Strong storms such as Nor'easters and hurricanes spur these processes along. Any man-made effort to remove soil from an inlet or bay, such as dredging open navigation channels, reduces the island's ability to preserve itself.

A natural barrier island is free to migrate with storms and changing conditions, allowing it to keep its presence as a buffer between the ocean and the mainland. Man-made structures placed along the beach, however, interfere with natural processes and the island's long-term ability to maintain itself. Structures such as groins and jetties are built perpendicular to the shoreline. The upstream side of the structure traps sand carried by longshore drift, building out the shoreline, but the longshore current no longer carrying sand picks up new sand on the downstream side of the structure, eroding away that section of the beach. Structures built parallel to the beach, such as a seawall, also encourage long-term erosion of the beach front. When waves hit the wall they can be deflected downward and scour away the beach sand at the base of the structure. Over time the beach in front of the wall is narrowed and steepened, and eventually the wall itself is undermined, possibly in a catastrophic failure. These narrowed stretches of the island are more prone to erosion and breaching during subsequent storms.

Along the New Jersey Shore, coastal hydrodynamics vary dependent upon local bathymetry, the presence of barrier islands, and shore line structures, such as groins, jetties, and breakwaters. However, the coast can be divided roughly into 3 zones of different wave climatology (Psuty and Ofiara, 2002) that have a large scale impact on coastal hydrodynamics. Southern New Jersey (Atlantic and Cape May counties) is exposed to wave action from the northeast to the south-southwest with the largest waves coming from the east-northeast (Figure 4.4). The prevailing flows are from north to south, which causes a net transport of sediment to the south. Monmouth County in Northern New Jersey, where there are no barrier islands, is provided protection from northeastern wave action by New England and Long Island. The bulk of the wave action therefore is from the southeast, and this leads to a predominant flow and movement of sediment to the north. A greater proportion of waves arrive directly onshore from the east and east-southeast along the central part of the New Jersey coast, in Ocean County. This is an indication that local features along the shoreline have greater effects on the determination of hydrodynamics and sediment transport (Psuty and Ofiara, 2002) than in zones that have a predominant northern or southern flow. Coastal, surfical soils in Atlantic and Ocean Counties consist of sandy fill with occasional areas of organic soils in tidal flats (USDA, 1978 and USDA 1989).

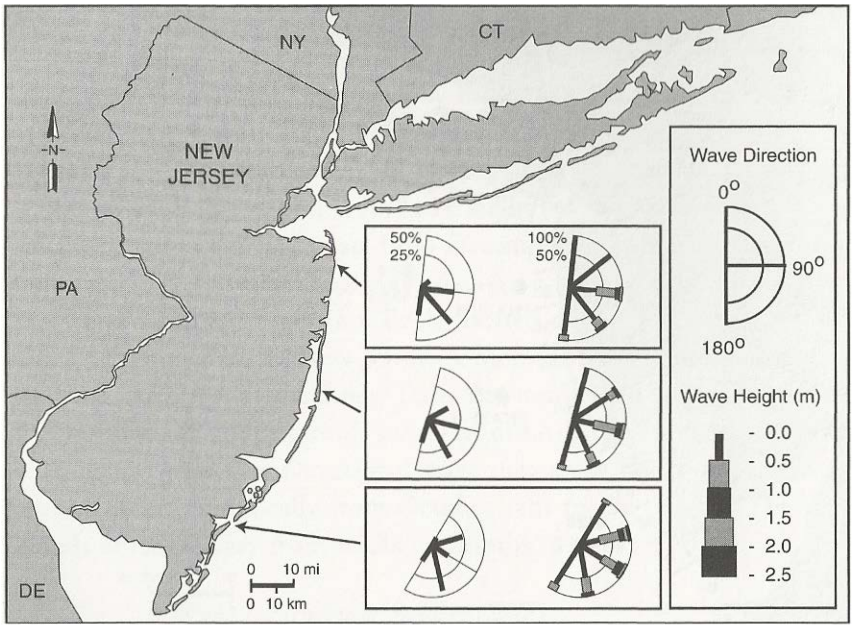


Figure 4.4 Wave roses showing the quadrants of oncoming waves, by percent (left) and percentage of waves of differing heights (right). Source: Psuty and Ofiara, 2002.

Hurricanes can affect a region in several ways. High wind and flooding rain can damage inland areas as well as the coastline. Beaches exposed to the open ocean will face wave damage, while beaches facing a more confined body of water such as a lake or bay will experience more limited wave damage related in part to fetch. A sustained wind blowing across water causes the water level to build up in the down-wind direction. The greater the distance of water over which the wind blows (“fetch”), the greater the height of water build-up (“storm surge”), and consequently the higher the waves that hit the shoreline. Tides also play a part by adding to the combined height of surge and waves during high tide and reducing the height during low tide.

The combination of fetch and tides played a key role in producing the record flooding seen in the New York City area during Hurricane Sandy. Figure 4.5 and Figure 4.6 illustrate how Hurricane Sandy's counterclockwise wind currents caused the predominant high velocity wind direction over Long Island and New York City to be from the east. This pattern was corroborated by the GEER Team's observation that many of the thousands of trees that fell in Long Island during the storm fell to the west.

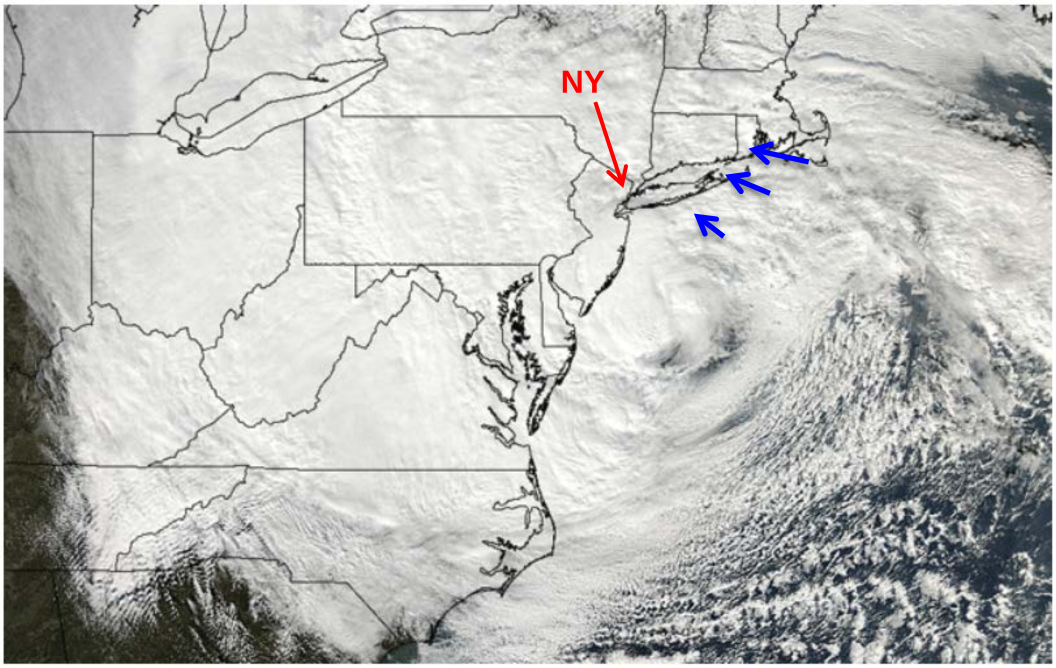


Figure 4.5 Image of Sandy's circulation on Oct. 29 at 2:20 p.m. EDT, as captured by NASA's Aqua satellite (Ref: www.nasa.gov/mission_pages/hurricanes/archives/2012/h2012_Sandy.html) Blue arrows show the direction of the wind as the storm approached landfall in southern NJ. The strongest winds are in the storm's NE quadrant. In the case of Sandy the strongest winds were directed at the NJ and Long Island shorelines. Given the long fetch across the open ocean and the full length of Long Island Sound, extremely large storm surges were allowed to build up and funnel into New York Harbor and into the East River through Long Island Sound.

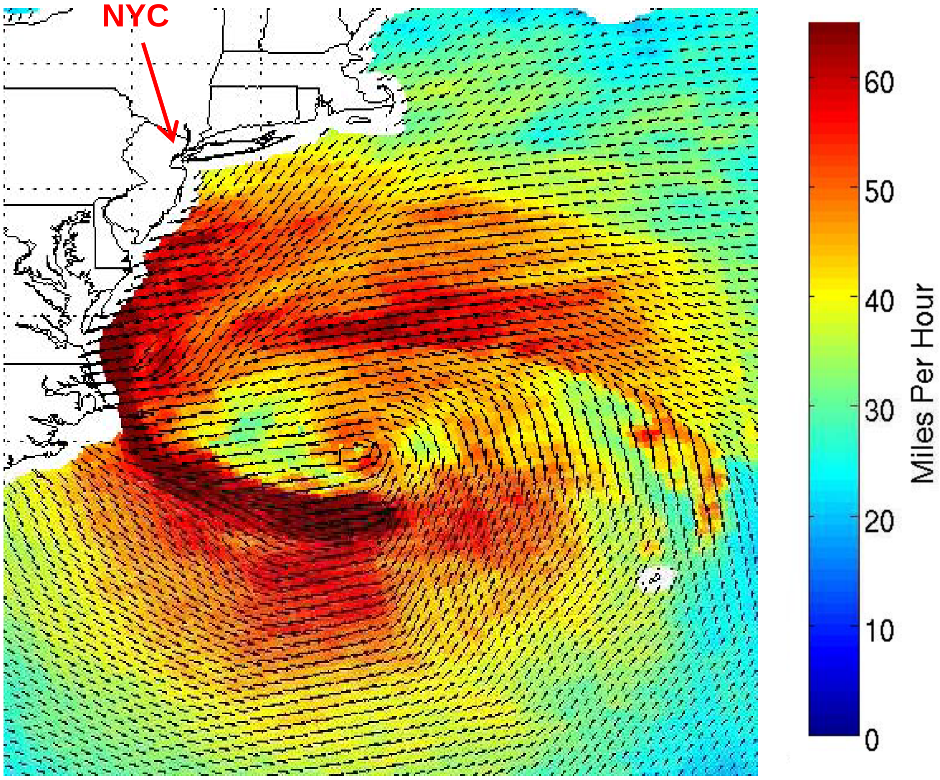


Figure 4.6 Ocean surface winds for Sandy observed at 12:00 a.m. EDT Oct. 29 by the OSCAT radar scatterometer on the Indian Space Research Organization's (ISRO) OceanSat-2 satellite. Colors indicate wind speed and arrows indicate direction. (Ref: www.nasa.gov/mission_pages/hurricanes/archives/2012/h2012_Sandy.html)

Figure 4.7 and Figure 4.8 illustrate how the Sandy wind direction, fetch, coastline shape, and the normal tidal cycle accentuated the storm surge height in the mouth of Raritan Bay and the west end of Long Island Sound. Specifically, the following factors combined to increase the surge:

- The westward direction of the winds created a long fetch distance from the east towards Raritan Bay and Long Island Sound.
- Both Raritan Bay and Long Island Sound narrow to the west. This “constricted” shape caused the surge height to increase as it moved into those areas due to a “funneling” effect.
- The slow movement of the storm resulted in the maximum surge being superimposed above the astronomical high tide.

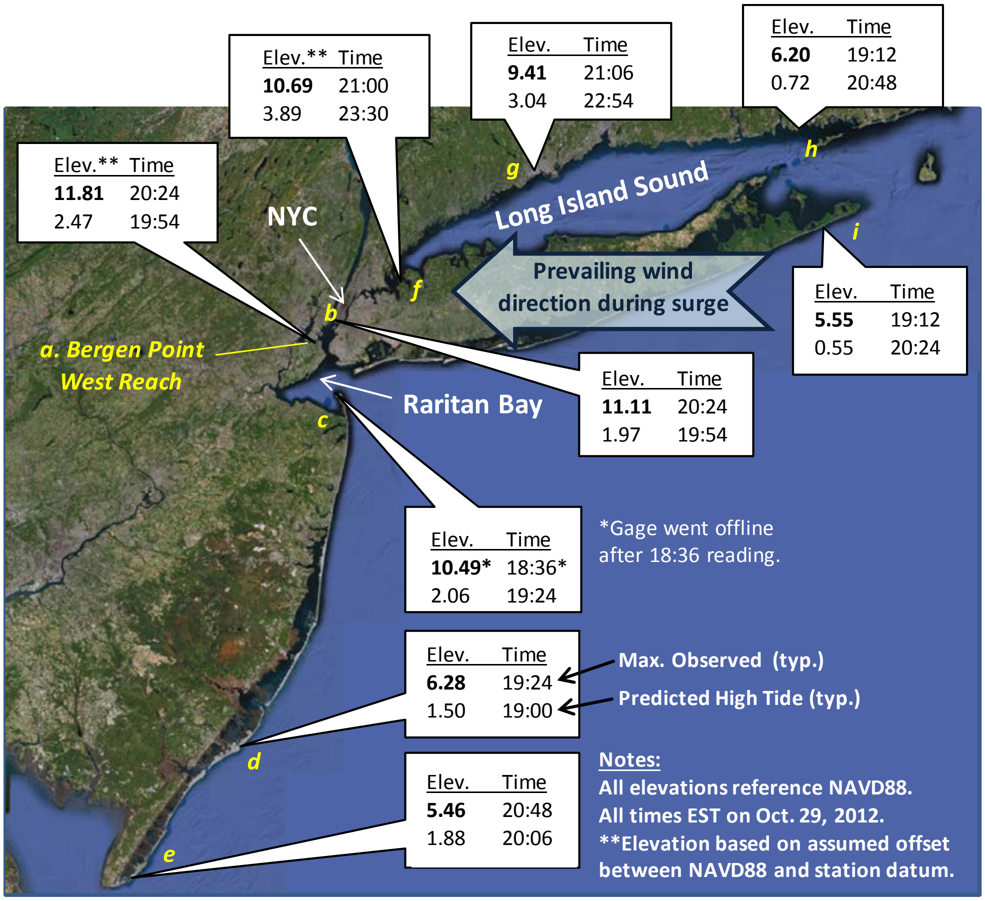


Figure 4.7 Observed and predicted tide data from selected NOAA stations on October 29, 2012 [tidesandcurrents.noaa.gov] with base image from Google Maps (© 2013). See Table 4.1 for station names.

Table 4.1 Summary of Data from Figure 4.7 and Figure 4.8

ID	Station	Predicted High Tide	Time of Predicted High Tide (EST)	Max Observed Water Level (NAVD88)	Time of Max Observed WL (EST)	Time Difference Between Predicted & Observed High (mins)
a	Bergen Point West Reach, NY**	2.47	19:54	11.81	20:24	0:30
b	Battery, NY	1.97	19:54	11.11	20:24	0:30
c	Sandy Hook, NJ	2.06	19:24	10.49	18:36	0:48
d	Atlantic City, NJ	1.50	19:00	6.28	19:24	0:24
e	Cape May, NJ	1.88	20:06	5.46	20:48	0:42
f	Kings Point, NY**	3.89	23:30	10.69	21:00	2:30
g	Bridgeport, CT	3.04	22:54	9.41	21:06	1:48
h	New London, CT	0.72	20:48	6.20	19:12	1:36
i	Montauk, NY	0.55	20:24	5.55	19:12	1:12

▨ - Gage went offline after 18:36 reading.

**Elevations based on assumed offset between Station Datum and NAVD88.

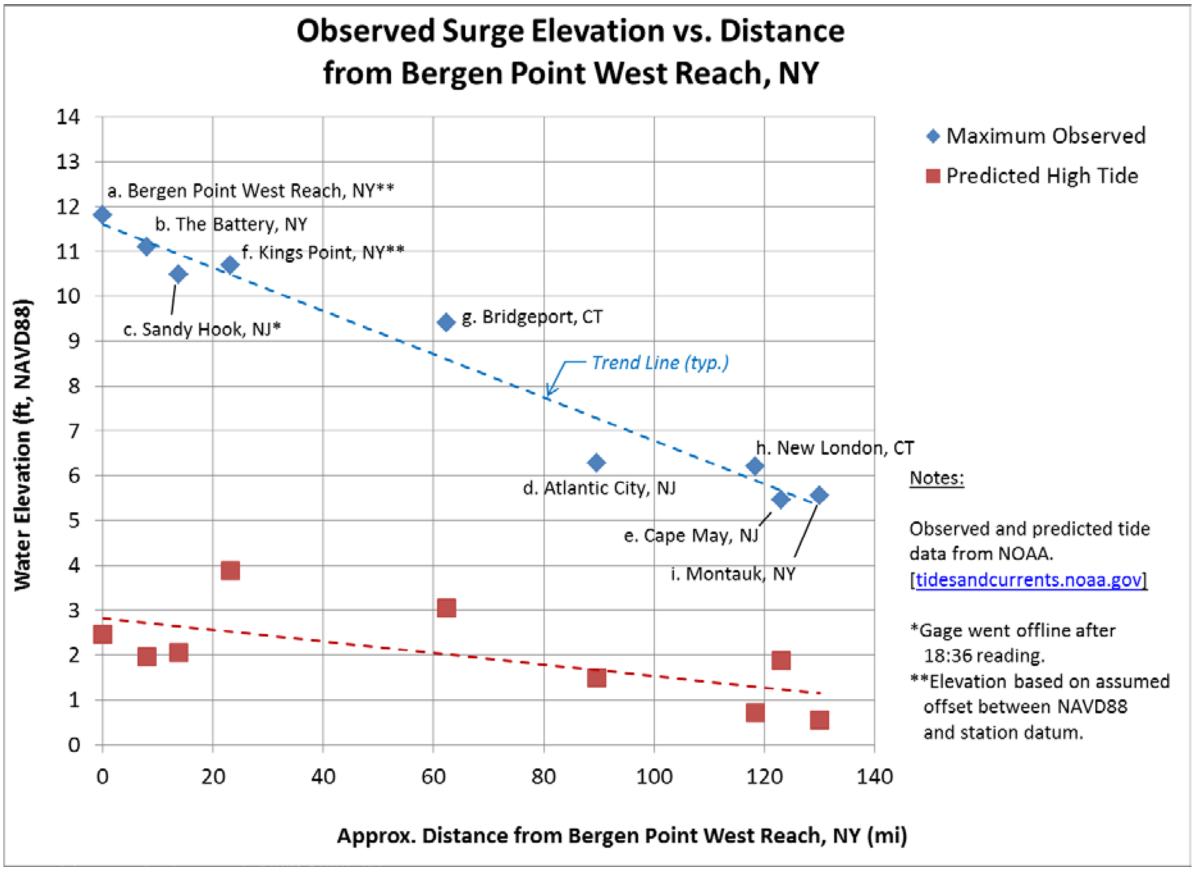


Figure 4.8 Surge elevation as a function of distance from Bergen Point West Reach, NY, illustrating how surge was “funneled” towards Raritan Bay and inner Long Island Sound.

Figure 4.9 through Figure 4.12 illustrate new inlets formed by Hurricane Sandy along the New Jersey and Long Island barrier islands.

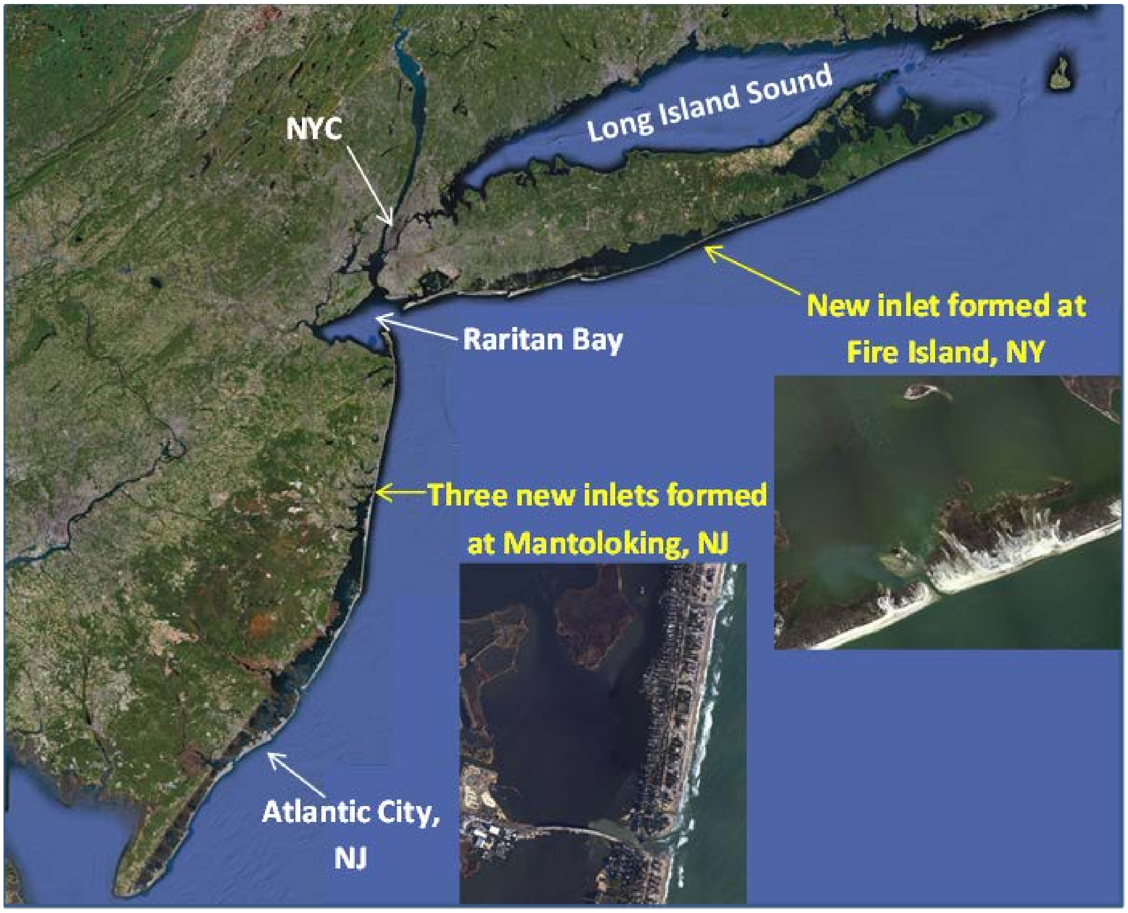


Figure 4.9 Locations of three new inlets formed during Hurricane Sandy. Base image from Google Maps (© 2013), with inset images from tmappsevents.esri.com/website/swipe_sandy/

Figure 4.10 Before and after photos – Houses destroyed and new Inlet formed at Mantoloking, NJ [developed by Schick, K., NJDEP] Ref: tmappsevents.esri.com/website/swipe_sandy/

Figure 4.11 Before and after photos – Houses destroyed and new Inlet formed at Mantoloking – Bayhead, NJ. note home with pool moved 100 yards west into the bay [developed by Schick, K., NJDEP] Ref: tmappsevents.esri.com/website/swipe_sandy/

Figure 4.12 Before and after photos – New Inlet formed at Fire Island, Long Island. Note inlet cut through where island was narrowed by embayment (indicated) Ref: tmappsevents.esri.com/website/swipe_sandy/

Hurricane Sandy's storm surge modified the coastal geomorphology of New York and New Jersey significantly, with the birth of new inlets and severe erosion and scour of soil on the shorelines. As devastating as these effects were for the coastal and barrier island communities in their path, observations suggest they were largely in accordance with predicted behavior. A list of data sources describing observations of coastal geomorphology in the aftermath of Hurricane Sandy, prepared by the United States Geological Survey (USGS), National Park Service, and other organizations, is provided below. While not intended to be comprehensive, this list below provides an indication of the response of the geology and geomorphology communities to the storm, and lessons learned:

1. From Montauk to Manhattan – Measuring Storm Tide and High-Water Marks caused by Hurricane Sandy in New York
    a. Description: Extended abstract for Stony Brook Long Island Geologists conference. Describes and provides links to the tide gage system used to measure Sandy.
    b. Website: http://www.geo.sunysb.edu/lig/Conferences/abstracts13/simonson.pdf
2. Impacts of Hurricane Sandy on the New Jersey Coastline & How Can We Respond?
    a. Description: Abstract and presentation from NE-Geological Society of America annual meeting; describes effects of storm on NJ coast.
    b. Website: https://gsa.confex.com/gsa/2013NE/webprogram/Paper216120.html
3. USGS website providing links to information on the effects of Sandy on the US coastline, including pre and post storm photos: http://coastal.er.usgs.gov/hurricanes/sandy/
4. USGS website providing links to information on the effects of Sandy on the US coastline, including storm surge and high water marks: http://coastal.er.usgs.gov/hazard-events/sandy/
5. Hurricane Sandy Storm Tide Mapper: http://54.243.149.253/home/webmap/viewer.html?webmap=c07fae08c20c4117bdb8e92e3239837e
6. National Park Service documenting changes mapped over time since the storm at the Fire Island Old Inlet breach site: http://www.nps.gov/fiis/naturescience/post-hurricane-sandy-breaches.htm
7. Responding to major storm impacts - Ecological impacts of Hurricane Sandy on Chesapeake & Delmarva Coastal Bays.
    a. Description: describes the storm changes to the Delmarva and Chesapeake regions.
    b. Website: http://www.nfwf.org/hurricanesandy1/Hurricane-Sandy-Chesapeake.pdf
8. NOAA website providing links to a mix of Sandy related websites, mostly from NOAA: http://www.csc.noaa.gov/digitalcoast/geozone/siftingsandydata
9. Delaware Geological Survey website documenting tides and flooding from Sandy in Delaware.: http://www.dgs.udel.edu/delaware-geology/stream-and-tide-gage-data-hurricane-sandy

5 COASTAL BRIDGES

This chapter documents the GEER team's observations of selected bridges located along the New Jersey coastline following hurricane Sandy that impacted the region on October 29, 2012. Eight bridges were identified as coastal bridges and their locations are shown on the vicinity map in Figure 5.1. The GEER team was only able to access five bridges during their deployment on November 3 and 4, 2012 due to security access issues. However, some members of the GEER team made follow up visits to selected sites in subsequent months to gather information. The team also compiled information collected by the New Jersey Department of Transportation (NJDOT 2012a; 2012b) and Ocean County Engineering Department (2012) and this data was used to supplement the reconnaissance data.

Based on the information available, condition assessments of eight bridges were made and summarized in subsequent sections. This included (from north to south) the following bridges:

- NJ 35- Cheesequake River Drawbridge
- Railroad Draw Bridge – Manasquan River
- NJ 35 – Manasquan River Draw Bridge
- NJ 70 – Manasquan River Bridge
- NJ 70 – Metedeconk River Bridge
- NJ 37- Thomas A. Mathis and J. Stanley Tunney Bridges
- NJ 528 – Mantoloking Bridge
- NJ 72- Dorland J. Henderson Memorial Bridge

The collected data suggests that the bridges in general performed well with the exception of the Mantoloking Bridge and were able to remain serviceable immediately or soon after the storm event. Two themes of damage were identified including (1) impacts to drawbridge electrical systems from flooding, and (2) erosion of soil at bridge approaches and abutments. The electrical systems of at least two coastal drawbridges were adversely impacted by flooding. This resulted in loss of function of one drawbridge (NJ 37) in particular that required significant electrical repair efforts. Some consideration might be given in the future toward protecting drawbridge electrical systems from flooding.

Soil erosion was observed near the approaches and abutments of four bridges. In some instances on the order of 5 feet of soil was removed. In the case of the Mantoloking Bridge, the bridge abutments and approaches were undermined and was unserviceable for a prolonged period of time. In two of the bridges (Route 37 and 72) the abutments are supported on fill structures formed by placing fill within a perimeter timber pile solider pile bulkhead wall. The erosion appeared to occur on the tops of these structures which became submerged during the storm flooding. In some cases rip-rap erosion protection has already been placed on these structures that will reduce the potential for erosion at these locations in the future.

Figure 5.1 Vicinity map showing the locations of coastal New Jersey bridges that were inspected by the GEER team or had gathered information on from other sources (Google Earth)

5.1 Route 35- Cheesequake River Drawbridge

The Route 35 drawbridge over Cheesequake Creek (40°27'46.41"N, 74°15'32.61"W) connects Old Bridge and Sayreville in Middlesex County as shown in Figure 5.2. The bridge is currently undergoing a $25 million restoration project to replace bridge decks, sidewalks, railings and median on the 70-year-old structure (NJDOT 2012b).

Information collected by NJDOT following the storm event (NJDOT 2012a) showed erosion adjacent to the southeast abutment wingwall as shown in Figure 5.3. The erosion exposed portions of the concrete wingwall but did not appear to undermine the foundations or compromise the integrity of the abutment. NJDOT’s reconnaissance also indicated that a barrier gate arm on the bridge was damaged from wind.

Figure 5.2 Cheesequake River Drawbridge looking eastward (NJDOT 2012b)

Figure 5.3 Erosion at the southeast abutment wingwall (NJDOT 2012a)

5.2 Railroad Draw Bridge – Manasquan River

The New Jersey Transit Coast Line provides rail service to the New Jersey shore communities to the north New Jersey urban areas and New York City. The railroad draw bridge at the Manasquan River runs from the communities of Manasquan and Brielle on the north bank to Point Pleasant Beach on the south and is located about 1 mile from the ocean inlet. The railroad bridge was at a relatively low elevation, with the stringers 3 to 4 feet above the water (Figure 5.4). The GEER assessment team visited the north abutment and observed no obvious damage and little evidence of the storm on the abutment. The assessment team did not observe the south abutment or the moving part of the drawbridge, which we would expect to have electrical/mechanical damage. The adjacent pleasure boat piers had suffered moderate damage such as loss of walkways (Figure 5.5). The damaged boat piers and the sea grass debris in a chain link fence (see next section) appear to indicate that flood levels would have covered the bridge. It was also noted that the Manasquan River at this location is relatively broad compared to the narrow inlet that connects the river to the Atlantic.

Figure 5.4 Railroad draw bridge at Manasquan River looking south (40.10700ºN, 74.04998ºW, November 5, 2012)

Figure 5.5 Damage to boat piers north of Manasquan River railroad drawbridge (40.10700ºN, 74.04998ºW, November 5, 2012)

5.3 Route 35 - Manasquan River Draw Bridge

The Route 35 draw bridge over the Manasquan River is located about ¼ mile west of the railroad draw bridge and similarly connects Brielle and Point Pleasant Beach. As with the railroad draw bridge, the assessment team visited only the north abutment and observed no damage. The team did not determine if the draw bridge components or the north abutment suffered damages. The Route 35 draw bridge is elevated and the north abutment is set back from the water by about 200 feet and covered with either well-established grass or cobble size riprap. The sea grass debris in a local chain link fence indicates that high water levels would have reached the lower parts of the west abutment but were well below the bridge (Figure 5.6).

Figure 5.6 North abutment of Route 35 draw bridge over Manasquan River. Note possible high water debris in fence. (40.10495ºN, 74.05422ºW, November 5, 2012)

Based on information provided by NJDOT (2012a), the electrical submarine cable room was flooded soon after the storm (Figure 5.7).

Figure 5.7 Flooding in the submarine cable room of the NJ 35 Manasquan River Draw Bridge (NJDOT, 2012a)

5.4 Route 70 – Manasquan River Bridge

The Route 70 bridge over the Manasquan River connects the towns of Brielle to the north and Brick to the south. The bridge is a large, elevated structure (Figure 5.8) located about 3.4 miles upriver from the inlet. The bridge abutments and piers are concrete or concrete-faced. The GEER assessment team saw no evidence of damage to the bridge. Even the surrounding boat piers appeared to have suffered little even though there were signs of high water (sea grass remnants on walkways, building water damage).

Figure 5.8 Route 70 Bridge over the Manasquan River (40.09686ºN, 74.08663ºW, November 5, 2012)

5.5 Route 70 – Metedeconk River Bridge

Another bridge on Route 70 in Brick crosses the Metedeconk River. The bridge is about 5 miles from the ocean. The bridge has one short span (~200 feet), concrete wall abutments, and a low height (~10 feet). There was no damage observed on the abutments or bridge. The disarray of boats in the adjacent boat yard and the level of sea grass debris indicated that the flood surge did reach this area but at a level slightly below the bridge (Figure 5.9).

Figure 5.9 Route 70 bridge over the Metedeconk River (40.06607ºN, 74.13284ºW, November 5, 2012)

5.6 Route 37- Thomas A. Mathis and J. Stanley Tunney Bridges

The Thomas A. Mathis and J. Stanley Tunney Bridges cross Barnegat Bay connecting the communities of Tom's River Township and Seaside Heights (Figure 5.10). Eastbound lanes of Route 37 are carried by the Mathis Bridge with the westbound lanes carried by the Tunney Bridge. Both are girder bridges, and the Mathis Bridge has a drawbridge at its mid-span to allow for ship traffic. The Tunney Bridge is at a higher elevation and has no drawbridge.

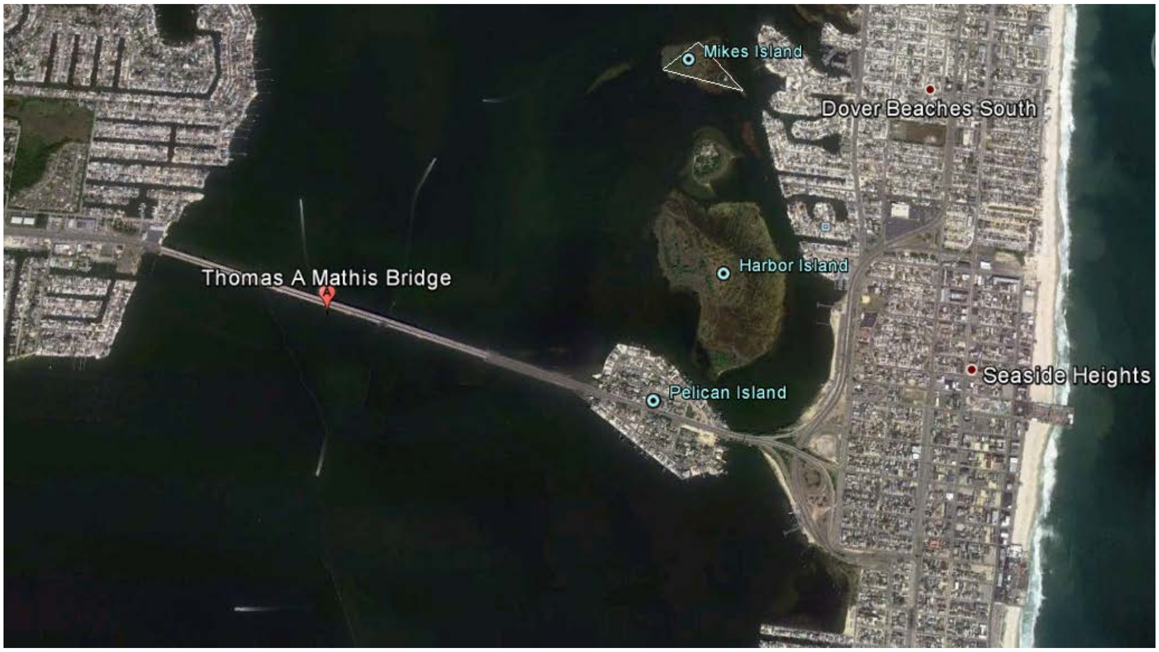


Figure 5.10 Location of Thomas A. Mathis and J. Stanley Tunney Bridges (Route 37). The approximate location of the center spans is 39° 56.7894'' N, 74° 06.2559" W (Google Earth)

The GEER team visited the bridge on November 3, 2012. Access was granted to the east and west abutments of both bridges and the length of the Mathis Bridge. At the time of the visit the Mathis Bridge was closed due to electrical damage to the drawbridge and a missing bearing from one of the stringers (Figure 5.11). The Tunney Bridge was open to emergency vehicles only. Both bridges were opened to residents on a limited basis beginning on December 15, 2012 (WOBM 2012).

Erosion was observed along the sides of both the west and east abutments. Along the northwest abutment, erosion of the soil between the concrete wingwall and the abutment retained by soldier piles and wood lagging undermined a section of the roadway and guardrail (Figure 5.12 and Figure 5.13). Similar erosion occurred on the southwest abutment. It appeared that a portion of the road had been undermined and had been repaired prior to the GEER team visit (Figure 5.14 and Figure 5.15).

On the east abutment there were damaged utility poles (Figure 5.16) and significant erosion (up to 6 feet) of the southeast abutment (Figure 5.17). At the time of the GEER visit this had already been repaired with fill, riprap and geotextiles (Figure 5.18).

Figure 5.11 Mathis Bridge (eastbound) looking north showing a missing bearing for Stringer 3 (NJDOT, 2012a)

Figure 5.12 Erosion along the northwest abutment of the Tunney Bridge (westbound Route 37) 39° 56.9610” N, 74° 06.8341 W (NJDOT 2012a)

Figure 5.13 Erosion along the northwest abutment of the Tunney Bridge (westbound Route 37) 39° 56.9610” N, 74° 06.8341 W

Figure 5.14 Evidence of erosion and recent repair of roadway along the southwest abutment of the Mathis Bridge (eastbound Route 37) 39°56.9610" N, 74° 06.8341 W

Figure 5.15 Erosion along the southwest abutment of the Mathis Bridge (eastbound Route 37) 39° 56.9610" N, 74° 06.8341 W

Figure 5.16 Damaged utility poles along eastern approach of Mathis and Tunney Bridges (westbound Route 37) (NJDOT 2012a)

Figure 5.17 Erosion of embankment and roadway along southeast approach of Mathis Bridge (looking northwest) (NJDOT 2012a)

Figure 5.18 Condition of the southeast abutment of Mathis Bridge during the GEER visit (eastbound Route 37)

5.7 Route 528 (Mantoloking Bridge)

The GEER team was unable to visit Mantoloking Bridge (40° 2’24.21” N, 74° 3’6.79” W), but relied on information provided by Ocean county Engineering Department (Ocean County Engineering, 2012). Mantoloking Bridge connects Mantoloking to Brick Township on the mainland across Barnegat Bay. The structure is approximately 1,200 feet long and is a double leaf bascule draw span (J.H. Reid General Contractor, 2011). The foundation is comprised of concrete-filled pipe piles. There are five piles for each pier to form the substructure of the approach spans. The superstructure consists of a reinforced concrete slab on pre-stressed concrete beams that connect to the piers (Brick Township Bulletin, 2006). Two 3,200-sq.-ft. steel sheet pile coffer dams support the bascule piers, each of which are supported on 100 steel pipe piles

(ConstructionEquipmentGuide.com). The Mantoloking end of the bridge suffered damage during Hurricane Sandy as a result of the storm surge when a breach opened between Barnegat Bay and the Atlantic Ocean (Figure 5.19).

The bridge remained unserviceable immediately following the storm. The bridge was opened to residents on January 7, 2013. The east abutment of the bridge suffered damage, especially on the south side due to erosion (Figure 5.20, Figure 5.21, Figure 5.22).

Sheet piles were driven along the barrier island in order to allow repair of the breach (Figure 5.23). In addition, the repair work included replacing the existing roadway and filling the eroded areas with rip rap and placing filter fabric cover in addition to reconstructing sections of the roadway (Figure 5.24).

Figure 5.19 Approach to Mantoloking Bridge, which was flooded soon after the storm and inundated by debris (40° 2’24.21” N, 74° 3’6.79” W , Ocean County Engineering, 2012)

Figure 5.20 Damage to the east abutment of the bridge due to erosion undermining the foundation (40° 2’24.21” N, 74° 3’6.79” W , Ocean County Engineering, 2012)

Figure 5.21 Damage to the south side of the east abutment due to erosion and large floating debris such as homes caused the loss of the T-wall, which allowed the coping and sidewalk to be cantilevered out approximately 10 ft (40° 2’24.21” N, 74° 3’6.79” W , Ocean County Engineering, 2012)

Figure 5.22 Damage to the north side of the east abutment due to erosion caused the T-wall to settle 4 ft (40° 2’24.21” N, 74° 3’6.79” W, Ocean County Engineering, 2012)

Figure 5.23 Sheet Piles driven in Mantoloking along the breached section (40° 2'22.95"N, 74° 3'0.53"W, NJ Task Force 1)

Figure 5.24 NJ-35 in Mantoloking looking north towards the bridge (40° 2'22.95"N, 74° 3'0.53"W, NJDOT, 2012a)

5.8 State Highway Route 72 (Dorland J. Henderson Memorial Bridge)

The Dorland J. Henderson Memorial bridge (39.6616°N, 74.2026°W) formerly known as the Manahawkin Bay Bridge is the only bridge connecting Long Beach Island (LBI) to the mainland. The bridge consists of four main sections running east to west with the easternmost section connecting to LBI in the Boro of Ship Bottom. Sections of the bridge appear to be supported on either steel or precast concrete girders on concrete abutments. Additionally some portions are supported on timber pile bents as shown in Figure 5.25. The bridge abutments appear to be supported on fill structures formed by placing soil within a perimeter timber solider pile bulkhead wall.

The bridge remained serviceable immediately following the storm. However, only emergency vehicles were allowed to pass over the period of October 29 to November 5, 2012. The bridge was opened to contractors on November 5, 2012 and residents on November 10, 2012.

Figure 5.25 Easternmost section of the Highway 72 Bridge looking westward (39°39'13.77"N, 74°11'4.11"W).

The GEER team attempted to access the site on November 3, 2013 but was denied access. The team later followed up with a site visit on November 26, 2012 accompanied by a Construction Official from Ship Bottom. Inspections were performed at that time on the east abutment of the span shown in Figure 5.26. The Construction Official indicated that the bridge section shown in Figure 5.25 is scheduled for replacement in 2013.

Photographs of the westernmost section obtained by NJDOT immediately after the storm (NJDOT 2012a) showed significant erosion on both the west and east abutments (Figure 5.26 and Figure 5.27) respectively. However, the erosion did not appear to undermine the abutment foundations.

Inspections by the GEER team on the east abutment of the easternmost bridge section showed some erosion along the approaches and adjacent to the abutment. A concrete walkway near the abutment had been washed away and was in the process of being reconstructed at the time of the visit as shown in Figure 5.28. In addition, erosion mats and soil had been placed to replace some of the eroded material along the approaches. The Construction Official stated that there was no major structural damage to the bridge.

Figure 5.26 Severe erosion observed at the Rt. 72 east abutment, looking north (NJDOT 2012a).

Figure 5.27 Severe erosion observed at Rt. 72 east abutment, looking south-east (NJDOT 2012a).

Figure 5.28 Replacement of the concrete walkway adjacent to Rt. 72 east abutment (39°39'13.44"N, 74°11'4.91"W).

6 COASTAL COMMUNITIES

A map of the New York City area communities described herein is provided as Figure 6.1. Communities visited in in New Jersey are shown in Figure 6.2.

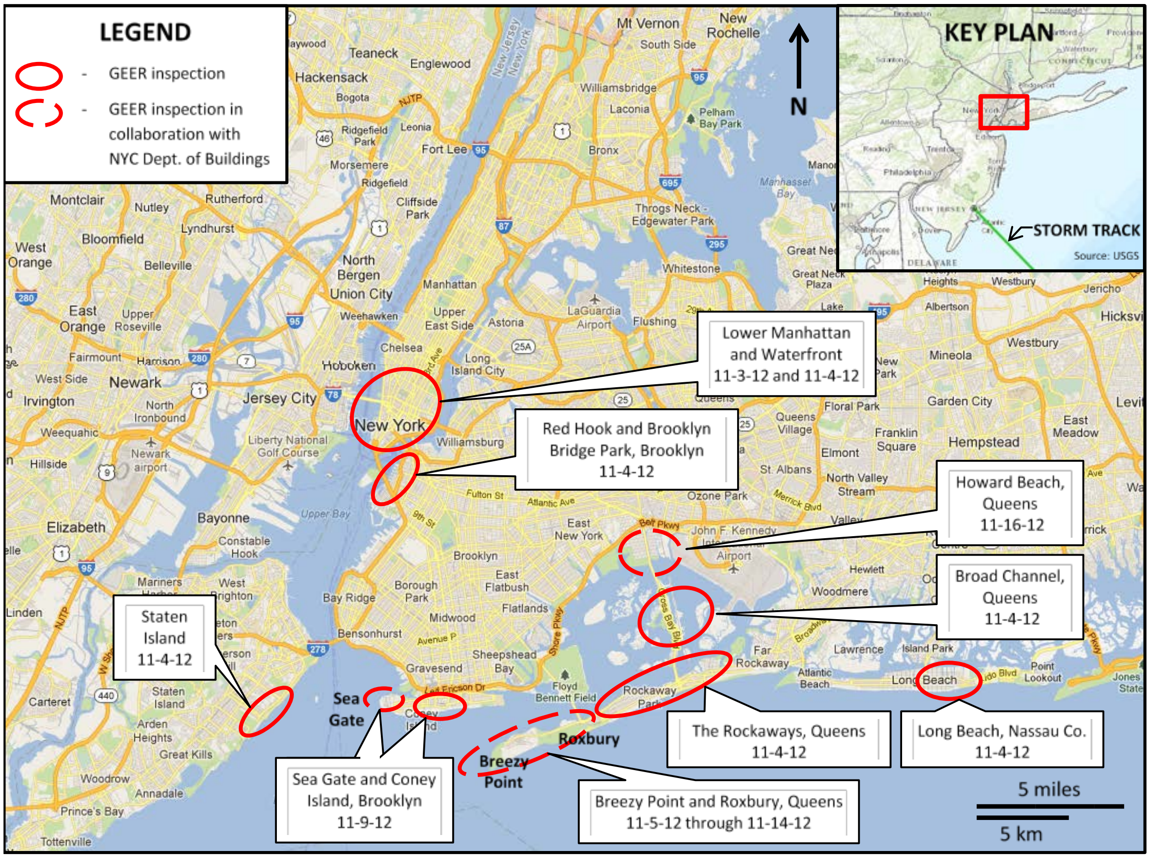


Figure 6.1 Map of New York City Reconnaissance Areas

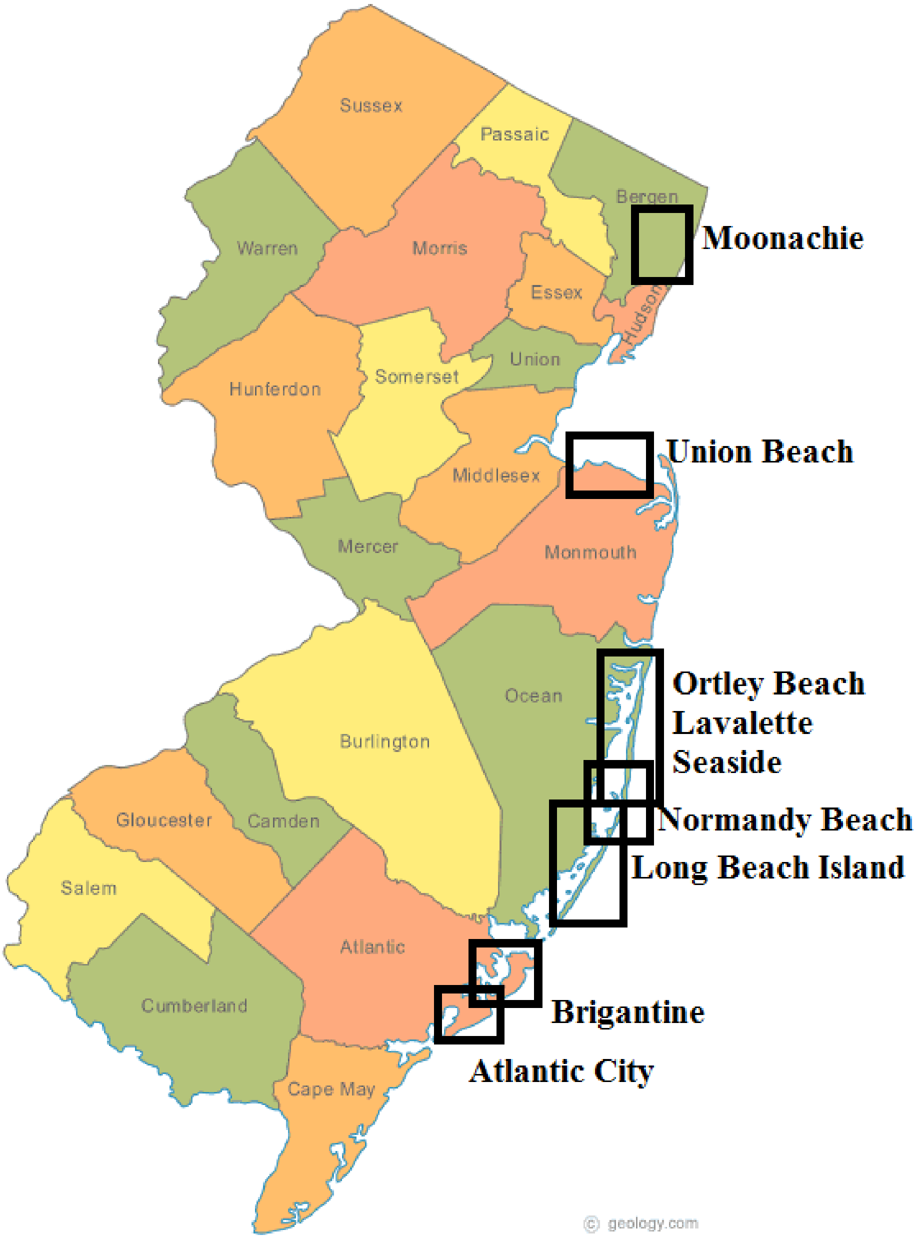


Figure 6.2 Map of New Jersey Reconnaissance Areas (http://geology.com/state-map/new-jersey.shtml)

6.1 Geology of New York City Area

The following summary of New York City geology is adapted primarily from Tamaro et al (2000). Refer to that reference for an in-depth description of the geologic conditions in New York City.

As illustrated in Figure 6.3 and Figure 6.4, New York City sits at the intersection of three major physiographic provinces: the Triassic Lowland to the west, the Manhattan Prong (a region of the New England Uplands) and the Coastal Plain to the south and east. The boroughs of Manhattan and the Bronx, as well as parts of Brooklyn, Queens, and Staten Island lie within the Manhattan Prong, a northeast- trending, deeply eroded sequence of metamorphic rock. Bedrock in these areas is relatively shallow. Eastern Queens and Brooklyn lie within the Coastal Plain, a low-lying region underlain by a thick, southeast-dipping sequence of Cretaceous sands and clays (Lloyd, Raritan, and Magothy Formations). The boundary between the Manhattan Prong and Coastal Plain provinces is termed the Fall Line.

Surficial geology in New York City and Long Island is dominated by glacial deposits overlain by tidal marshland and man-made fill. As shown in Figure 6.5, an east-northeast-trending ridge of sand, gravel, clay, silt, boulders, and cobbles marks the location of the terminal moraine left behind by the last Pleistocene glacial advance and forms the topographic “backbone” of Staten Island and Long Island. Northwest of the moraine, bedrock is overlain by a relatively thin mantle of glacial till or ground moraine, an unsorted mixture of sand, gravel, clay, cobbles, and boulders. During the glacial retreat about 20,000 years ago, present-day New York Harbor was dammed by the terminal moraine, and impounded melt water created a series of glacial lakes (including Glacial Lake Hackensack), resulting in a glacial lake deposit of varved silt, clay, and fine sand which underlies parts of all five New York City boroughs and northeastern New Jersey (Stanford and Harper 1991). South and east of the terminal moraine, a broad outwash plain composed of sand and gravel underlies eastern Brooklyn and Queens. In recent times, organic silty clay and peat were deposited in tidal marshes along low-lying coastal areas, and man-made fill was placed along much of the perimeter of New York City.

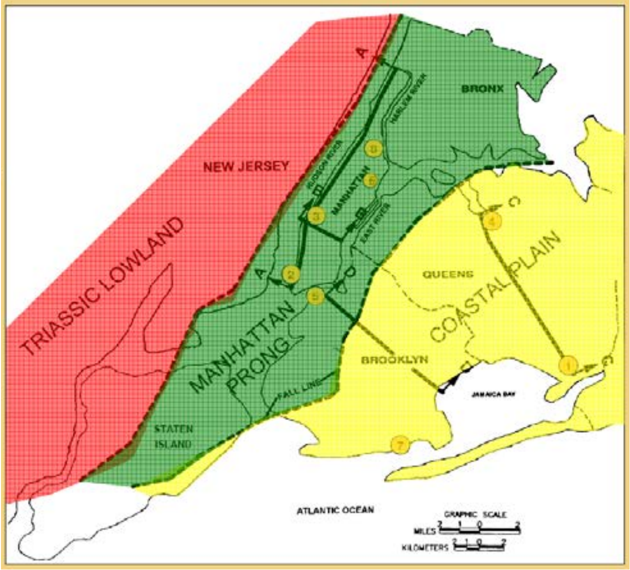
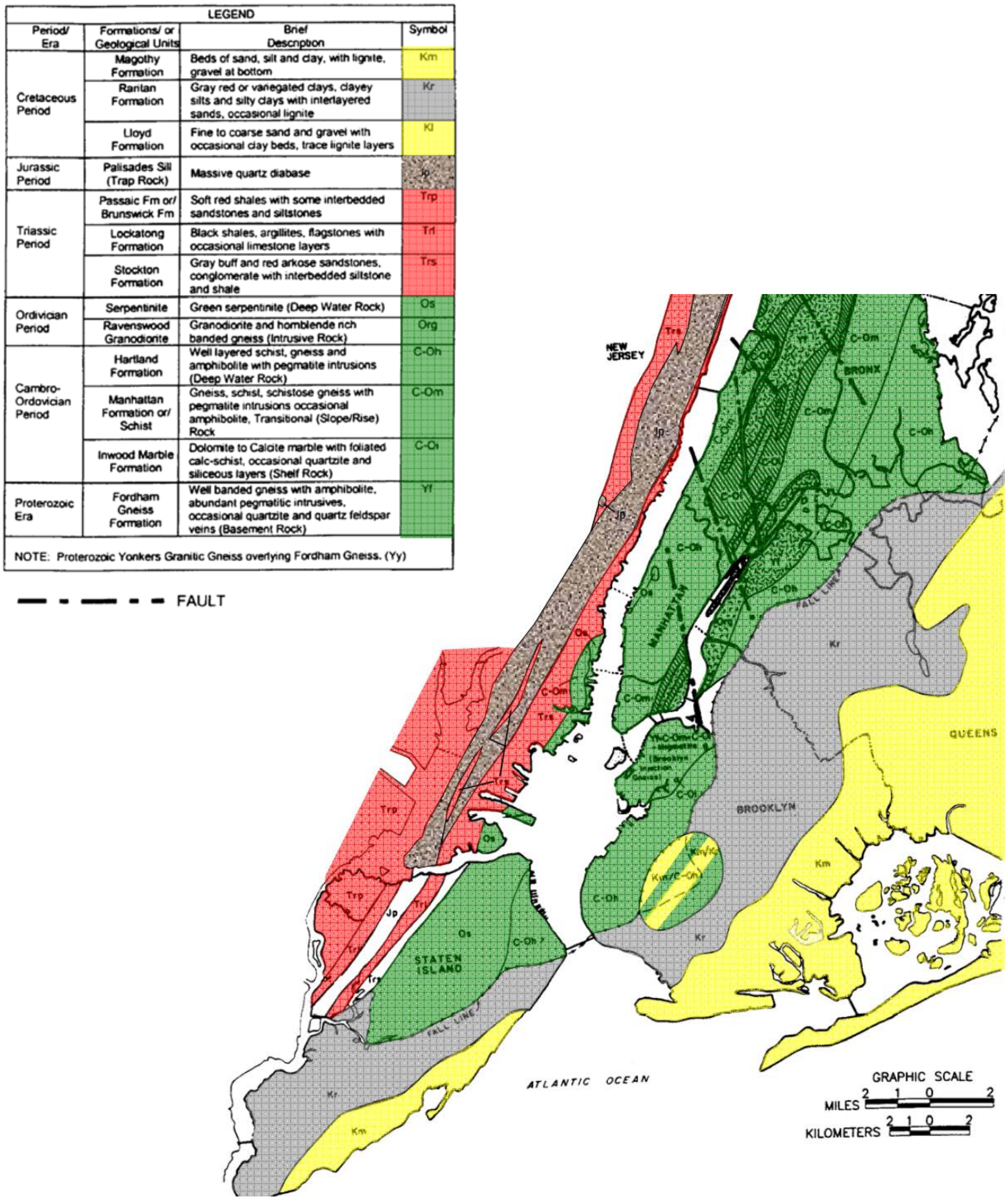


Figure 6.3 Physiographic Provinces of New York City (Tamaro, Kaufman, and Azmi [2000]).



LEGEND			
Period/ Era	Formations/ or Geological Units	Brief Description	Symbol
Cretaceous Period	Magothy Formation	Beds of sand, silt and clay, with lignite, gravel at bottom	Km
	Raritan Formation	Gray red or variegated clays, clayey silts and silty clays with interlayered sands, occasional lignite	Kr
	Lloyd Formation	Fine to coarse sand and gravel with occasional clay beds, trace lignite layers	Kl
Jurassic Period	Palisades Sill (Trap Rock)	Massive quartz diabase	Jp
Triassic Period	Passaic Fm or/ Brunswick Fm	Soft red shales with some interbedded sandstones and siltstones	Trp
	Lockatong Formation	Black shales, argillites, flagstones with occasional limestone layers	Trl
	Stockton Formation	Gray buff and red arkose sandstones, conglomerate with interbedded siltstone and shale	Trs
Ordivician Period	Serpentinite	Green serpentinite (Deep Water Rock)	Os
	Ravenswood Granodiorite	Granodiorite and hornblende rich banded gneiss (Intrusive Rock)	Org
Cambro-Ordovician Period	Hartland Formation	Well layered schist, gneiss and amphibolite with pegmatite intrusions (Deep Water Rock)	C-Oh
	Manhattan Formation or/ Schist	Gneiss, schist, schistose gneiss with pegmatite intrusions occasional amphibolite, Transitional (Slope/Rise) Rock	C-Om
	Inwood Marble Formation	Dolomite to Calcite marble with foliated calc-schist, occasional quartzite and siliceous layers (Shelf Rock)	C-Oi
Proterozoic Era	Fordham Gneiss Formation	Well banded gneiss with amphibolite, abundant pegmatitic intrusives, occasional quartzite and quartz feldspar veins (Basement Rock)	Yf
NOTE: Proterozoic Yonkers Granitic Gneiss overlying Fordham Gneiss. (Yy)			

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Figure 6.4 Geologic Map of New York City and Eastern Part of New Jersey (Tamaro, Kaufman, and Azmi [2000]).

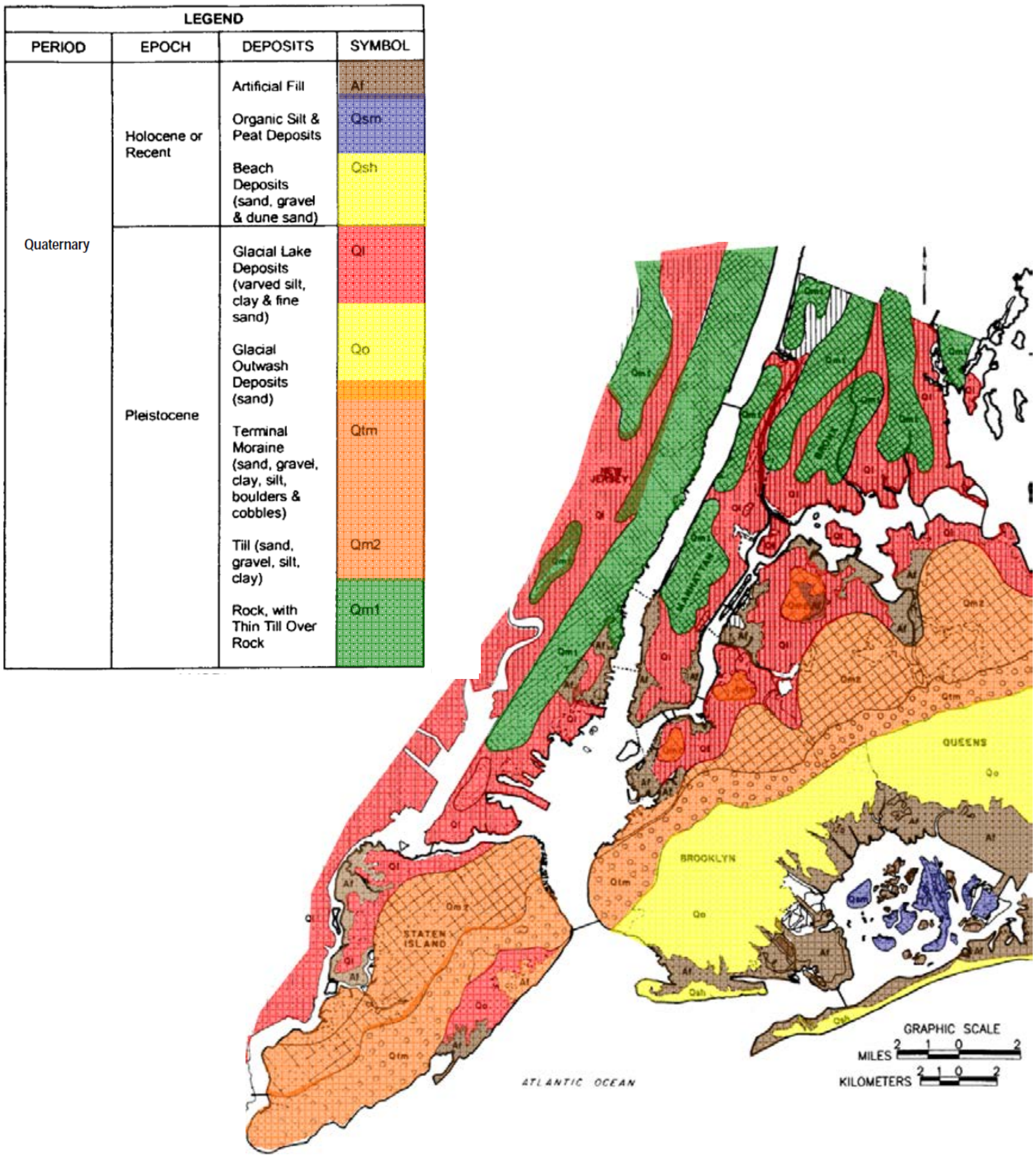


Figure 6.5 Surficial Geology Map of New York City and Eastern Part of New Jersey (Tamaro, Kaufman, and Azmi [2000]).

6.2 Staten Island, New York

Midland Beach and South Beach are primarily residential neighborhoods on the southeast shoreline of Staten Island. This portion of the Staten Island shoreline faces the mouth of Raritan Bay and is directly exposed to open ocean to the east. Father Capodanno Boulevard, which defines the eastern edge of these neighborhoods, runs parallel to the shoreline and is separated from the beach by a 250- to 500-foot wide strip of vegetated park land. Development in the areas examined is mostly one- and two- story houses, with interspersed zones of three to six story multi-family dwellings.

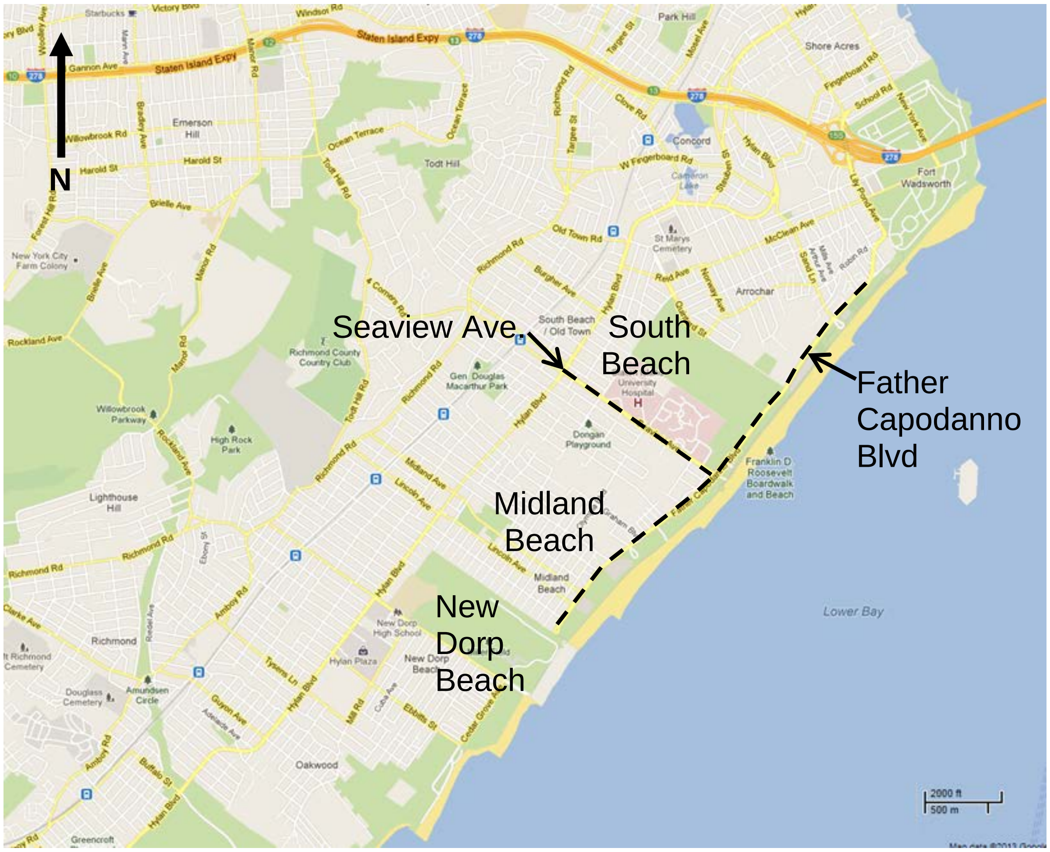


Figure 6.6 Map of a portion of Staten Island.

As described in Section 6.1, the Staten Island shoreline in the area investigated is underlain primarily by glacial outwash sand overlain by artificial fill in some locations.

Destruction of timber-frame houses in Staten Island, particularly in the New Dorp Beach neighborhood, was well publicized in news media. Figure 6.7 shows “before” and “after” aerial photography of a row of houses located directly on the beachfront which was completely removed by the storm, and Figure 6.8 shows an aerial photo of damaged homes on Cedar Grove Ave. in New Dorp Beach.

Figure 6.7 Aerial photographs of portion of New Dorp Beach, Staten Island before and after Sandy showing row of houses completely removed, with debris moved inland. Imagery from: [tmappsevents.esri.com/website/swipe_sandy/.](tmappsevents.esri.com/website/swipe_sandy/)

Figure 6.8 Aerial photograph of damaged homes on Cedar Grove Ave. in New Dorp Beach. Imagery from Staten Island Advance by B. Lyons at www.silive.com/news/index.ssf/2013/02/hurricane_sandy_was_the_second.html

Severe soil erosion (scour) was observed by the GEER team along Father Capodanno Boulevard in Midland Beach. Sinkholes had undermined the street, curbline, sidewalks, utility poles, and house foundations in this area. In at least one location, a concrete masonry unit (CMU) block foundation wall was damaged and partly removed, causing severe distress to the timber-frame house above. Throughout the area, timber decks, trees, cars, and other debris had been picked up and deposited inland.

Many areas visited inland of Father Capodanno Boulevard in Midland Beach and South Beach had extensive water damage to the first floors and basements of all buildings; however, most were on concrete foundations and withstood the rising waters without damage except to possessions within, interior construction, and utility installations.

Figure 6.9 Scour undermining street, curb, sidewalk, and utilities, Seaview Blvd and Father Capodanno Blvd, Staten Island (40.579283° N, 74.077849° W, November 4, 2012). GEER team co-leader Dr. Sissy Nikolaou in background.

Figure 6.10 Scour undermining overhead power pole and sign, Slater Blvd and Father Capodanno Blvd, Staten Island (40.576173° N, 74.082629° W, Nov. 4, 2012). GEER team co-leader Dr. Youssef Hashash in background.

Figure 6.11 Scour undermining sidewalk, infrastructure utilities, and light pole foundation, Seaver Ave and Father Capodanno Blvd, Staten Island (40.575944° N, 74.083015° W, November 4, 2012).

Figure 6.12 Scour undermining stair foundation and foundation drain, Seaver Ave and Father Capodanno Blvd, Staten Island (40.575944° N, 74.083015° W, November 4, 2012).

Figure 6.13 Damaged CMU block foundation, distressed timber frame house, and relocated wood deck, Staten Island (40.575944° N, 74.083015° W, November 4, 2012).

Figure 6.14 Flood water displaced timber debris and cars, Staten Island (40.575944° N, 74.083015° W, November 4, 2012).

6.3 Brooklyn, Queens, and Long Beach, New York

Reconnaissance focused on the coastal or near-coast neighborhoods of Sea Gate and Coney Island in Brooklyn; The Rockaways, Broad Channel, and Howard Beach in Queens; and the city of Long Beach in Nassau County. These primarily residential communities are located along the barrier peninsula and island that border the south shoreline of New York City and Nassau County, New York. The Rockaway Peninsula, more commonly referred to as The Rockaways, comprises multiple communities from Breezy Point at the west end to Roxbury, Fort Tilden, Jacob Riis Park, Neponsit, Belle Harbor, Rockaway Park, Rockaway Beach, Arverne, and Far Rockaway at the east end. These communities vary distinctly in character. A map of the communities described in this section is provided below.

Figure 6.15 Map of coastal communities in Brooklyn, Queens, and Nassau County

The GEER November 4th, 2012 reconnaissance focused primarily on the ocean-facing blocks between Beach 44th and Beach 116th Streets (neighborhoods of Rockaway Park, Rockaway Beach, and Arverne) in the Rockaways, between Harrogate Street and Monroe Boulevard in Long Beach, and along Cross Bay Boulevard in Broad Channel. Subsequent reconnaissance in Sea Gate, Coney Island, Breezy Point, Roxbury, and Howard Beach was performed by MRCE engineers in collaboration with the New York City Department of Buildings (NYCDOB).

Development in the coastal communities of Brooklyn, Queens, and Long Beach is characterized by a diverse stock of wood frame “bungalow” houses, two- to three- story wood and brick veneer townhouses, three- to six-story apartment buildings, and high-rise residential towers. The ocean-facing fronts of these neighborhoods are often characterized by beaches with concrete pier-supported wooden boardwalks over most of their lengths, approximately 2.5 miles in Coney Island, five miles in the Rockaways, and two miles in Long Beach.

As shown in Figure 6.16, the southern shoreline of Brooklyn, Queens, and Long Beach are generally underlain by a thick profile of sand and clay with bedrock at depths exceeding 800 feet. Below surficial deposits of fill, beach and barrier island sand, or tidal marsh deposits of organic silt, clay, and peat, the upper 100 to 150 feet of the soil profile are characterized by Pleistocene glacial outwash sand. Figure 6.17 shows that much of what is now Breezy Point in The Rockaways sits on barrier island sand deposited in the last several hundred years.

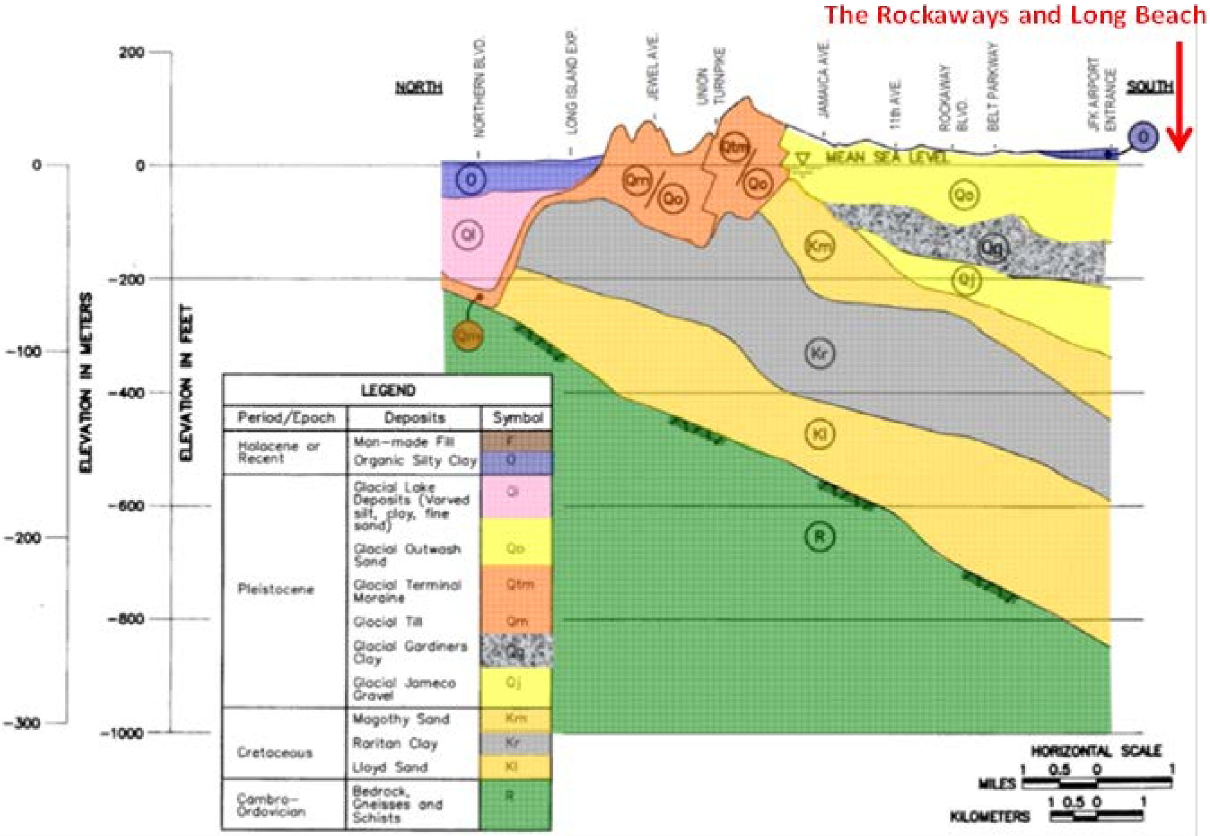
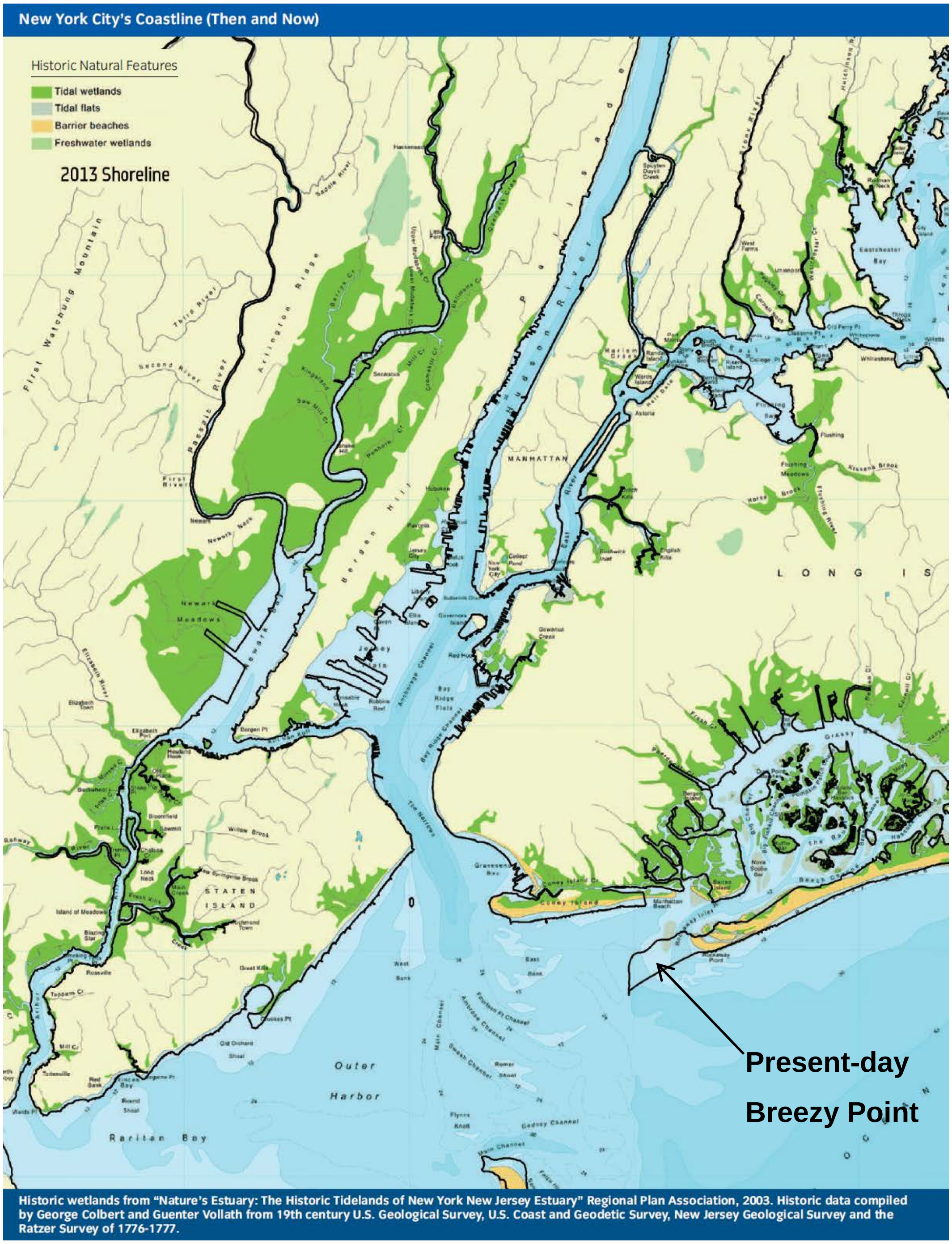


Figure 6.16 Geological Section of Queens (from Tamaro et al 2000)


New York City's Coastline (Then and Now)

Present-day Breezy Point

Historic wetlands from "Nature's Estuary: The Historic Tidelands of New York New Jersey Estuary" Regional Plan Association, 2003. Historic data compiled by George Colbert and Guenter Vollath from 19th century U.S. Geological Survey, U.S. Coast and Geodetic Survey, New Jersey Geological Survey and the Ratzer Survey of 1776-1777.

Figure 6.17 Comparison of historic and present New York City coastline (from New York City Special Initiative for Rebuilding and Resiliency report "A Stronger, More Resilient New York," June 2013).

6.3.1. Sea Gate

Sea Gate is located at the southwestern extreme of the New York City borough of Brooklyn, on a peninsula which extends westward into Raritan Bay and is surrounded by the ocean on three sides. Its shoreline is defined by a sand beach that faces open ocean to the south and southeast. Development is characterized by two- and three-story wood frame and brick veneer houses. Many beachfront houses are separated from the beach by concrete or sheet pile retaining walls.

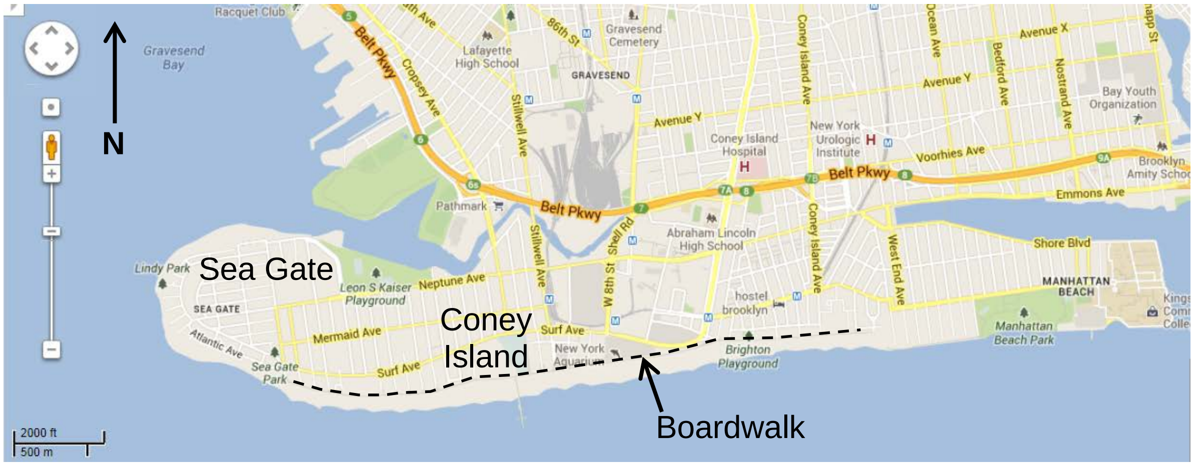


Figure 6.18 Map of Sea Gate and Coney Island, Brooklyn

Many observed homes in Sea Gate suffered significant structural damage ranging from partial collapse of brick siding to loss of walls and floors. This damage appeared to be related to wind and wave attack or debris impact. A majority of the observed buildings in this area had concrete wall foundations which suffered relatively little damage. In at least one area, the beachfront concrete retaining wall was undermined and broken, and the soil behind the wall washed out.

	
Figure 6.19 Damage to brick siding, Sea Gate, Brooklyn (November 9, 2012 – MRCE in collaboration with NYCDOB)	Figure 6.20 Brick veneer building on concrete wall foundation, Sea Gate, Brooklyn (November 9, 2012 – MRCE in collaboration with NYCDOB)

	
Figure 6.21 Undermining of beachfront retaining wall and loss of retained soil, Sea Gate, Brooklyn (November 9, 2012 – MRCE in collaboration with NYCDOB)	Figure 6.22 Partial wall and floor collapse, wood building on concrete wall foundation. Sea Gate, Brooklyn (November 9, 2012 – MRCE in collaboration with NYCDOB)

6.3.2. Coney Island

Coney Island is located at the south edge of the New York City borough of Brooklyn. Its shoreline faces open ocean to the south, but is protected to the southeast by the Rockaway Peninsula (See Figure 6.18 above). Development is characterized by high and low rise housing, shops, public spaces (including the

New York Aquarium) and an amusement park. A boardwalk and beach define the southern edge of Coney Island.

Damage in the observed areas in Coney Island was primarily related to flood inundation and sand movement. High water marks two to three feet above the ground surface were observed between Surf and Neptune Avenues (one to two blocks inland of the beach). One high-rise development experienced damage to landscaping and buried utilities when flood waters from outside the buildings entered the basement crawl spaces by eroding ("piping") through the soil beneath the perimeter grade beams, creating sinkholes on the exterior perimeter of the buildings, undermining some service pipes. No apparent damage to the building structures or pile supported foundations was observed. The Coney Island boardwalk sustained damage to lighting and restroom facilities, but escaped major structural damage.

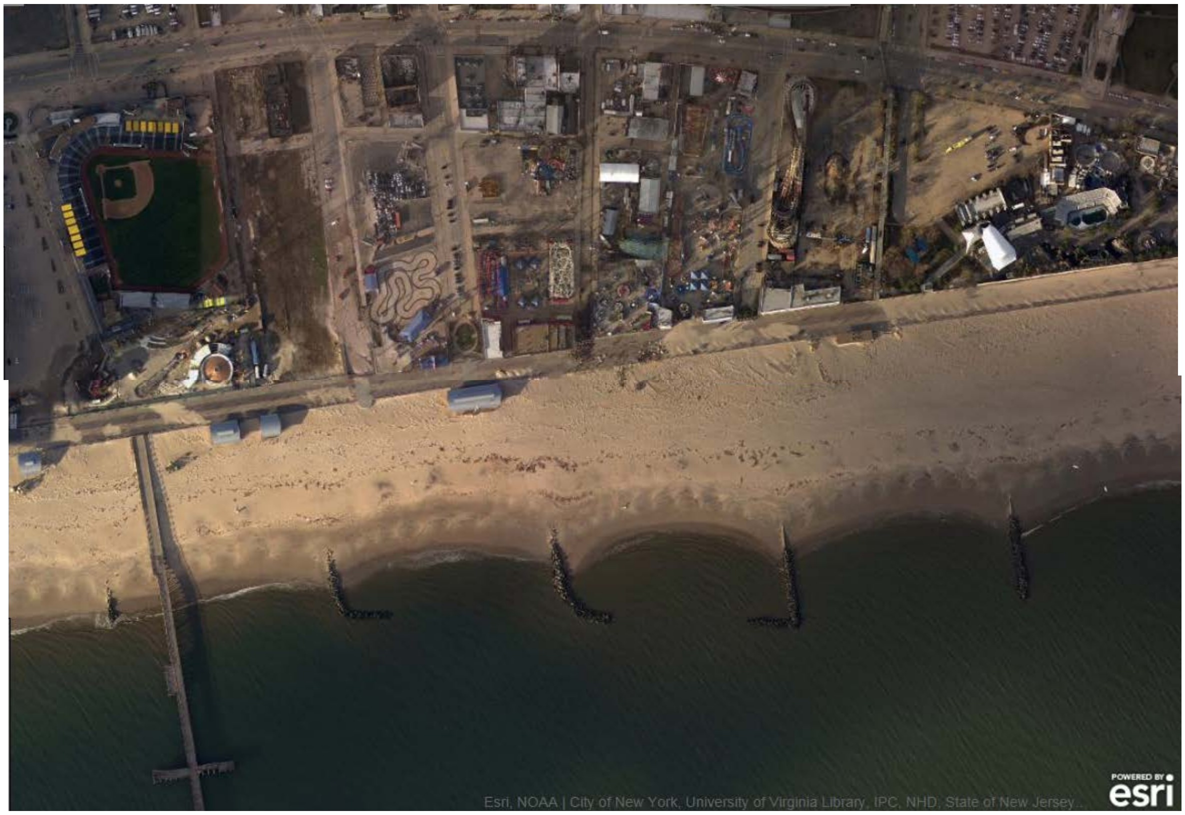


Figure 6.23 Aerial view of Coney Island boardwalk after Sandy showing sand movement but no major structural damage. Imagery from: tmappsevents.esri.com/website/swipe_sandy/

Figure 6.24 Sinkhole created by erosion and piping of flood water into building crawl space, Coney Island, Brooklyn. Note broken utilities undermined by the sinkhole.

6.3.3. The Rockaways – Rockaway Park, Rockaway Beach, and Arverne

Damage to shorefront residences and infrastructure in these neighborhoods was significant. Evidence of flooding to a level approximately 2.5 to five feet above street level was observed throughout. Nearly all basements and most first floors appeared flooded. In Rockaway Park, a fire had destroyed multiple buildings north of Rockaway Beach Boulevard near Beach 115th Street. In Rockaway Beach, approximately one foot of sand had been deposited on the streets closest to the ocean, extending as far inland as Rockaway Beach Boulevard (approximately 500 to 1,000 feet inland) in some locations (See Figure 6.25). The wood boardwalk had been lifted off its piers and damaged or destroyed over its entire length, and debris carried up to 200 feet inland.

Figure 6.25 Map of a portion of the Rockaways, Queens.

Figure 6.26 Elevated subway structure at Beach 44th Street showing little visible damage, Arverne, Queens (40.593287° N, -73.775318° W, November 4, 2012)

Figure 6.27 Electrical substation at Beach 53rd Street with high water mark at 4.8 feet on fence, Arverne, Queens (40.592752° N, 73.783396 ° W, November 4, 2012)

Figure 6.28 High water line on house, Beach 46th Street, Rockaway Beach (40.594443° N, 73.77725° W, November 4, 2012)

Figure 6.29 Typical evidence of flood damage, Beach 46th Street, Rockaway Beach (40.594322° N, 73.777252° W, November 4, 2012)

(a) (b)

Figure 6.30 Sand moved inland at Beach 61st Street and Beach Front Road, Rockaway Beach, Queens (40.588684° N, 73.790166° W, Nov. 4, 2012)

Figure 6.31 Three-story buildings with little visible structural damage, Beach 76th Street and Rockaway Beach Blvd, Rockaway Beach, Queens (40.588689° N, 73.803595° W, November 4, 2012)

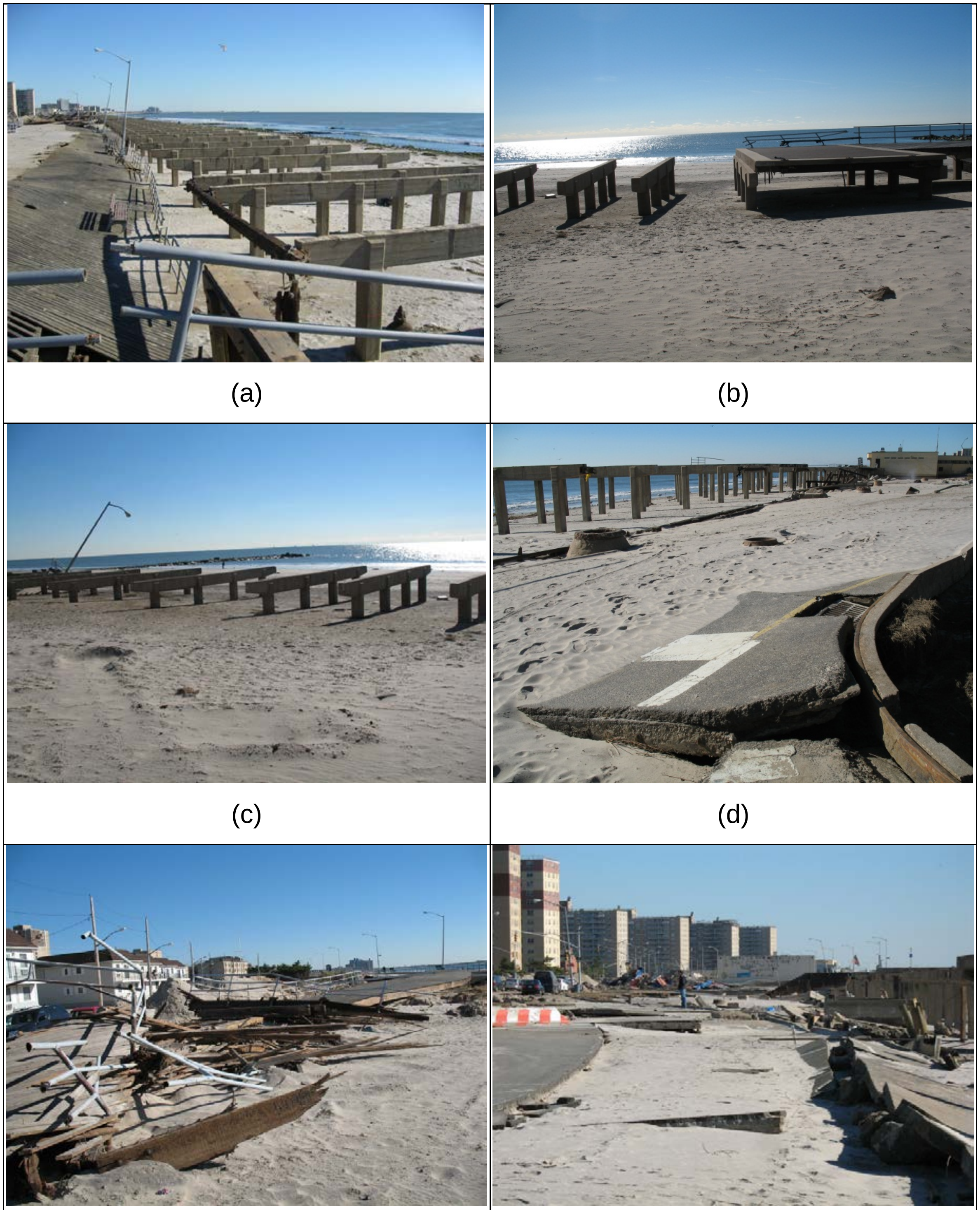
Figure 6.32 Seven-story buildings with little visible structural damage, Beach 81st Street & Rockaway Beach Blvd, Rockaway Beach, Queens (40.587999° N, 73.807333° W, Nov. 4, 2012)

Figure 6.33 Debris and cars moved inland, Beach 94th Street and Shore Front Road, Rockaway Beach, Queens (40.584691°N, 73.815873° W, November 4, 2012)

Figure 6.34 Void in CMU block foundation wall; wood frame building still standing, Rockaway, Queens (November 17, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.35 Erosion at CMU foundation wall, Rockaway, Queens (November 17, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.36 Beachfront houses with concrete wall foundations, Rockaway, Queens (November 18, 2012 – MRCE in collaboration with NYCDOB)



(a) (b) (c) (d) (e) (f)

Figure 6.37 Typical damage to boardwalk and shore front road, Beach 95th Street, Rockaway Beach, Queens (40.583445° N, 73.815529° W, Nov. 4, 2012)

(a) (b)

Figure 6.38 Fire damage, Beach 115th St and Rockaway Beach Blvd (40.580079 °N, 73.836268 °W, November 4, 2012)

6.3.4. The Rockaways – Breezy Point and Roxbury

In Breezy Point and Roxbury, one- and two-story “bungalow”-style wood-frame dwellings on CMU block wall and pier foundations (the predominant house type in these neighborhoods) sustained major structural damage. Flooding up to and exceeding five feet above street level was prevalent. Many homes were washed off of their foundations. The foundations themselves were often partially or completely destroyed. Homes with cast-in-place concrete wall foundations generally sustained less structural damage. A massive fire destroyed 126 homes and damaged 22 in Breezy Point (New York Times, 12-24-12). The fire is believed to have been started by an electrical short circuit, and exacerbated by the close proximity of houses, wind, and inability of fire fighters to reach the fire due to flooding. Homes facing the ocean sustained the most significant foundation damage.

Figure 6.39 Map of Breezy Point and Roxbury, Queens.

Figure 6.40 House washed off of pile foundations, Breezy Point, Queens (November 5, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.41 Destroyed CMU wall foundation, Breezy Point, Queens (November 5, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.42 Concrete wall foundation with minor structural damage, Breezy Point, Queens (November 5, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.43 House washed off of CMU wall foundation, Breezy Point, Queens (November 5, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.44 Collapsed CMU wall foundation, Breezy Point, Queens (November 5, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.45 Concrete wall foundation with minor structural damage, Breezy Point, Queens (November 5, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.46 Scour and erosion at concrete wall foundation, Breezy Point, Queens (November 5, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.47 Destroyed CMU wall foundation, Breezy Point, Queens (November 12, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.48 House washed off of pile foundation, Breezy Point, Queens (November 12, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.49 House washed off of CMU wall foundation, Breezy Point, Queens (November 12, 2012 – MRCE in collaboration with NYCDOB)

(a) (b)

Figure 6.50 Fire damage, Breezy Point, Queens (November 13, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.51 Washout and breach of CMU wall foundation; structure remains standing, Breezy Point, Queens (November 13, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.52 Partially collapsed CMU pier foundation, Breezy Point, Queens (November 13, 2012 – MRCE in collaboration with NYCDOB)

6.3.5. Long Beach

Evidence of flooding to a level approximately 2.5 to five feet above street level was observed throughout. At Harrogate Street (see Figure 6.53), the sand dune between the waterfront properties and the ocean appeared to have prevented the surge from flooding the immediate neighborhood. Water seemed to have flowed in from the adjacent areas and appeared to have topped off at approximately one foot at Harrogate Street. High-rise residential building foundations (typically founded on deep foundations) generally performed well. Localized sinkholes and washouts were observed throughout these neighborhoods.

Figure 6.53 Map of a portion of Long Beach, Nassau County.

	
Figure 6.54 Sand deposited on street East Broadway, Long Beach (40.584842° N, 73.646121° W, November 4, 2012)	Figure 6.55 Damage to Boardwalk at Lincoln Blvd, Long Beach (40.583257° N, 73.652419 ° W, November 4, 2012)

Figure 6.56 Sandbags and high water mark on garage door, East Broadway, Long Beach (40.584989 °N, 73.644769 °W, November 4, 2012)

Figure 6.57 High water mark at 2.5 feet on fence, north side of Lido Blvd at Buxton Street, Long Beach (40.588431 °N, 73.627142 °W, November 4, 2012)

Figure 6.58 Typical sinkhole near Long Beach Blvd, Long Beach (40.585174 °N, 73.65811° W, November 4, 2012)

Figure 6.59 Sand dunes which appeared to have reduced flooding and protected inland neighborhood, Harrogate Street, Long Beach (40.586427 °N, 73.624878 °W, November 4, 2012)

6.3.6. Broad Channel

Broad Channel, Queens is a residential neighborhood located on the inland (north, protected) side of the Rockaway Peninsula in Jamaica Bay. Broad Channel is one of the lowest lying communities in the New York City area and is surrounded on all sides by tidal marshland and water. Development consists primarily of one- and two-story "bungalow"-style wood-frame dwellings on CMU block wall / pier, concrete wall, or pile foundations.

Figure 6.60 Map of Broad Channel, Queens

Damage in the observed areas in Broad Channel was primarily related to flood inundation, without the extent of foundation structural damage and sand movement observed in the Rockaways and Long Beach. High water marks up to six feet above the ground surface were observed.

Extensive debris was piled outside buildings and on the road, and several boats were encountered in the median and along the sides of the road. At many homes, exterior residential heating oil tanks had floated, in some cases tipping and rupturing connections. Some soil washout was observed.

(a) (b) (c) (d)

Figure 6.61 Piled debris, boats, and oil tank, Broad Channel, Queens (November 4, 2012)

Figure 6.62 Soil washout, Broad Channel, Queens (November 6, 2012)

Figure 6.63 High water mark at 5’-4” on fence, Broad Channel, Queens (40.607984 °N, 73. 819895 °W, November 6, 2012)

6.3.7. Howard Beach

Howard Beach, Queens is a residential community located on the north shore of Jamaica Bay, on the north (protected) side of the Rockaway Peninsula. The south and west borders of Howard Beach are defined by an approximately 1,000 feet wide strip of vegetated land separating the residential areas from a sand beach. The eastern border is defined by the NYC subway Rockaway Line tracks, which are separated from Bergen Basin by an approximately 800 feet wide vegetated strip. Two canals, Shellbank and Hawtree Basins, divide the community into sub-neighborhoods of Howard Beach, Old Howard Beach, and Hamilton Beach. Development in observed areas consists primarily of one- and two-story wood frame and brick veneer houses on concrete wall or CMU block wall / pier foundations.

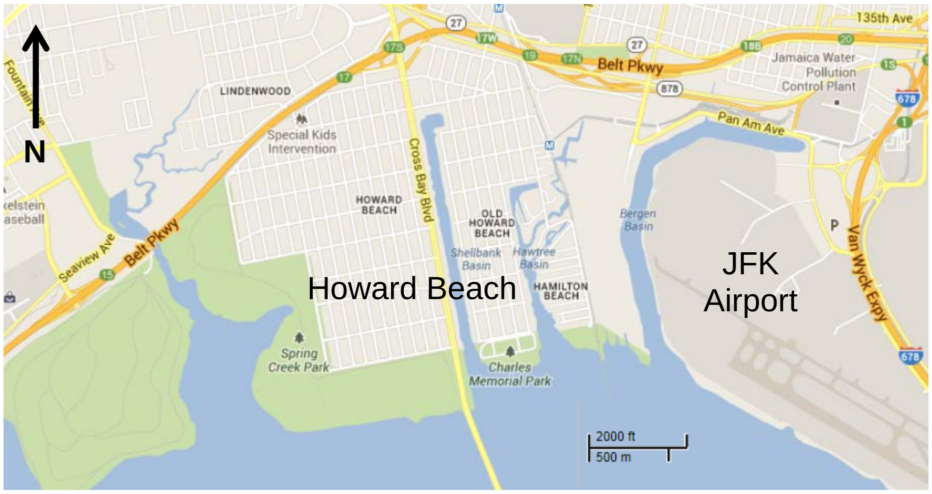


Figure 6.64 Map of Howard Beach, Queens

Damage in Howard Beach was related primarily to flood inundation, with one instance of partial collapse of a CMU wall foundation possibly related to erosion.

Figure 6.65 Typical home with flooding damage, Howard Beach, Queens. (November 16, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.66 Basement flooding, Howard Beach, Queens. (November 16, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.67 Soil washout at foundation wall, Howard Beach, Queens. (November 16, 2012 – MRCE in collaboration with NYCDOB)

Figure 6.68 Partial collapse of CMU foundation wall, possibly related to erosion at footing, Howard Beach, Queens. (November 16, 2012 – MRCE in collaboration with NYCDOB)

6.4 General Observations of Foundation Performance in New York City Coastal Communities

The GEER reconnaissance resulted in several general observations regarding foundation performance in New York City coastal communities:

- Structural damage was generally most prevalent in communities with direct exposure to the open ocean (e.g. The Rockaways and Long Beach). Damage was less for buildings further inland, or communities on the protected sides of barrier islands or peninsulas (e.g. Howard Beach, Broad Channel, and Coney Island).
- Dunes (e.g. at Harrogate Street in Long Beach) and vegetated strips (e.g. along Father Cappodanno Street in Staten Island) appeared to have a positive effect in reducing the magnitude of foundation damage for inland communities.
- Washing off of foundations (i.e. inadequate anchorage) was a common mode of structural damage for timber frame houses, particularly in the communities of Breezy Point and Roxbury, Queens.
- Concrete masonry unit (CMU) wall foundations generally performed poorly, and were frequently buckled, broken, or completely removed, resulting in tilt, dislocation, or collapse of the overlying structure.
- CMU piers performed poorly in the rows of houses adjacent to the ocean. Further inland, CMU piers performed better than CMU walls, possibly because the openings between the piers allowed flood water to move through the foundation without building up hydrostatic pressure.
- Concrete wall foundations generally sustained little or no structural damage, but sometimes experienced erosion and scour along their perimeters.

Additional observations made with the benefit of building type and age data provided by NYCDOB:

- The majority of residences damaged in Hurricane Sandy were wood frame structures, some of which are especially sensitive to buoyant forces. These forces may lead some one story wood buildings to wash off foundations. Most commonly, buoyant forces discharge the foundation walls of the structure's stabilizing dead load, allowing these foundations walls (especially light CMU) to break or overturn.
- The majority of structural failures in Sandy occurred in dwellings built prior to 1938. One reason for the extensive damage to pre-1938 buildings is that some communities (e.g. Breezy Point) were developed before 1938 as summer vacation homes and were constructed less robustly.

6.5 Tree Damage in Long Island, New York

As described in Section 2, Hurricane Sandy’s counterclockwise wind currents caused the predominant high velocity wind direction over Long Island and NYC to be from the east. This pattern was corroborated by the GEER Team’s observation that many of the thousands of trees that fell in Long Island during the storm fell to the west. Observations made following these storms indicate that tree roots in this area of Long Island extend primarily at shallow depth, where the topsoil remains moist due in part to intensive watering of lawns and runoff from adjacent paved areas. Deep groundwater levels and very porous sands below topsoil contribute to this condition. (It is interesting to note that tall trees are not particularly native to much of Long Island; for example, Garden City, NY and the surrounding area used to be a treeless plain known as the Hempstead Plains, once used for numerous air fields including where Charles Lindbergh took off for the first trans-Atlantic flight.) Shallow root systems resulted in uprooting of many trees, causing damage to residences, sidewalks and utility lines. As an example, Garden City lost 5% of their 13,000 street trees (generally 8-inch caliper or larger and often 60 to 100 ft high) in a community of only 7,200 residences. Total number of trees that fell in this city is estimated to be between 2,100 and 2,400, of which 63 fell on houses. A number of houses experienced serious damage. The city is consulting with Cornell University Extension Service on how to start planting trees that are more resistant to high winds.

6.6 Atlantic City, New Jersey

Atlantic City is located along the Southern New Jersey Shoreline within the Outer Coastal Plain region. This region is composed of unconsolidated sands, gravels, silts, greensands, marls, limes, and clays (Dike 1987). The region of Atlantic county is described as an "eastward thickening apron of unconsolidated and partly consolidated sediments which extend along the east coast of the country" (Jogan 1978). A geological cross section of the county shows the region underlain by the Raritan and Salisbury Embayments. The overlying Cohansey

Sand comprises the largest surface area of the Coastal Plain. This sand is characterized by white to yellow sand with occasional lenses of clay. The Cohansey Formation along with the Kirkwood Formation act as a single hydrologic unit allowing rainfall to permeate into the ground and reach the water table quickly.

The coastline of Atlantic City is composed of sand with an average diameter that is half the average diameter of that found on beaches further north. Also the sand contains a completely different set of trace materials (Coastal Research Center 2013). These minerals include quartz or rock fragments of orthoquartzite.

The location of the site surveyed on November 6 and 11, 2012 was at the intersection of Atlantic Avenue and Maine Avenue (39.368722,-74.411615). The high water mark as obtained from the USGS website (USGS, 2012) is at El. 7.2 ft. Bulkheads along this section of shore were breached at three locations. The timber and pile bulkheads were supported with tierods attached to deadman anchors. The piles for the bulkheads were located on 5-ft centers. The breaches resulted primarily from damage to the timber facing, which was destroyed and washed away due to the force of the storm (Figure 6.69 and Figure 6.70).

Figure 6.69 One of the breaches in the bulkheads along the coastline; in the backdrop are the remains of the boardwalk.

As a result of the storm surge and water washing through the breaches, the tierods and deadman anchors were exposed.

Figure 6.70 The backfill soil had been washed away exposing the severely corroded tie rods.

The vinyl sheeting used as protection for a nearby playground did not fare very well either. There were several pieces of vinyl sheeting that had been damaged (Figure 6.71).

Figure 6.71 Damaged vinyl sheeting surrounding a children’s playground.

There was severe erosion noticed at various locations including at various access points to the boardwalk. This was especially a problem at the breaches along the bulkhead (Figure 6.72).

Figure 6.72 Erosion undermined the foundation causing significant damage to walkways and roadways.

In addition, the boardwalk had also been washed away along the stretch of the shoreline. This section of the boardwalk had been scheduled for demolition in four months. The concrete piers for the boardwalk were still intact at most locations (Figure 6.73).

Figure 6.73 Damaged concrete piers that served as the supports for the boardwalk.

Most of the piers were reinforced concrete. There was partial destruction of some of the concrete piers. In addition, there were several reinforced concrete piers that showed severe cracking. The foundation was also examined for scour and some visible scouring was evident (Figure 6.74).

Figure 6.74 Existing concrete piers with evidence of cracking and some scour

An example of the waste generated by this storm is evident from Figure 6.75. The reported data for Atlantic County shown in Table 6.1 shows the scale of the problem being faced even though Atlantic County did not suffer the damage experienced by Ocean County.

Figure 6.75 Waste generated by the storm includes hazardous waste such as refrigerators,home appliances and considerable debris

Table 6.1 Waste Generated at Atlantic County Utility Authority in tons showing the increase for the same period in 2012 (soon after the storm) compared to 2011 (Press of Atlantic City, December 21, 2012)

Type of Waste	Waste Generated in tons from Oct. 31-Dec. 18, 2011	Waste Generated in tons from Oct. 31-Dec. 18, 2012	% increase
Bulky	2529	19117	656
Construction	7728	11935	54
Household	17653	30612	73
Yard	3633	4947	36
Total	31543	66611	111

6.7 Brigantine, New Jersey

Brigantine, New Jersey, is the barrier island community located immediately north of Atlantic City. The town has a population of just over 9,000 and is a residential / vacation community. The GEER assessment team visited Brigantine on November 3, 2012, because it was one of the few coastal communities open at that time.

Brigantine beach is located in Atlantic County within miles of Atlantic City. Due to the proximity of this site, Brigantine beach has nearly the same geology as Atlantic City. Its geology consists of the fine, unconsolidated sand characteristic of the Cohansey Formation.

In general, the damages from Sandy in Brigantine were light compared to that reported for communities to the north. The damages that the assessment team observed were associated with the loss of beach material or wave action on the beachfront and with water damage from flooding.

It appeared that Hurricane Sandy flooded the first floor of many of the residences, especially those houses with a first floor only a few feet above grade. At the time of the visit, many residents had returned and were removing damaged materials such as rugs (Figure 6.76).

Figure 6.76 Discarded materials from residential clean-up (39.40756º N, 74.36239º W, November 3, 2012)

Much of the beach front had a grassed barrier dune abutted by residences, typically multi-unit condos. The barrier dune was severely eroded in many locations (Figure 6.77). Erosion damage and sand transport were more pronounced at locations where the barrier dune either did not exist or had been largely eroded (Figure 6.78, Figure 6.79, Figure 6.80).

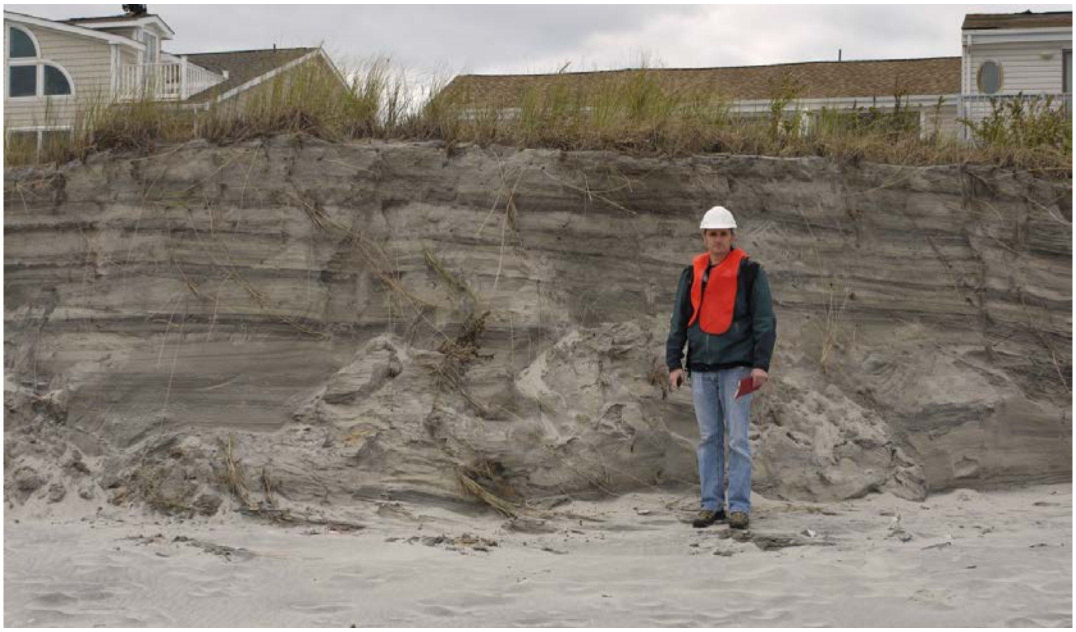


Figure 6.77 Barrier dune erosion (39.40929 º N, 74.35996 º W, November 3, 2012)

Figure 6.78 Erosion around the foundation of a beachfront condo at a location with little or no barrier dune (39.41112 º N, 74.35811 º W, November 3, 2012)

Figure 6.79 Sand deposition in the first floor garage of that same condo (39.41112 º N, 74.35811 º W, November 3, 2012)

Figure 6.80 Erosion around utilities on landside of beachfront structures, again at a location with no barrier dune (39.41081 º N, 74.35887 º W, November 3, 2012)

A seawall built along the north end of the beach front showed signs of stress from the wave and flood loading. Specifically, the beach access stairway had been washed away (Figure 6.81), and the sidewalk along the top of the wall had settled in places up to about ½ foot, presumably from erosion loss of backfill sand (Figure 6.82).

Figure 6.81 Washed-out stair on seawall (39.41387 º N, 74.35460 º W, November 3, 2012)

Figure 6.82 Settlement along the top of the seawall (39.41440 º N, 74.35395 º W, November 3, 2012)

The assessment team notes that the observations and descriptions were limited to a few areas in Brigantine, but these damages were representative for this area.

6.8 Ship Bottom and Long Beach Island, New Jersey

Long Beach Island and Ship Bottom are situated on a barrier island in Ocean County, New Jersey. Located about a mile away from each other, the geology of the areas are very similar. Ocean County is considered part of the Coastal Plain Region. The geology of this area is comprised of about 98% quartz pebbles along with coarse and medium sand, and granules of shell (McMaster, 1954). These sands are of a grayish-yellow color. Darker colored sands are also found in the area due to the wind spreading dune materials. This region also has an abundance of black opaque minerals compared to other regions in New Jersey. It contains traces of feldspar which is consistent with surrounding regions. Sea bottom samples of this area contained "olive gray quartz sand with over 10% mud and a few shell fragments" at a depth of about five feet (McMaster, 1954).

The GEER Assessment Team met with the Construction Code Official for the Borough of Ship Bottom and representatives of the NJ Department of Environmental Protection, and FEMA on November 26, 2012, to assess the damage to the town, which was one of the hard hit communities. A preliminary, approximate assessment of the damage to residential homes in the area (1831 homes) would be that about half were subjected to flooding in their living areas, and only 5 homes were noted with substantial structural damage. The most damage happened on the bayside (along Bay Terrace, 39°38'45.88"N, 74°11'12.80"W, Figure 6.83) and not along the ocean. The ground elevation at this location is about 5.5 feet and the high water mark from the flood was at 1.7 feet above ground elevation (USGS website).

Figure 6.83 Bayside area that appeared to suffer the most damage in Ship Bottom (39°38'45.88"N, 74°11'12.80"W).

It can also be concluded from a survey of the damaged buildings that structures which complied with the current building codes for construction within the Flood Hazard Area performed satisfactorily and suffered minimal structural damage. The structures that suffered the most damage were older buildings, as in Figure 6.84, which did not conform to current code requirements (ref. Ship Bottom Municipal Code, adopted 12/20/2011). These wood-frame homes were built on shallow foundations with no structural connections. A number of homes were observed along the NJ coast that had been shifted off their foundations, conceivably due to wave action and lateral, hydrostatic pressure. Bayside, however, the wave heights were much less and the mechanism(s) for displacing homes from their foundations is thought to be due to a combination of lateral water pressure and buoyant forces.

Figure 6.84 Damage to older structures on shallow foundations (39°38'41.15"N, 74°11'7.01"W)

The other damage that many structures suffered was due to collision forces from floating objects such as boats in Figure 6.85. Many of the newer homes founded on piles have breakaway walls for the first floor. These walls are supposed to yield under the lateral forces of either water or wind, and they functioned as expected as shown in Figure 6.86.

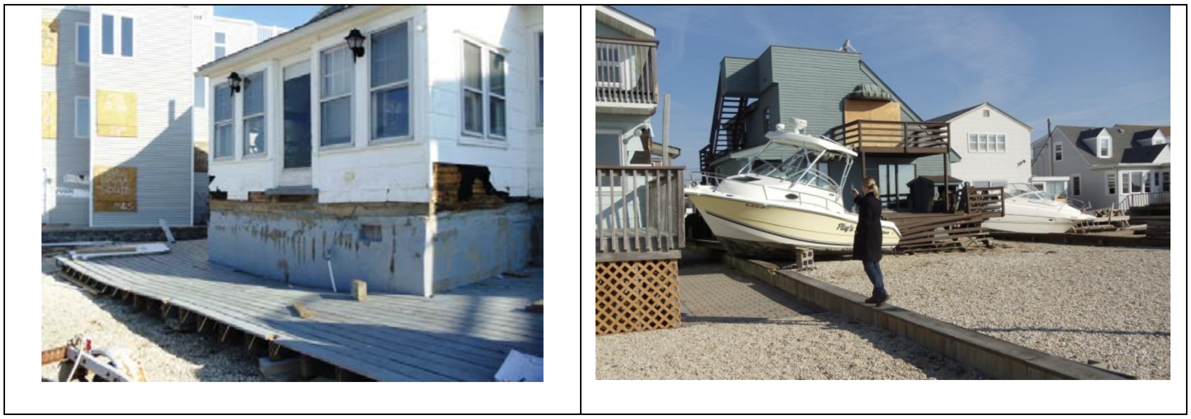


Figure 6.85 Damage to structures due to collision with floating objects such as boats (39°38'22.57"N, 74°11'18.89"W).

Figure 6.86 Breakaway walls that yielded under the lateral loading imposed by the storm surge as they were designed to perform (39°38'45.13"N, 74°11'12.87"W).

It was the team's judgment that where a beach or dune buffer was present between the bay and adjacent homes, the damage to the homes was noticeably less than where these natural features were not present. Figure 6.87 shows a comparison of the condition of homes with and without a beach buffer, while Figure 6.88 shows vegetated beach buffer that appeared to protect the adjacent homes.

Figure 6.87 Bayside homes without (left) and with (right) a beach buffer between them and the bay.

Figure 6.88 Vegetated beach and dunes, bayside on the right, helped protect homes.

At a bayside park in Ship Bottom, water had washed out sandy soils from behind a sheet pile bulkhead exposing the steel tie-back rods, as in Figure 6.89. Design of earth retaining walls which rely on the backfill for anchorage support, such as tie-back and mechanically-stabilized earth walls, can be compromised by such erosion.

Figure 6.89 Erosion exposing steel tie-back anchors for bulkhead, bayside (39°37'17.62"N, 74°11'55.88"W)

Inspections were also conducted on homes in Pehola Park, Long Beach Island, and one of the more spectacular failures was of a home located at 39.610016 N, 74.206657 W (Figure 6.90). The approximate ground elevation at this location is 7.72 feet and the high water mark was approximately 2.3 feet above ground (USGS, 2012). The two-story home had been sheared off all its piles due to lateral forces imposed by the storm surge and wave action. The other homes surrounding the damaged home were all intact. The only difference between this structure and the surrounding homes was that it was at a lower elevation than the surrounding homes. Only the upper story of the damaged home was visible, nearby. This disappearance and/or flattening of the lower story of homes displaced off their foundations was often observed in other areas.

Figure 6.90 Timber pile foundation remains after home was sheared off, ocean-side in Pehola Park (39.610016, -74.206657)

6.9 Seaside Park to Normandy Beach, New Jersey

Seaside, Lavalette, and Ortley Beach are all closely situated along the coast of Ocean County, New Jersey. The region is considered to be part of the Coastal Plain Region. The geology of this region is similar to that of Long Beach Island due to their proximity to each other. The geology of the region consists of coarse and medium sand, shell granules, clay, and an abundance of quartz pebbles. There are minimal traces of heavy minerals, while there are more light minerals in this area compared to other regions. Black Opaques and Feldspar are the most frequent minerals in this area. Traces of Staurolite and Zircon are also present in this zone (McMaster, 1954). The beaches have medium texture with a grayish-yellow color.

The GEER Assessment Team performed a visual inspection of the towns from Seaside Park to Normandy Beach on December 3, 2012. Between the northern portion of Normandy Beach and the Borough of Mantoloking, access was restricted due to severe storm damage. Photographs taken by New Jersey first responders and the Ocean County Engineering Department (2012) were available and reviewed for these areas. The high water mark from the flood was at 7 to 8.5 feet above ground elevation (USGS website).

The island is divided longitudinally by Route 35 which runs north to south down its center, with the bay on the west and ocean on the east. The “island” is contiguous with the mainland at its northern end, and is technically a peninsula. It’s very long, thin shape makes it appear as a barrier island. This lack of an outlet to the ocean at its northern end is one factor differentiating it hydraulically from Long Beach Island to the south, which is a true island.

Figure 6.91 shows post-Sandy conditions at Mantoloking. Flooding from the hurricane caused in a breach through the island along a preferential flow path on the north side of the Route 528 Bridge. Figure 6.92 shows efforts to backfill the breach and reconstruct Route 528. Sheet piling was driven to restrain the water so the channel could be properly backfilled.

Figure 6.91 Post-Sandy conditions, Borough of Mantoloking. The bay has joined the ocean at the Route 528 Bridge, 40° 2'24.21"N, 74° 3'8.32"W (NJ Task Force 1).

Figure 6.92 Installation of sheet piles to allow backfilling erosional channel and rebuilding of Route 528, Borough of Mantoloking, 40° 2'24.21"N, 74° 3'8.32"W (Mantoloking, 2012).

Utilities and traffic signals were damaged during the storm. Storm forces overcame soil resistance and pushed over utility poles often without breaking them as in Figure 6.93. Sinkholes appeared in localized areas due to subsoil erosion, such as from a broken sewer or water pipe in Figure 6.94.

Figure 6.93 Foundation failures of utility poles (left) and damage to traffic signals, 39°57'12.03"N, 74° 4'25.09"W (NJ Task Force 1, 2012)

Figure 6.94 Sinkhole due to broken water/sewer line (Ocean County Engineering, 2012)

Natural gas leaked from broken laterals as buildings shifted on their foundations, resulting in gas fires. Figure 6.95 shows gas leaking through a hole in the soil and the remnants of a natural gas fire in Mantoloking. These were difficult to control as roadways were not passable for conventional fire fighting vehicles.

Figure 6.95 Natural gas leak and fires (NJ Task Force 1, 2012)

The bulkheads at Brinley Avenue near Ortley Beach had collapsed and caused the roadway to be undermined as shown in Figure 6.96.

Figure 6.96 Bulkheads and roadway that was washed away at Brinley Avenue, Ortley Beach (39°57'41.63"N, 74° 4'38.29"W, Ocean County Engineering, 2012)

In many areas, only the upper stories of homes were intact due to collapse of the first floor as a result of static and dynamic water forces.

Figure 6.97 Remnants of the upper story of a home and home on the verge of collapse (NJ Task Force 1, 2012-left and A. Brenner, 2012-right).

At Seaside Heights, a portion of a pile-supported amusement pier that extended into the ocean was destroyed as shown in Figure 6.98. Not only was part of the pier deck missing, but the timber piles were no longer visible, having been removed to below the water line.

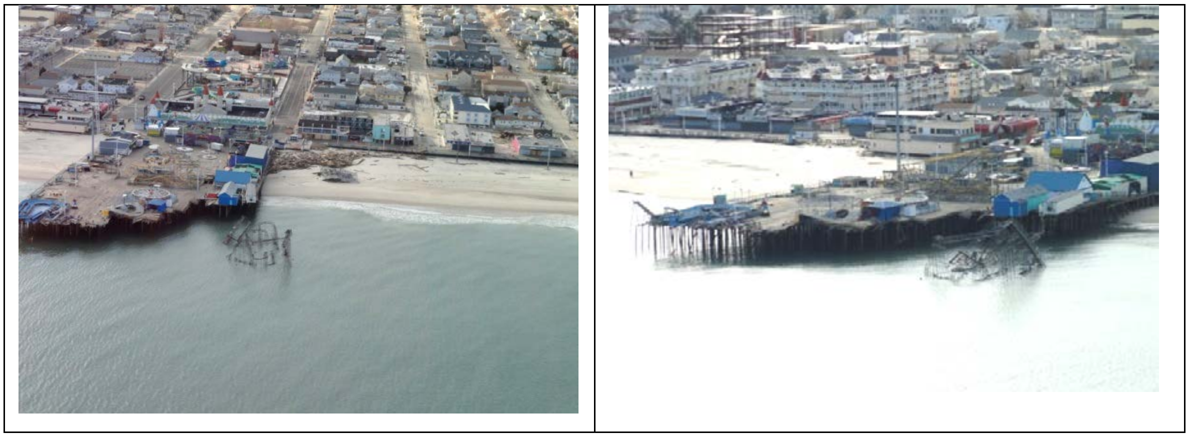


Figure 6.98 Damaged amusement pier with missing timber piles, 39°56'33.52"N, 74° 4'9.26"W (A. Brenner, 2012), Seaside Park. See also Piazza, G. (2013)

Figure 6.99 shows sand transported upland by the ocean-side storm surge in the Borough of Lavallette. Many communities along the New Jersey shore require removal of large volumes of sand. Sand in the streets is being moved by front-end loaders back to the ocean beach, while sand on private properties is largely removed by manual labor.

Figure 6.99 Homes partially buried in ocean sand, Borough of Lavallette (A. Brenner, 2012)

Topographically low areas, such as Lake Como, in Figure 6.100, overfilled with storm, surface, and flood water, impacting adjacent homes. Pumps are being operated to draw down Lake Como.

Figure 6.100 Lake Como, Borough of Como, with dewatering pumps, 40°10'1.50"N, 74° 1'1.65"W (NJ Task Force 1, 2012)

The GEER assessment team visited accessible areas of Seaside Heights, Lavallette and Ortley Beach on December 3, 2012. The destruction in these communities were the worst of all the areas surveyed and was still not open to the general public during the visit. The team started bayside and proceeded to the ocean side. The first site that was visited was the Ocean Beach Yacht Club shown in Figure 6.101, where the pier had collapsed.

Figure 6.101 Boat Pier at Ocean Beach Yacht Club, Lavalette, NJ
(39°59'15.14"N, 74° 4'19.41"W)

The team also observed that areas with vegetated beaches performed well especially on the bayside. Along the ocean side of the communities the damage was extensive. There was considerable sand washed up on the streets and there was debris removal and cleanup happening during the visit.

The GEER team then proceeded Oceanside and started surveying damage at Seaside heights. The pier was not accessible and therefore we relied on pictures from the first responders for a better assessment of the damage soon after the storm as was discussed earlier in this section. From Seaside Heights, the team travelled north to Ortley Beach, where the damage was extensive along the ocean. Figure 6.102 shows the scale of damage in this section including the problem with sand deposition. Homes on shallow foundations were displaced. Those on deep foundations survived but with considerable damage to the structure (Figure 6.103). Figure 6.104 shows another structure about 100 feet from the structure shown in Figure 6.103 that collapsed completely.

Figure 6.102 The building on the left, which was on shallow foundations was displaced. In the far end, there is a boat that is stuck in between the buildings.

Figure 6.103 Buildings on deep foundations survived with serious structural damage

Figure 6.104 Collapse of a structure on the ocean front due to the storm surge along with an aerial shot of the area from Google Earth (39°57'16.47"N, 74° 4'6.09"W)

6.10 Moonachie, New Jersey

Moonachie is located in the southern portion of Bergen County, between the Hackensack River to the east and the Passaic River to the west. Large area surrounding Moonachie are tidal marsh, known as the Hackensack Meadowlands. Moonachie lies within the Piedmont Province which is a rolling plain underlain by soft shale and sandstone (Lucey 1971). The terrain at Moonachie is near sea level. The surficial soil strata int his area are predominantly fills underlain by sand, silt and clay deposited in the glacial Hackensack (USDA, 1995).

The flooding of Moonachie, Little Ferry and Carlstadt, three communities sandwiched between Teterboro Airport, MetLife Stadium and the Hackensack River, was caused by tidal surges along the Hackensack River. Some portions of the banks of the Hackensack River had earthen berms, which were constructed by the Mosquito Control Commission in the early 1900s for access purposes. There is also a recently-constructed section which has geocell walls, which were installed to facilitate development of a wetlands region (Figure 6.105). Many sections along the western bank of the Hackensack River did not have elevated berms or structures. The berms and geocell walls were not intended for flood protection, when originally built.

Figure 6.105 Location of the earthen berm and geocell wall with respect to the Hackensack River (40°49'36.51"N, 74° 2'18.12"W); Bergen County Utility Authority is also seen in the upper central portion; brown area is a wetlands enhancement project.

The earthen berms were built to El. 7 with clayey soils, are approximately 1000 ft., long, and were breached due to a tidal surge in the Hackensack River at 5 locations (Figure 6.105). Some short sections of the earthen berm consisted of crushed stone (Figure 6.106) separated from the overlying topsoil by a plastic sheet. Most of the breached sections were along these sections containing crushed stone.

Figure 6.106 Breached section of the earthen berm showing remnants of sections with crushed stone (40°49'43.45"N, 74° 2'19.87"W).

The geocell walls that were approximately one-half mile long, were 3 feet wide and 5 feet high. They ran along the length of the Hackensack River from the earthen berm section to the NJ Turnpike Viaduct. Some of the geocell walls tipped or lost soils during the storm surge (Figure 6.107). It is unclear whether any cells failed completely.

Figure 6.107 Location of the Geocell wall along the Hackensack River; a closer view of the Geocell wall can be seen on the right (40°49'37.27"N, 74° 2'18.16"W).

Since the breaches occurred, the failed sections have been rebuilt with compacted clay at flatter slopes to improve stability (Figure 6.108). The heights of the berms that have been rebuilt have not been raised from the previous level and are also at Elevation 7.

Figure 6.108 Repair of the breached section with compacted clay at flatter slopes (40°49'43.45"N, 74° 2'19.87"W)

6.10.1 Transco Gas Pipeline

Transco (Williams Transcontinental Gas Pipeline Company, LLC) owns and operates a 36” high-pressure natural gas pipeline near the NJ Meadowlands Commission in Lyndhurst, NJ. The pipeline was constructed in 1959 and was designed to handle the normal tidal changes in the area. The pipeline runs near the NJ Meadowlands Commission Building and the Kingsland Landfill, in Lyndhurst, Bergen County. It is located south of Moonachie near the Hackensack River. It’s adjacent to a tidal inlet/pond that is connected to the Hackensack River (Figure 6.109).

During Hurricane Sandy, tidal waters surged to a height that the pipeline had never seen. In certain areas, soil saturation and buoyant forces caused earth movement and pipeline exposure (Figure 6.110).

After carefully inspecting, surveying, and analyzing the pipeline and soil conditions, the solution engineers came up with was to add soil cover over the pipeline and top it with an articulating concrete mat (Figure 6.111). This would do three things:

1. Provide the necessary weight to negate buoyant forces.
2. Prevent soil from eroding.
3. Add a layer of protection for the pipe.

Top soil will be spread over the mats and seeded to allow vegetation to grow.

Figure 6.109 Location of the Transco Pipeline Failure

Figure 6.110 Pipeline exposed soon after Hurricane Sandy

Figure 6.111 Repair work was completed by placing articulating concrete mats over displaced pipeline.

6.11 New York Harbor, Raritan Bay, and Newark Bay, New Jersey

In general, much of this area is commercial and shorelines are hardened with bulkheads. This includes the Hudson River shoreline to the north. Damage along the waterfront was especially noticeable near marinas where docks were floated off their pilings, and boats broke free. Damage to residential structures and infrastructure was similar to that observed to the south, except that the effects of erosion were less. Sediment transport and shoaling patterns varied from those in the south, along the barrier islands, due to the differing hydrological regimes.

Liberty State Park in Hudson County fronts the New York Harbor at the mouth of the Hudson River. Grounds and structures in the park suffered damage from both water and debris it carried. Figure 6.112 shows displaced stone pavers in front of the former Central Railroad of NJ Terminal Building. Although some of these needed repairs, more serious erosion of the subsoils, and costly damage to underground structures, was potentially avoided.

A marina on the Raritan Bay without hardscaping behind the bulkhead experienced severe erosion of the sandy soils, and exposure of the tieback anchors (Figure 6.113).

Figure 6.112 Damage to stone pavers at Liberty State Park occurred but these protected subsoil from erosion (40˚42´26″N, 74˚02´05″W).

Figure 6.113 Erosion of sandy soils behind bulkhead (40˚24´36″N, 74˚00´02″W).

7 DENSE URBAN AREAS

7.1 Lower Manhattan

Lower Manhattan is a dense urban area characterized by high-rise development with hardened streetscape and waterfront. Much of the Lower Manhattan perimeter lies on reclaimed land filled between 1650 and 1980, as illustrated by the historic shoreline shown in Figure 7.1.

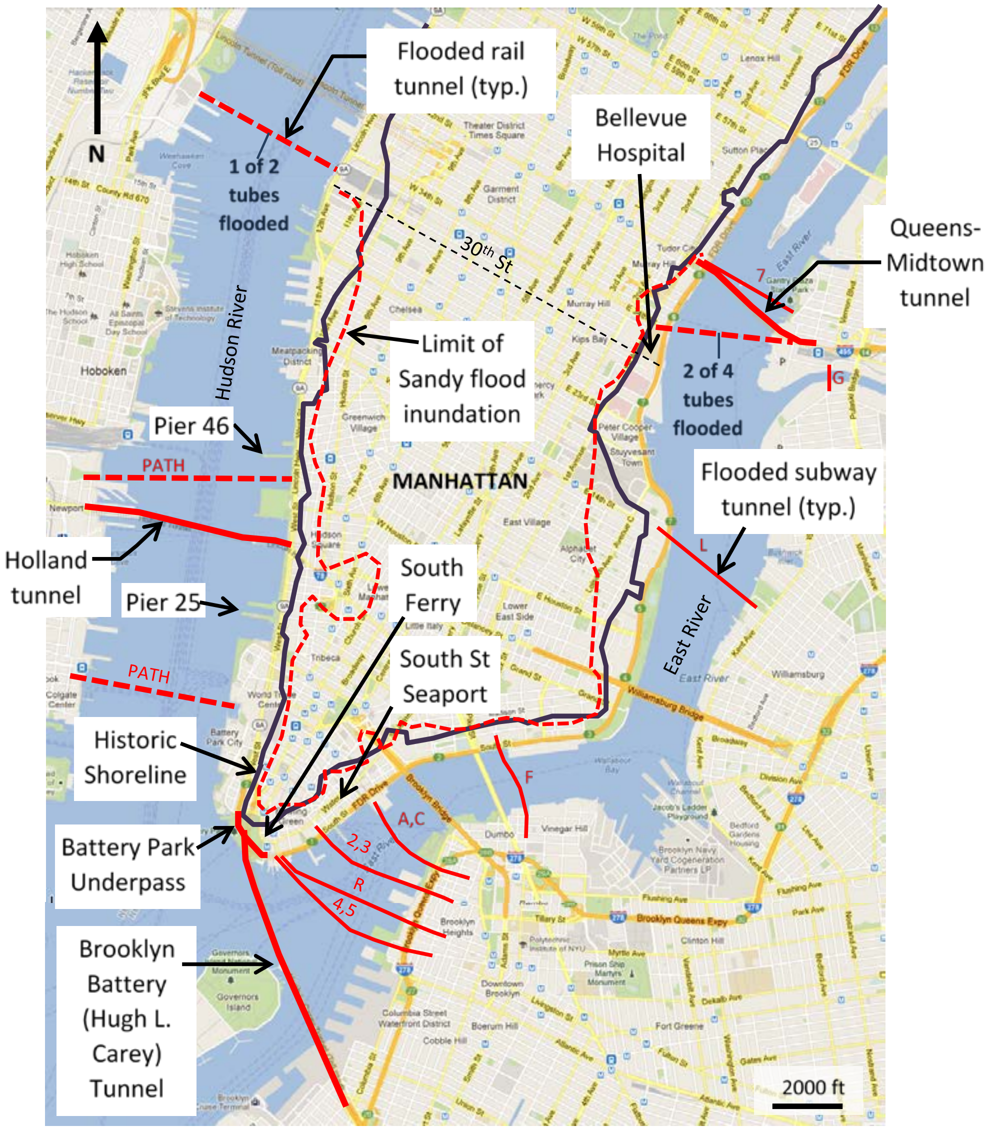


Figure 7.1 Map of Lower Manhattan showing historic shoreline and tunnels flooded in Sandy. Historic shoreline based on E. L. Viele (1865) "Sanitary & Topographical Map of the City and Island of New York". Flooded tunnels based on descriptions in news media (degree of flooding varied). Limit of Sandy flood inundation line adapted from T. D. O’Rourke (2012).

As shown in Figure 7.2, bedrock beneath Manhattan lies at or near the ground surface north of about 30th Street, but dips to more than 100 feet below grade in portions of Lower Manhattan, before rising to as little as 20 feet below grade at the tip of Lower Manhattan at the Battery (Tamaro et al 2000). The soil profile overlying rock consists of glacial lake deposits of varved silt, clay, and fine sand overlain by pockets of organic silty clay and a mantle of man-made fill.

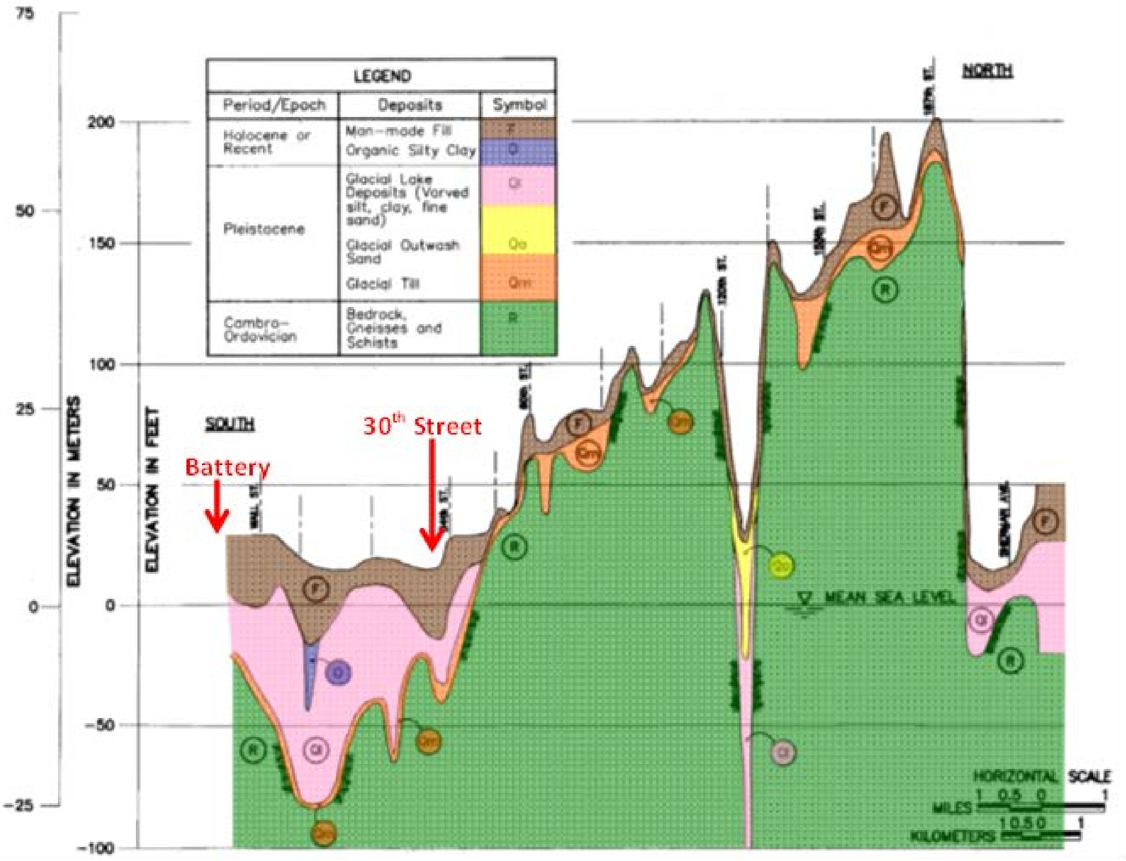


Figure 7.2 North-south Geologic Section of Manhattan (Tamaro et al 2000).

Damage in Lower Manhattan was primarily related to flood inundation. High water marks and evidence of flood damage to approximately four to seven feet above street level were observed throughout low-lying neighborhoods (e.g. South Street Seaport) and waterfront areas, consistent with observations made by USGS and The National Ocean Service (Figure 7.3).

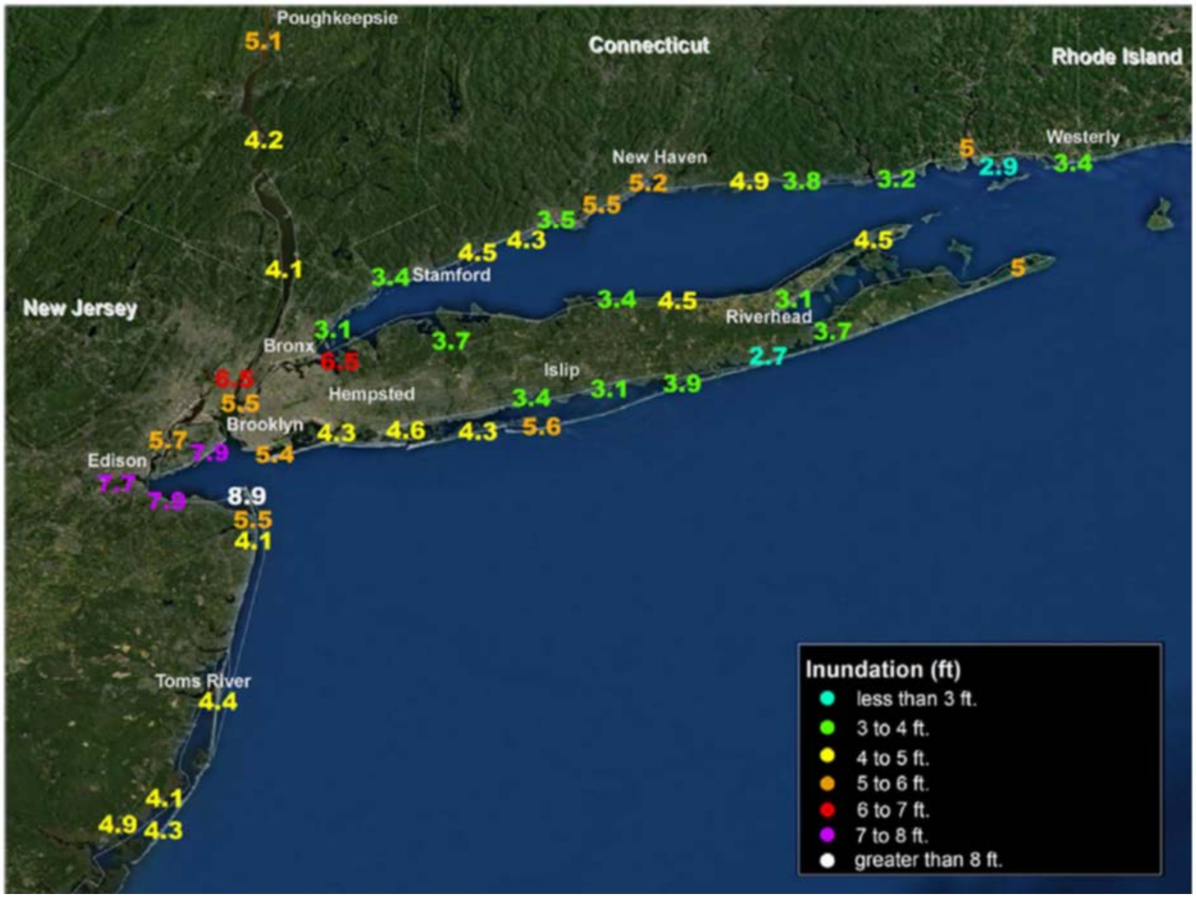


Figure 7.3 Estimated inundation (feet above ground level) calculated from USGS high-water marks and NOS tide gages in New Jersey, New York, and Connecticut from Sandy (Blake et al 2013).

7.1.1 Basement and First Floor Flooding

Inundation of basements and flooding of first floors was prevalent throughout Lower Manhattan, particularly in the South Ferry, South Street Seaport, and Water Street areas. Damage to utilities and interior finishes caused many buildings to be shut down for two to more than four weeks. Active pumping of flooded basements was prevalent throughout the area at the time of the GEER investigation.

Figure 7.4 Flood damage, Governors Island ferry terminal (40.701061° N, 74.01177° W, November 3, 2012)

Figure 7.5 Flood damage, Pier 11 water taxi terminal (40.703277° N, 74.006237° W, November 3, 2012)

Figure 7.6 Flood damage, South Street seaport (40.706685° N, 74.003554° W, November 3, 2012).

Figure 7.7 High water line at 5.7 feet on storefront window, South Street seaport (40.706935° N, 74.003322° W, November 3, 2012).

Figure 7.8 High water line at 3.5 feet on restaurant wall, Water Street (40.708393° N, 74.001612° W, November 4, 2012). Volunteer NYC Team, Ramon Gilsanz, GMS.

Figure 7.9 Damage at restaurant due to flooding. Water at 5 feet reached electric system in restaurant, which has no basement. (40.708314° N, 74.001959° W, November 4, 2012)

Figure 7.10 High water line on restaurant window, South Street seaport (40.706233° N, 74.003284° W, November 4, 2012). GEER Team co-leader Youssef Hashash.

Figure 7.11 Typical flooded basement, South Street seaport (40.708301° N, 74.000605° W, November 4, 2012).

7.1.2 Subway stations, tunnels, parking garages, and foundations

Below-grade subway stations, tunnels, parking garages, and foundation excavations in Lower Manhattan experienced widespread flooding, as widely reported in news media. While access to many of these locations was restricted at the time of the GEER investigation due to ongoing recovery work, evidence of flood inundation was visible from the surface, for example at the Battery Park underpass and Bellevue Hospital. Based on reports in the days following the storm, the flooded tunnels included the Brooklyn Battery (Hugh L. Carey), Holland, and Queens-Midtown highway tunnels, the PATH rapid transit tunnels, New Jersey Transit / Amtrak / Long Island Railroad Hudson and East River rail tunnels, and seven subway tunnels beneath the East River (Figure 7.1). The degree of flooding varied from partial flooding of ventilation ducts to complete submergence. Several subway stations were flooded, including the South Ferry station, which flooded to the ceiling. An excavation at the World Trade Center site also experienced flooding.

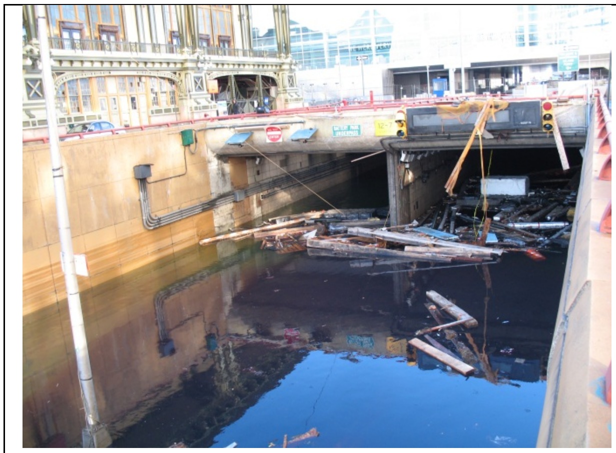


Figure 7.12 Flooded Battery Park underpass, Lower Manhattan. (40.701603° N, 74.011742° W, November 3, 2012).	Figure 7.13 Evidence of flood inundation, Bellevue Hospital, East 30th Street (40.73983° N, 73.973263 ° W, November 3, 2012).

Figure 7.14 Flooding at South Station subway station, Lower Manhattan (Reuters, 10-29-12, Mike Segar).

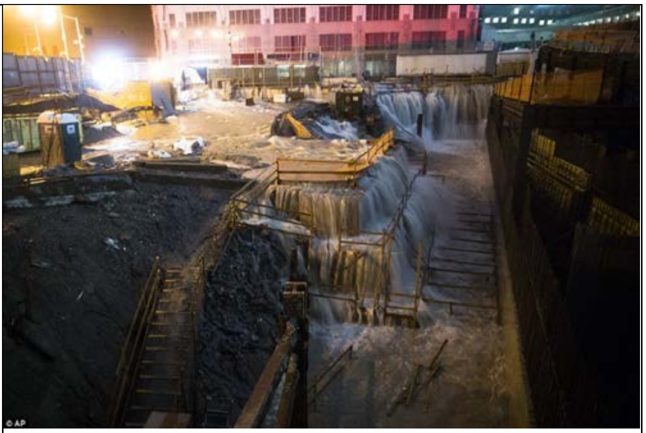


Figure 7.15 Flooding at World Trade Center site, Lower Manhattan (©Associated Press).

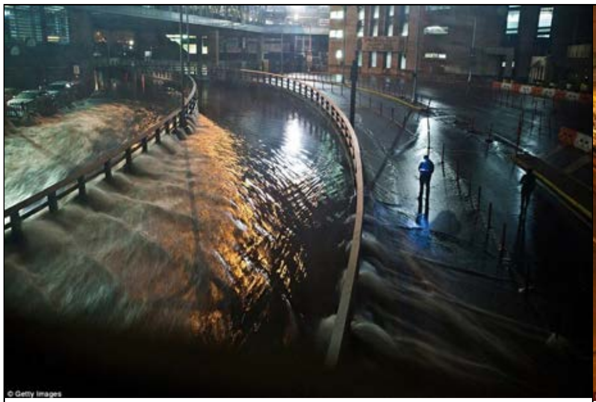


Figure 7.16 Flooding at Brooklyn Battery Tunnel (© Getty Images).

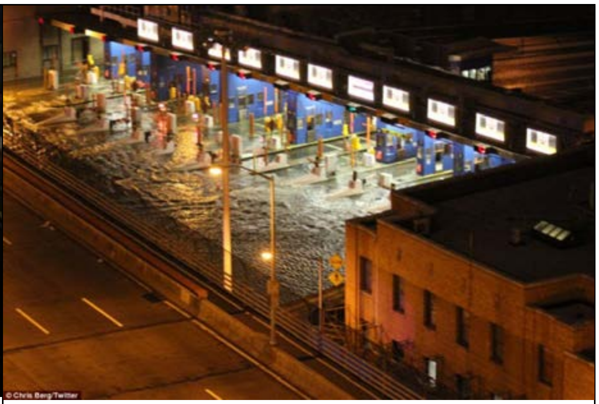


Figure 7.17 Flooding at Queens-Midtown Tunnel (© Chris Berg / Twitter).

Figure 7.18 NYC Subway Recovery Map, Nov 1, 2012 (shaded lines indicate no service).

While most of the tunnels experienced very little structural damage, service was significantly affected, as the utilities and ventilation systems were severely damaged. Most required at least a week or more of repairs. The Montague Street subway (R line) and World Trade Center PATH tunnels did not return to full service for two and three months, respectively. The R line tunnel was again taken out of service in the summer of 2013 to repair lingering flood damage. A summary of the NYC flooded tunnels and re-opening dates is provided in Table 7.1.

Table 7.1 Summary of New York City Flooded Tunnels in the aftermath of Hurricane Sandy (Sources: Kaufman et al., 2012; Khinda, J.S., 2013; North American Tunneling Journal 2012, and news media reports).

Type	Tunnel	Crosses	Length (ft)		Date
			Total	Flooded	Re-Opened
Subway	2-3 (Clark St Tunnel)	East River	6,700	600	11/04/12
Subway	4-5 (Joralemon St Tunnel)	East River	7,080	0	11/03/12
Subway	7 (Steinway Tunnel)	East River	5,910	1,000	11/03/12
Subway	A-C (Cranberry St Tunnel	East River	8,580	1,000	11/04/12
Subway	F (Rutgers St Tunnel)	East River	5,490	1,000	11/04/12
Subway	L (14th St Tunnel)	East River	7,350	2,700	11/08/12
Subway	E-M (53rd St Tunnel)	East River	5,545	800	11/04/12
Subway	R (Montague St Tunnel)	East River	10,115	4,025	12/21/12
Subway	G (Greenpoint Tunnel)	Newtown Creek	3,910	1,000	11/07/12
PATH	Blue (33rd - Hoboken)	Hudson River	5,500	significant flooding	01/09/13
PATH	Yellow (33rd - Journal Sq)	Hudson River	5,500	significant flooding	11/06/12
PATH	Green (Hoboken - WTC)	Hudson River	5,650	significant flooding	01/30/13
PATH	Red (WTC - Newark)	Hudson River	5,650	significant flooding	11/26/12
Vehicular	Brooklyn Battery Tunnel	East River	9,118	6,000	11/19/12
Vehicular	Midtown Tunnel	East River	6,545	flooded to ceiling	11/09/12
Vehicular	Holland Tunnel	Hudson River	8,558	fresh air ducts flooded	11/07/12
Vehicular	Battery Park Underpass	-		flooded to ceiling	11/13/12
Vehicular	West Street Underpass	-		flooded to ceiling	11/13/12
Amtrak/ NJT Rail	East River Tunnels 1 to 4	East River	3,949	2 of 4 tunnels flooded	11/09/12
Amtrak/ NJT Rail	North River Tunnels 1 and 2	Hudson River	14,575	1 of 2 tunnels flooded	11/09/12

7.1.3 Manhattan Waterfront

The Manhattan waterfront, where investigated (south of 30th Street on the east side, south of 25th Street on the west side), consists of a combination of concrete and stone gravity bulkheads, steel and concrete anchored bulkheads, and pile-supported piers and relieving platforms. While evidence of flood inundation was visible throughout, the post-storm condition of waterfront structures was generally good. Displacement of architectural elements (paving stones, planters, etc.) was occasionally observed. Small (less than about five feet width) washouts were observed at two locations, one at a storm drain inlet on East 26th Street and one at change in bulkhead type at East 15th Street. Settlement of the waterfront walkway, possibly related to storm damage, was observed at East 15th and East 16th Streets. Heaving of paving stones and landscaping, possibly related to flotation of below-grade elements, was observed at Piers 25 and 46 on Manhattan's west side. Damage to floating docks was observed at several locations.

Figure 7.19 Displaced paving stones along Lower Manhattan waterfront, typical (40.706952° N, 74.01892° W, November 1, 2012).

Figure 7.20 Upset planters along Lower Manhattan waterfront, typical (40.70713° N, 74.000665° W, November 3, 2012)

Figure 7.21 Heaved paving stones at Pier 46, west side of Manhattan (40.734326° N, 74.01092° W, November 2, 2012).

Figure 7.22 Damage to floating dock at Hudson River Park, Pier 40, west side of Manhattan (40.728161° N, 74.011395° W, November 2, 2012).

Figure 7.23 Damage to floating timber dock, Battery Park, Lower Manhattan. Note lifted planks (40.707888° N, 74.018282° W, November 1, 2012).

Figure 7.24 Settlement of waterfront walkway between East 15th and East 16th Streets, indicated by band of exposed unpainted concrete on wall. Damage not confirmed to be storm related (40.728454° N, 73.971484° W, November 3, 2012).

	
Figure 7.25 Washout at bulkhead type change, East 15th Street (40.727755° N, 73.971612° W, November 3, 2012).	Figure 7.26 Washout at storm drain inlet, East 26th Street (40.737767° N, 73.974794° W, November 3, 2012).

7.2 Brooklyn and Queens

Red Hook, Brooklyn, is an industrial and residential neighborhood located on the west edge of the borough of Brooklyn fronting the Upper New York Bay. Damage in this area was primarily due to flooding, with flood water levels approximately four to five feet above sidewalk grade observed throughout the low-lying near-shore areas. The southern terminus of the flooded Brooklyn Battery (Hugh L. Carey) Tunnel lies within this area (Figure 7.27).

Brooklyn Bridge Park is low-lying land at the southern terminus of the Brooklyn and Manhattan Bridges along the East River. The waterfront is a combination of rip-rap slope, beach, pile-supported piers, bulkhead, and relieving platform. No significant damage (beyond flood debris accumulation) was observed at Brooklyn Bridge Park.

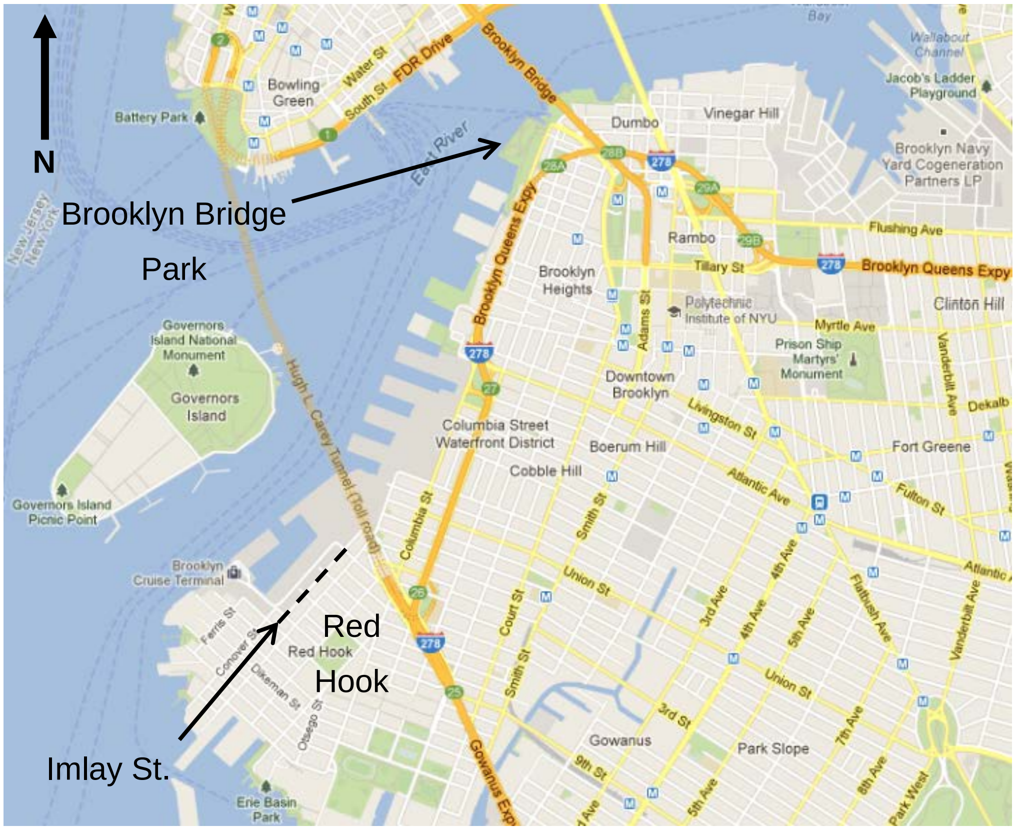


Figure 7.27 Map of a portion of Brooklyn

Figure 7.28 High water mark approximately five feet above sidewalk along Imlay Street, Red Hook, Brooklyn (40.680721° N, 74.010008° W, November 4, 2012).

In Queens, NYC, two major washouts along the earth embankment crossing Jamaica Bay took a large segment of the Rockaway (A) subway line out of service for nearly seven months (Figure 7.29).

Figure 7.29 Washouts in Queens, along Rockaway subway [A] line after Sandy (left) and post mitigation work (right). Damage to earth embankment exposed old LIRR infrastructure (left). Photos credit: Khinda, J.S., ed., 2013.

7.3 Water levels

High water marks were documented by the GEER team where observed. These typically consisted of debris lines on buildings, fences, landscape, or wet/dry lines on masonry walls. High water marks were measured from the closest reference level (e.g. ground surface, top of sidewalk, etc.). When possible, measurements were related to NAVD 88 datum and Borough President of Manhattan datum, and converted to elevations. In general, the GEER high water mark observations agreed with those of other investigators (e.g. USGS) and high water levels observed at NOAA tide gages. GEER water level observations are summarized in Table 7.2.

Table 7.2 GEER High Water Mark Observations

ID #	Date Observed	Locale / Borough	Neighborhood	Distance from Reference Point to High Water Mark (ft)	Description of Reference Point	High Water Elevation*	
						NAVD88	Borough President of Manhattan
1	11/3/2012	Manhattan	South Ferry	4.0	Floor	9.3	7.7
2	11/3/2012	Manhattan	South Street Seaport	5.7	Sidewalk	10.6	9.0
3	11/3/2012	Manhattan	East 30th	4.5	Sidewalk	10.4	8.8
4	11/3/2012	Manhattan	Lower East Side	2.5	Running track	10.9	9.3
5	11/3/2012	Manhattan	Fulton Fish Market	6.0	Pavement	10.9	9.3
6	11/2/2012	Manhattan	West 24th	4.5	Sidewalk	11.0	9.3
7	11/4/2012	Brooklyn	Red Hook	5.3	Sidewalk	10.2	8.6
8	11/4/2012	Brooklyn	Red Hook	2.5	Top of Pier		
9	11/4/2012	Brooklyn	Red Hook	2.5	Sidewalk	11.5	9.8
10	11/5/2012	Queens	Breezy Point	3.3	Paved Walks		
11	11/4/2012	Queens	Rockaway	4.8	Sidewalk		
12	11/4/2012	Queens	Rockaway	4.6	Sidewalk		
13	11/4/2012	Queens	Rockaway	4.8	Sidewalk		
14	11/4/2012	Queens	Long Beach	2.3	Sidewalk		
15	11/4/2012	Queens	Long Beach	2.4	Sidewalk		
16	11/6/2012	Queens	Broad Channel	6.5	Sidewalk		
17	11/6/2012	Queens	Broad Channel	5.3	Curb		
18	11/9/2012	Brooklyn	Coney Island	2.5	Ground Surface	11.0	9.3
19	12/2/2012	NJ	West New York	5.5	Sidewalk		

*Note: High water elevations are based on field measurements of debris lines or wet/dry lines which were not always sharply defined, and relation of those measurements to the closest available elevation reference. Therefore, high water elevations reported here should be considered approximate.

7.4 Underground Utilities

Flooding affected underground utilities, including telecommunications (internet and cable TV), electrical power, steam, and gas. Many large office buildings were shut down for weeks because their first floor and basements were flooded causing them to have no utility service, escalators, heat or elevators due to damage below ground equipment.

7.4.1 Telecommunications – Verizon Building

The New York City Building Code at the time of Hurricane Sandy required that fuel for emergency generators be placed in the bottom level basements of buildings. There were numerous instances of fuel tanks and pumps being damaged by basement flooding during the hurricane. An important example is the Verizon Building at 140 West St. at the World Trade Center site, which has 5 basement levels. Flooding at the Verizon Building inundated and damaged the fuel tanks and pumps at the lower basement levels. Electricity supplied by Consolidated Edison to lower Manhattan was lost during and after the hurricane so that emergency generators were needed to power the telecommunication equipment. Even though the emergency generators were placed on the 10th floor of the building, they were not able to operate because of lack of fuel.

The Verizon Building is one of the main central offices providing telecommunication services for the New York Stock Exchange (NYSE). The other Verizon central office providing this service is located on Broad St., which was also flooded by the hurricane. Verizon fuel trucks were dispatched to the 140 West St. where pumps were set up at the street level, and fuel was pumped to the 10th floor generators for electricity to power telecommunications critical for opening the NYSE. Similar difficulties with fuel tanks and pumps in basements were experienced by hospitals that were flooded adjacent to the East River.

7.4.2 Electric Power, Gas, and Steam – Consolidated Edison

Consolidated Edison (Con Ed) supplies electric power to nearly all of NYC's three million customers, representing 8.3 million people and 250,000 businesses (Con Ed's territory excludes only the Rockaways in Queens). Con Ed also provides 41% of the city's natural gas service as well as a steam system serving 1,700 customers in Manhattan (NYC SIRR, 2013). The electric system includes 24 in-city generation plants, 24 transmission substations, and a network of area substations. About 86% of Con Ed's electric distribution system is underground; 53% of generation capacity and 37% of transmission substation capacity lie within the 100-year floodplain. Hurricane Sandy caused loss of power to more than 800,000 Con Ed customers (over 2 million people), interrupted steam service to nearly a third (561) of Con Edison's steam customers, and caused gas outages to another 4,200 customers (Khinda ed., 2013, NYC SIRR, 2013).

Despite multiple precautionary measures taken by Con Ed in advance of the storm (which included placement of sand bags and "Aqua Dams" [large, polyethylene berms filled with water] at multiple substations and vaults, pre-emptive de-energizing of some equipment, isolation of 26 steam main segments, and pre-emptive shutdown of the East River Generating Station and the Brooklyn Navy Yard Cogeneration Plant [BNYCP] steam plants), Hurricane Sandy's storm surge exceeded expectations and caused unprecedented damage to Con Edison's infrastructure. The East River, East 13th Street, and Seaport substations were flooded, resulting in a loss of almost one third of the city's generating capacity and 11 electric networks that supply most of Manhattan south of 34th Street. The power outage in Lower Manhattan lasted four days and severely impeded the recovery effort and restart of subways. The Goethals and Fresh Kills transmission substations in Staten Island were also flooded, causing the loss of 3 area substations.

Figure 7.30 Consolidated Edison's East 13th Street complex, which was flooded in Hurricane Sandy. Photo credit: Consolidated Edison, in Khinda et al (2013).

Figure 7.31 Power outage in Lower Manhattan after Hurricane Sandy, October 29, 2012. The power outage affected most of Lower Manhattan south of 34th Street. Power was not fully restored for four days. Photo credit: Iwan Baan for New York Magazine.

The storm surge overcame protective barriers and forced the 59th Street and 74th Street steam-generating stations and the First Avenue steam tunnel to shut down. Twenty-two steam main segments were isolated in addition to those that were de-energized before the storm, affecting an additional 431 steam customers. Flooding in the Bronx led to isolation of more than 240 gas services, while uprooted trees in Queens and Westchester caused damage to 33 gas services.

As significant as Sandy's impact on Con Ed infrastructure was, the impact could have been worse. Because Sandy hit in late October, when electricity demand is relatively low, Con Ed had enough reserve capacity to meet NYC's demand after the storm, even after sustaining significant damage to a large portion of the city's generating capacity and power-importing infrastructure. Had Sandy hit during the peak (summer) season for electrical demand, the reserve capacity would not have been sufficient to meet post-storm demand, which could have resulted in severe, long-lasting outages (NYC SIRR 2013). Also, had the peak storm surge coincided with high tide in Long Island Sound (which occurs about two hours later than high tide in New York Harbor; see Figure 4.7), it is likely the Astoria, Queens generating facilities would also have been flooded, resulting in a loss of an additional 29% of the city's generating capacity (NYC SIRR 2013).

7.4.1. Recovery and Restoration

Restoration began immediately after the storm had passed. Within four days, all power networks in Manhattan were restored. Power outages in surrounding communities, including the outer boroughs of New York City, Long Island, and New Jersey, where much of the electrical infrastructure is overhead, lasted as long as two weeks after the storm. Steam systems were restored within one week of the storm to all steam customers at sufficient loads, and nearly two weeks after the storm, Con Ed had increased service to approximately 60%

capacity. Similarly, gas service was restored to customers that could accept it within two weeks following the storm.

7.4.2. Planned Storm Hardening

In preparation for the 2013 hurricane season, Con Ed has internally developed updated design criteria based on the higher of the following flood levels: peak flood levels observed during Sandy at each location, the Cat 1, 2010 SLOSH maps (prepared by the National Weather Service), or the 2007 FEMA 100 year flood maps. Immediate work, planned to be constructed by June 2013, includes raised-moat walls surrounding flood-vulnerable equipment, barriers, and new sealing materials at potential intrusion points. Long-term efforts include high capacity flood pumps, sluice gates for tunnels, elevating critical equipment and control rooms, and surge walls around station perimeters.

Figure 7.32 Examples of raised walls around critical equipment installed by Consolidated Edison soon after Hurricane Sandy for storm hardening. Photos provided by L. Villani (Consolidated Edison), May 2013.

7.5 Wastewater Treatment Plants

Flooding as a result of hurricane sandy took a number of water treatment plants offline for varying periods of time allowing untreated wastewater to flow into the environment. The following information is summarized from the April 2013 Climate Central report “Sewage Overflows from Hurricane Sandy,” which collates data from waste water treatment plants collected in the six months following the storm (Kenward, Yawitz and Raja, 2013).

Eleven (11) billion gallons of untreated and partially treated sewage flowed into rivers, bays, canals, and in some cases, city streets. Much of the sewage overflow occurred as a result of the record storm surge flooding that overtook waste water treatment plants on the Eastern Seaboard.

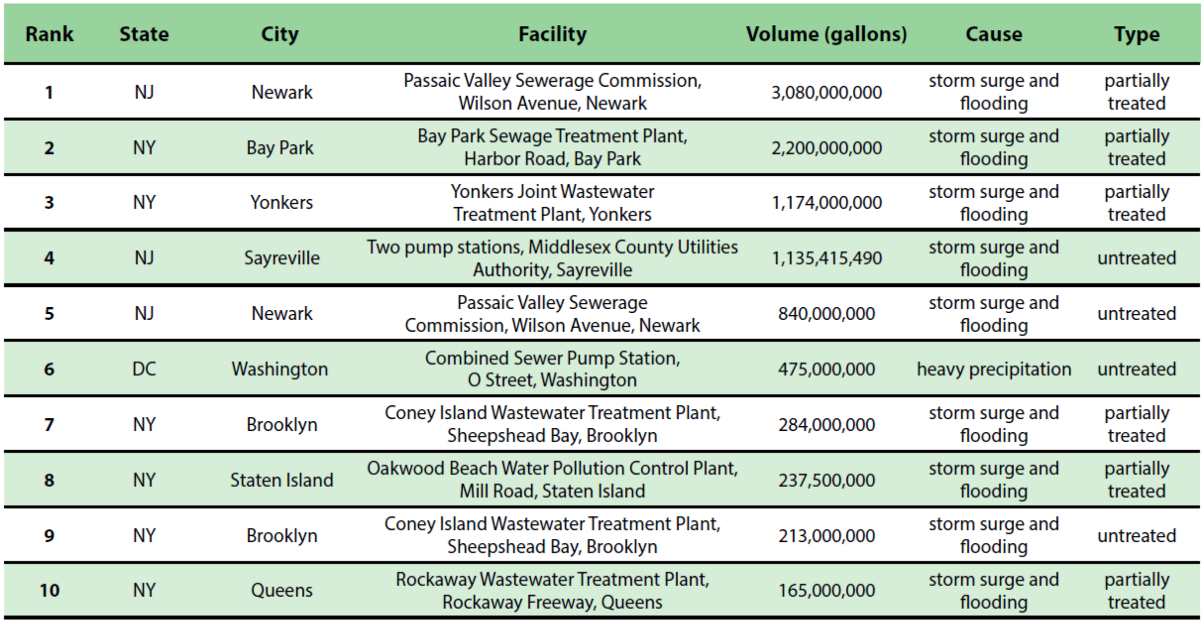
One third of the overflow, approximately 3.45 billion gallons, consisted of untreated raw sewage. The remainder, approximately 7.45 billion gallons, was partially treated, indicating that it underwent at least some form of filtration and, in some cases, chlorination. 94% of the sewage overflow was caused by damage resulting from coastal flooding. In many cases, the storm surge simply flooded plants and pumping stations. In other cases, overflow was facilitated by a combination of power outages and flood conditions leading to the closure of critical facilities or the diversion of sewage into waterways. Figure 7.33 below shows sewage outflow into a Long Island Estuary.

Figure 7.33 Overflow from the Bay Park Sewage Treatment Plant in East Rockaway, N.Y. Hurricane Sandy resulted in over 2 billion gallons of sewage overflow from this facility. Some of this overflow (estimated at 68 million gallons) was released adjacent to the Western Long Island South Shore Estuary (above). Photo courtesy of Doug Kuntz. *Modified from Kenward, Yawitz and Raja, 2013.*

New York and New Jersey experienced over 94% of the total sewage outfall caused by the storm event. Six sewage spills greater than 100 million gallons were reported in New York, as were twenty eight spills greater than 1 million gallons. In New Jersey, 840 million gallons of untreated sewage and another 3 billion gallons of partially treated sewage flowed directly into Newark Bay as a result of storm surge induced flooding at the Passaic Valley Sewage Commission (NJ). The Middlesex County Sewage Authority (Sayersville, NJ) experienced severe damage to two pumping stations, sending over 1 billion gallons of untreated sewage into the Raritan River and Raritan Bay.

In Washington D.C., heavy precipitation (5” of rainfall) led to an overflow of the O Street Combined Sewer and 475 million gallons of untreated sewage and contaminated storm runoff flowed into the Anacostia River. Table 7-2 summarizes the ten largest untreated and partially treated sewage outflows caused by Hurricane Sandy.

Table 7.3 Ten largest sewage outflows caused by Hurricane Sandy. *Modified from Kenward, Yawitz and Raja, 2013.*



Rank	State	City	Facility	Volume (gallons)	Cause	Type
1	NJ	Newark	Passaic Valley Sewerage Commission, Wilson Avenue, Newark	3,080,000,000	storm surge and flooding	partially treated
2	NY	Bay Park	Bay Park Sewage Treatment Plant, Harbor Road, Bay Park	2,200,000,000	storm surge and flooding	partially treated
3	NY	Yonkers	Yonkers Joint Wastewater Treatment Plant, Yonkers	1,174,000,000	storm surge and flooding	partially treated
4	NJ	Sayreville	Two pump stations, Middlesex County Utilities Authority, Sayreville	1,135,415,490	storm surge and flooding	untreated
5	NJ	Newark	Passaic Valley Sewerage Commission, Wilson Avenue, Newark	840,000,000	storm surge and flooding	untreated
6	DC	Washington	Combined Sewer Pump Station, O Street, Washington	475,000,000	heavy precipitation	untreated
7	NY	Brooklyn	Coney Island Wastewater Treatment Plant, Sheepshead Bay, Brooklyn	284,000,000	storm surge and flooding	partially treated
8	NY	Staten Island	Oakwood Beach Water Pollution Control Plant, Mill Road, Staten Island	237,500,000	storm surge and flooding	partially treated
9	NY	Brooklyn	Coney Island Wastewater Treatment Plant, Sheepshead Bay, Brooklyn	213,000,000	storm surge and flooding	untreated
10	NY	Queens	Rockaway Wastewater Treatment Plant, Rockaway Freeway, Queens	165,000,000	storm surge and flooding	partially treated

A GEER investigation team conducted a case study and site visit at the Yonkers Joint Wastewater Treatment Plant, which experienced the third largest sewage outflow of any plant on the Eastern Seaboard during Hurricane Sandy. This case study can be found in Section 7.6.

The US Environmental Protection Agency (EPA) requires all plants and outfalls to report all bypasses and outflows directly. The majority of data collected in the Climate Central report comes from these reports. However, the storm destroyed many of the electrical monitoring systems used to measure outflow and bypasses. In these cases, estimates of discharged sewage were obtained from testimonials of plant operators and simple calculations based on typical plant flow rates.

The incredible recovery effort ensured that close to all plants were treating sewage, at least partially, within hours after the storm. Nonetheless, Hurricane Sandy revealed how vulnerable critical below-ground components of our waste water management system are to coastal flooding and heavy precipitation.

7.6 Case Study – Yonkers Joint Wastewater Treatment Plant

On December 20, 2012, Ms. Sissy Nikolaou and Mr. Aaron Sacks visited the Yonkers Joint Wastewater Treatment Plant (WWTP) to interview plant operators regarding Super-storm Sandy impacts and observe and ongoing recovery efforts and remaining damage features at the plant. The visit was sponsored by the NSF through GEER. The visit was hosted by Plant Superintendent Charles C. Beckett and Director of Wastewater Treatment Joseph Gibney.

7.6.1. Plant Background Information

The Yonkers Joint WWTP is located in Yonkers, New York, on the east bank of the Hudson River, approximately 15 miles north of lower Manhattan. An aerial photograph of the plant is shown in Figure 7.34.

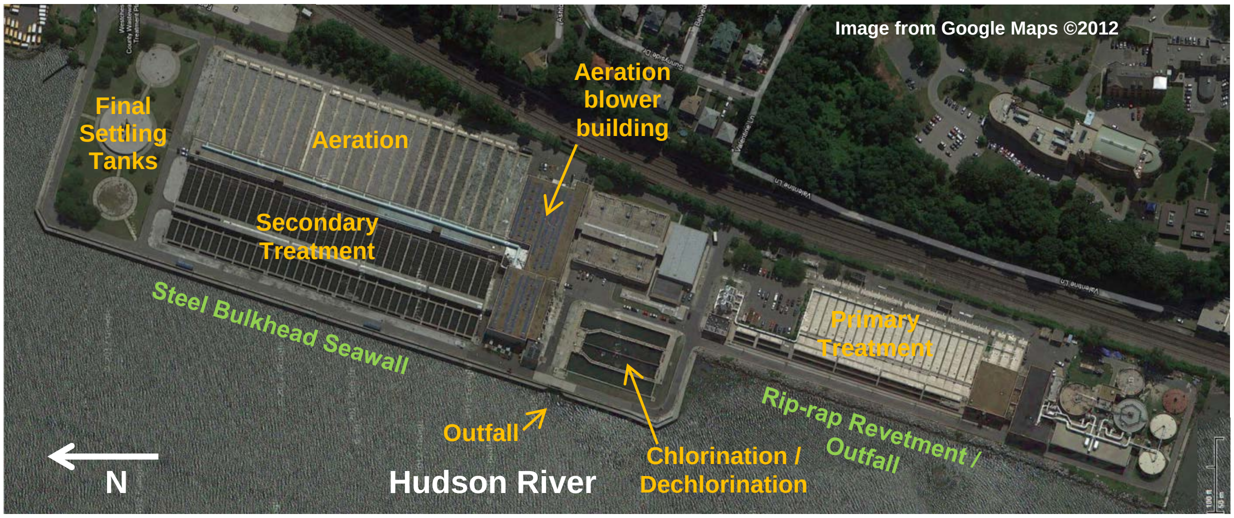


Figure 7.34 Yonkers Joint Wastewater Treatment Plant

The plant site consists primarily of filled land along the Hudson River, as shown in Figure 7.34. The river frontage is characterized by a rip-rap revetment along the southern segment, and a steel seawall along the northern segment. As shown in Figure 7.35, the top elevation of the seawall is about five feet higher than the top elevation of the rip-rap revetment. Note: elevations herein reference the North American Vertical Datum of 1988 (NAVD 88).

Figure 7.35 Junction of rip-rap revetment and seawall, looking south.

The plant treats waste water from the Yonkers metropolitan area and sewer districts to the north. During dry weather, the plant handles an average of 95 million gallons per day (MGD). Due to the presence of combined sewers within the network, the plant occasionally handles spikes of up to 240 MGD during storms, although blending within the treatment process occurs above 140 MGD. According to Mr. Beckett, the plant processed 300 MGD during Hurricane Irene in August 2011. The plant functions primarily as a gravity system, with preliminary treatment, primary treatment, aeration, secondary treatment, and final chlorination/dechlorination stages situated at successively lower elevations. When the Hudson River tail-water elevation exceeds approximate Elev. 9, gravity flow is lost and the treatment process is impaired.

7.6.2. Preparation Measures

Several measures undertaken by the plant prior to the storm aided the recovery. These included:

- Establishing emergency service contracts with electrical and mechanical contractors.
- Sandbagging doors to the electrical feeder and Motor Control Center (MCC) room
- Sandbagging outside doors to treatment plant areas
- Repositioning emergency equipment

7.6.3. Sequence of Events during Storm

On the evening of October 29, 2012, Mr. Beckett was on-site as the plant superintendent. As the Hudson River rose, it first entered the site by back-flowing through storm drains in the parking lot (Figure 7.36), and subsequently overtopped the rip-rap revetment. According to Mr. Beckett, the parking lot had previously been submerged only once in his memory, most likely during Hurricane Charley in August 2004. Between 7:30 and 8:00 PM, as river level continued to rise, the plant contacted the Emergency Operations Center to obtain clearance and then contacted electrical authority Consolidated Edison to have power to the plant cut, which occurred at about 8:45 PM. By 8:30 PM, the chlorination/dechlorination stage of the treatment process had been inundated and gravity flow through the plant was lost. Shortly thereafter, flood water entered the aeration blower building through vent grates in the outside walls (Figure 7.37) and subsequently entered other parts of the plant through similar vents (Figure 7.39). Flood water ultimately reached a level about three feet above the site parking lot grade, as illustrated in Figure 7.37 and Figure 7.38, before receding.

Figure 7.36 Typical storm drain inlet in parking lot where storm surge first entered, looking south. Note elevation of lip of chlorination tanks at right.

	
Figure 7.37 Vent grates in aeration blower building where flood water entered. Ultimate flood water elevation indicated.	Figure 7.38 Ultimate flood water elevation indicated by plant superintendent.

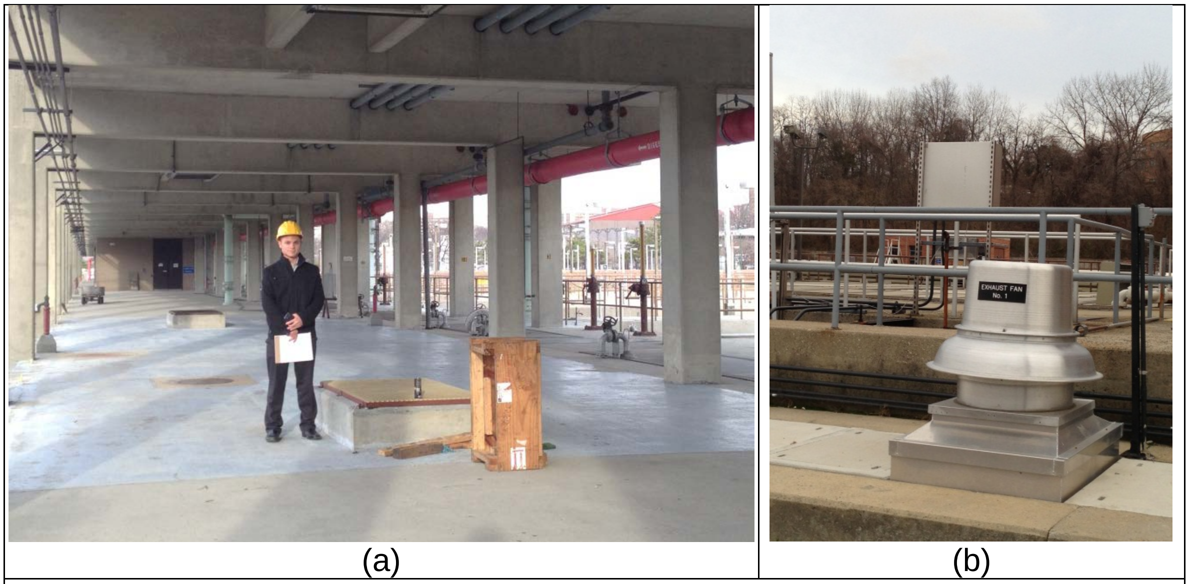

(a) (b)

Figure 7.39 Vent grates which allowed flood water to enter.

7.6.4. Storm Damage to Plant

Essentially all damage sustained by the plant was the result of flood inundation. Primary damage features observed and described to the GEER team are listed below. Photographs of several of these observations are included as Figures Figure 7.40 to Figure 7.48.

- Boiler rooms in the aeration blower building basement were submerged. These boilers supply hot water used to heat buildings and also in the anaerobic digestion process.
- The plant communication and control room, located in a basement space, was submerged, disabling the plant's automated ("SCADA") control system.
- A new fire alarm system was disabled by flood water.
- Many electrical motors were submerged and required rebuilding or replacement.
- The subsurface gallery between the aeration and final settling tanks, as well as the network of underground rooms and passageways between and beneath the various plant facilities, was inundated.

- Insulated pipes in submerged areas were soaked and required stripping, cleaning, and re-insulation.
- Doors between underground rooms and passageways temporarily impeded the advance of floodwater from room to room, but in many cases failed due to hydrostatic pressure on the flooded side. In one location, large steel doors were twisted open by flood waters.
- An unreinforced concrete masonry unit (CMU) stairwell wall in the screening grit basement was destroyed when flood water filled the stairwell and hydrostatic pressure exceeded the wall’s lateral strength. The stairwell doors had been closed.
- A lubrication oil depot at the site was compromised, creating an oil slick which exacerbated cleanup efforts.

Notably, some portions of the plant escaped damage. These were as follows:

- The 13.2 kV electrical feeder and MCC room was not flooded, thanks to successful sandbagging of the doors. Lack of damage to the electrical feeders and MCC’s greatly aided the recovery process.
- The emergency generator room was not flooded, thanks to successful sandbagging of the doors.

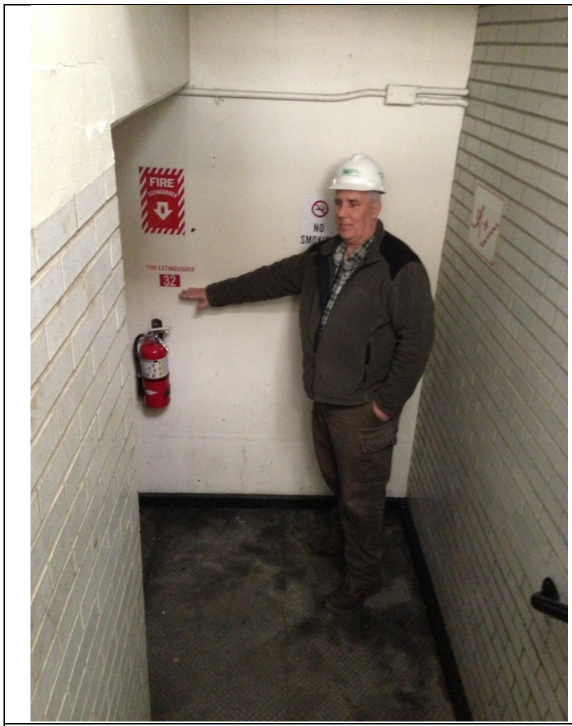


Figure 7.40 Flood level reached in aeration blower building stairwell.

Figure 7.41 Flood level reached at aeration blower building door. This door was pushed open by flood water.

Figure 7.42 Steel doors twisted open by flood water.

Figure 7.43 Plant automated control system room. Flooding disabled the system necessitating manual operation of valves.

Figure 7.44 Insulated pipes required stripping and re-insulation.

Figure 7.45 Unreinforced CMU wall overcome by flood water. The door to the stairwell had been closed, allowing water to fill the stairwell.

Figure 7.46 Door to electrical feeder and MCC room which was successfully sandbagged.

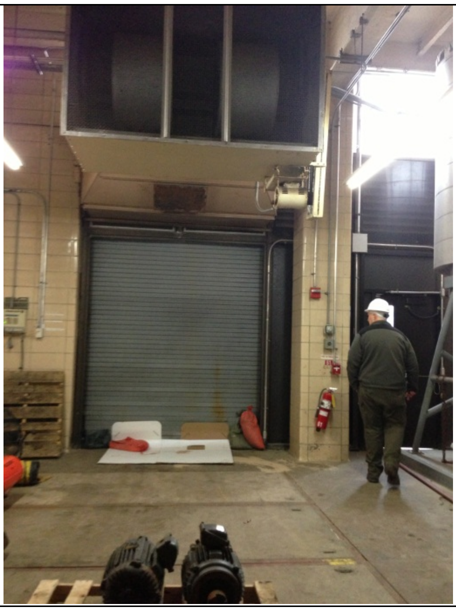


Figure 7.47 Door to emergency generator room which was successfully sandbagged.

Figure 7.48 Electrical feeder and MCC room not flooded thanks to sandbagging measures.

7.6.5. Recovery

The plant recovery proceeded relatively smoothly, thanks to preparation measures and decisions taken by plant personnel before, during, and after the storm. The recovery timeline as reported to the GEER team was as follows:

- Submerged areas fully pumped out 30 hours after storm
- Primary treatment resumed in 3-4 days
- Secondary treatment resumed in 14 days
- Plant restored to permit conditions in 21 days

7.6.6. Lessons Learned

Several observations of the performance of the Yonkers Joint Wastewater Treatment Plant and its personnel in Super-storm Sandy lend themselves to improving the resiliency of treatment plant infrastructure during future events. These are listed below:

1. Inundation of below-grade areas was the primary damage mode. Because of inundation, it was necessary to rebuild or replace significant portions of the plant's electrical and mechanical infrastructure. Preventing inundation would greatly reduce recovery time.
2. Vent Grates. Air intake grates, vents, and louvers were a primary point of entry for flood water. Raising or blocking these grates to an elevation well above the maximum considered flood level would substantially reduce or prevent inundation.

3. Doors. Architectural doors served as the last line of defense against the spread of flood water through the plant. Designing such doors to withstand hydrostatic pressure (not typical design practice) could prevent inundation of interconnected plant areas. If doors are designed to impound flood water, walls and floors must also be designed to handle flood loads.
4. Sandbagging. Sandbagging of outside doors successfully prevented flooding of several key plant areas, including the main electrical feeder / MCC and emergency generator rooms.
5. Protection of Critical Infrastructure. The protection of the electrical feed, primary MCCs, and emergency generators greatly aided the recovery. On the other hand, loss of the automated control system because of submergence of the control room was an impediment. Locating critical power supply, communication, and control infrastructure above flood elevation improves resiliency. In fact, a plan to relocate the electrical feeder room to a higher level at the plant is currently underway.
6. Organizational Structure. Several decisions made by on-site management before, during, and after the storm greatly mitigated damage and sped the recovery. These included the decisions to sandbag critical areas of the plant, cut plant power prior to inundation, early placement of replacement part and service orders, and the proper prioritization of repair work during the recovery. An organizational structure which allowed key decisions to be made by on-site management during the storm improved the resiliency of the plant.

Human Experience. Having on-site personnel who were intimately familiar with the plant design and layout improved resiliency. For example, when the automated control system was disabled during the flood, it was critical that on-site personnel knew the physical locations of valves. In this case, automation did not function as a substitute for human experience.

7.7 Case Study Waste Water Treatment Plant and Contaminated Sediments, New Jersey

Northeastern NJ is heavily industrialized and has left a legacy of contaminated sites. Some of these, including the Passaic River Superfund Site and the Syncon Resin Superfund Site, lie within areas that were inundated by the storm surge from Superstorm Sandy (Figure 7.49). Figure 7.50 shows the Passaic River shoreline near where it empties into Newark Bay. Newark Bay and the Passaic and Hackensack Rivers contain sediments contaminated with a variety of organic and inorganic hazardous compounds. These generally lie relatively undisturbed in the water bodies, but extreme events can resuspend and transport the sediments to upland areas where human exposure is possible. In addition, leaks and spills of fuel oil and untreated waste from sewerage plants occurred, causing noticeable odors along the shorelines.

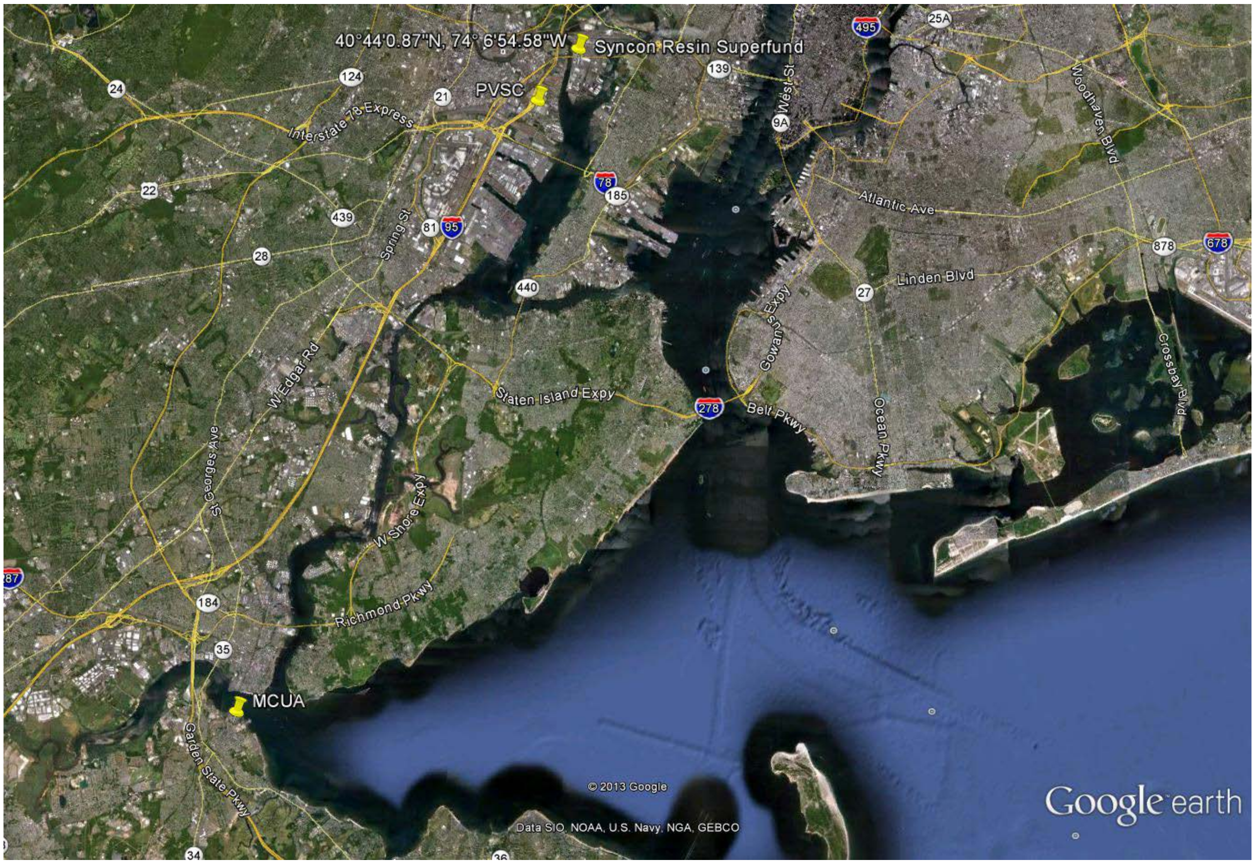


Figure 7.49 Location of the sewerage treatment plants and Superfund sites within the Newark Bay/Raritan Bay Complex

Figure 7.50 Passaic River Shoreline near Newark Bay

Major sewerage treatment plants, including those of the Middlesex County Utilities Authority and the Passaic Valley Sewerage Commission (PVSC, 40°42'51.80"N, 74° 8'6.01"W) suffered damage. PVSC is the fifth largest treatment plant in the US and handles sewerage from 1.5 million customers. Flood waters covered the PVSC plant which has little freeboard between it and Newark Bay, as seen in Figure 7.51. The brackish water inundated a tunnel network several miles in length that houses pumps and electrical infrastructure as shown in Figure 7.52, causing shutdown. Sewerage backflowed into homes and industrial waste combined with flood waters flowed untreated into Newark Bay and the New York Harbor. Coliform counts at the mouth of the Passaic River at Newark Bay were reported up to 1,500 per 100 milliliters, while the maximum acceptable level is 14. As of 11/15/12, the PVSC plant had reportedly discharged some 4 billion gallons of raw or primary-treated sewerage (O'Neill, 2012). Security systems were disabled and the laboratory was destroyed. To restart the PVSC plant, the USACE provided pumps which removed some 200 million gallons of water from the tunnels. Some 260 motors required cleaning, drying or replacement.

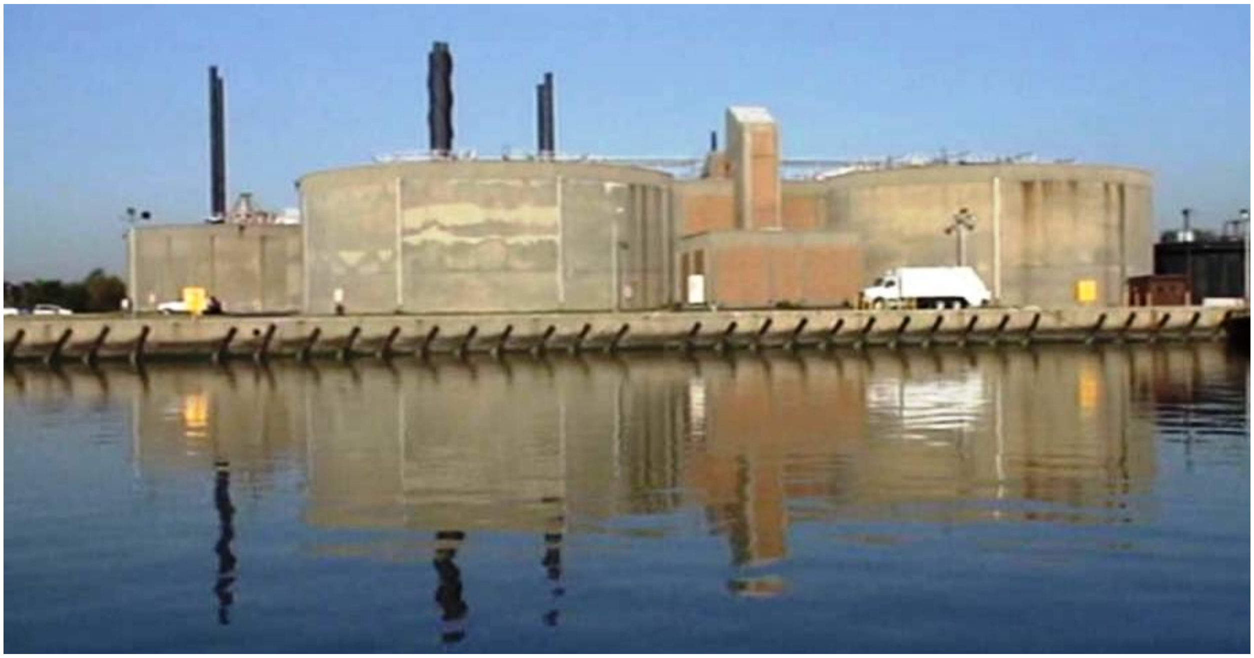


Figure 7.51 PVSC Wastewater Treatment Plant from Newark Bay

Figure 7.52 Tunnels housing pumps, controls, and worker offices at PVSC (USACE, Nov. 2012).

The Middlesex County Utility Authority (MCUA, 40°29'19.10"N, 74°16'52.78"W) lost power to the water utility intake pump. Although the MCUA was situated above the storm surge, three major pumping stations were flooded and required more than one month of repair work. USEPA and the State assisted with the repairs.

The Syncon Resins Superfund Site (40°44'0.87"N, 74° 6'54.58"W) along the Passaic River, on the eastern side of the Town of Kearny, was flooded and the ground water treatment plant disabled. Although the plant was located above the regulatory Flood Hazard Elevation, the storm surge from Sandy exceeded this. Figure 7.53 shows the water level in the plant during the storm. Pumps and Programmable Logic Controllers (PLCs) were damaged or ruined. The building is undergoing an expensive disassembly and decontamination from the contaminated flood water.

Figure 7.53 Syncon Resins Superfund Site Treatment Plant. Arrow shows high water mark (left). Motor cleaning and drying (right).

8 POST HURRICANE RESPONSE

New York City and the coasts of New Jersey and Long Island are some of the most densely populated and metropolitan areas in the United States. Accordingly, Hurricane Sandy's impact was felt across not only millions of people, but also a wide variety of organizations, agencies, authorities, jurisdictions, infrastructure operators, and a diverse community of architects, engineers, institutions, and city planners. Many affected entities undertook assessments of preparation measures, response to the storm, and hardening measures to enhance resilience to future events. These largely regional efforts in turn sparked the engagement of engineers, planners, and policy makers at state, national, and international levels.

Table 8.1 is a non-comprehensive list of entities and reports issued since Hurricane Sandy. Full citations to these reports can be found in the References section at the end of this report.

In light of the strong regional response to Hurricane Sandy, an important part of the GEER reconnaissance took place in the months following the storm. This effort has consisted in tracking the Sandy recovery in engineering/architecture publications and news media, attending industry events and seminars, and building relationships with individuals in the affected agencies and organizations. A non-comprehensive list of post-Sandy industry events attended by GEER volunteers is provided in Table 8.2. Much of the information provided in this report is the product of this "post-event reconnaissance."

Table 8.1. Non-Comprehensive List of Post-Sandy Entities and Reports

ENTITY / ORGANIZATION AND ASSOCIATED MEMBERS	PUBLICATION	DATE	GOALS / RECOMMENDATIONS / UPDATES
NYS 2100 Commission [New York state gvm't & industry professionals]	Recommendations to Improve the Strength and Resilience of the Empire State's Infrastructure	Jan-13	Identify immediate improvements; identify long term projects to increase climate resilience; investigate hard barriers and natural systems for coastal protection; incorporate resilience into economic development; reform risk related to natural disasters
NJ Department of Community Affairs [New Jersey state government]	Community Development Block Grant Disaster Recovery Action Plan	Mar-13	Develop adequate storm resistant housing; hold workshops to educate public about land use and zoning; enforce new code requirements
New York City Transit (MTA)	MTA-NYCT's Hurricane Planning and Infrastructure Mitigation (ASCE Met Section April 8-9 Seminar)	Apr-13	Develop, design, and implement necessary repairs; understand future flood levels
Consolidated Edison	Storm Preparation and Restoration: Con Edison's Response to Hurricane Sandy & Impact on its Infrastructure (ASCE April 8-9 Seminar)	Apr-13	Enhance and storm-harden electric, gas and steam systems with a focus on wind loads and storm surge.
Port Authority of New York and New Jersey	Storm Surge Impacts on Port Authority Structures (ASCE Met Section April 8-9 Seminar)	Apr-13	Improve communication among in-house staff and consultant responders; increase regional approach to storm response.
US Army Corps of Engineers	Two interim reports, comprehensive study	May-13	Provide risk reduction strategies and promote resiliency in coastal communities.
Post Sandy Initiative [American Institute of Architects (AIANY), NYC Dept. of City Planning]	Building Better, Building Smarter: Opportunities for Design and Development	May-13	Promote long term resilience through consensus on building standards, building better and stronger with careful planning.
NYC Recovery [Office of the Mayor]	Hurricane Sandy After Action: Report and Recommendations to Mayor Michael R. Bloomberg	May-13	Improve evacuation, communication, data integration, additional capacity to respond to loss of power, better relief effort coordination, mid to long term housing for the displaced, partner with state and federal gov't to regulate and enforce standards for critical services.
NYC Special Iniative for Rebuilding and Resiliency (SIRR) [Office of the Mayor, PlaNYC]	A Stronger, More Resilient New York	Jun-13	Analyze impacts of storm on the city’s buildings, infrastructure, and people; assess risks city faces from climate change in the medium term (2020s) and long term (2050s); and outline ambitious, comprehensive, but achievable strategies for increasing resiliency citywide.
Building Resiliency Task Force [Urban Green Council]	Report to Mayor Michael R. Bloomberg and Speaker Christine C. Quinn	Jun-13	Consider extreme weather events and climate change impacts on NYC buildings (new and existing). Identify measures to increase building resiliency and facilitate recovery after an event. Develop fast-tracked process for policy proposal review. Engage with independent industry group efforts.
NYC Office of Emergency Management (NYCOEM)	nyc.gov/oem	Jun-13	Proposes updated system of six evacuation zones considering both hurricane strength and path (bearing).
New York Building Congress Task Force on NYC Storm Preparedness [New York Building Congress (NYBC)]	Risk and Resiliency After Sandy	Jun-13	Harden power grid; clear authority and responsibility for emergency response; improve building codes; pre-approve and indemnify catastrophic response contractors; promote "good samaritan" laws protecting emergency responders from legal action
NYC Department of Buildings (NYCDOB)	Rebuilding NYC after Hurricane Sandy	Ongoing (Updated 6/10/13)	Provide design professionals with information on codes and zoning changes; owners encouraged to raise LHF to save on insurance
FEMA Mitigation Assessment Team [FEMA Building Science Branch]	Seven Recovery Advisories, Two Fact Sheets (Foundation Req'ts and Rec's for Elevated Homes)	Ongoing	Provides design recommendations for commercial and residential structures and utilities
FEMA Coastal Analysis and Mapping [FEMA Region II]	Best Available Flood Hazard Data for New Jersey and New York	Ongoing	Gives most up to date flood elevations during the development of the new FIRM maps
New Jersey Transit	Superstormsandyrecovery.com	N/A	Outlines undertakings to repair and rebuild NJT facilities

Table 8.2. Non-Comprehensive List of Post-Sandy Industry Events

DATE	TITLE	SPONSORING ORGANIZATION	LOCATION
12/12/2012	The New Normal for Natural Disasters	SEAoNY / EERI	Center for Architecture, New York, NY
2/13/2013	NYC's Post-Sandy Recovery: How're we Doin'?	AIA NY - Design for Risk	Center for Architecture, New York, NY
3/5/2013	FEMA'S Hurricane Sandy mitigation Assessment; Critical Facility Observations and Lessons Learned	AIA NY - Building Codes Committee	Center for Architecture, New York, NY
4/4/2013	Exploring ways to help move New York forward post-Super Storm Sandy	Crain's NY Rebuilding Conference	Sheraton NY Times Square, New York, NY
4/4/2013	Recovery and Rebuilding after Superstorm Sandy - Legal Perspectives	Hofstra University	Hempstead, NY
4/4/2013	Effect and Aftermath of Hurricane Sandy on the Hugh L. Carey Tunnel	ASCE Metropolitan Section - Construction Group	Helen Mills Theatre, New York, NY
4/8/2013-4/9/13	Impact of Sandy's Storm Surge on NY/NJ Infrastructure"	ASCE Metropolitan Section - Infrastructure Group	Polytechnic Institute of NYU, Brooklyn, NY
4/13/2013	Twentieth Conference on "Geology of Long Island and Metropolitan New York." 3 Presentations on Sandy.	Long Island Geologists	Stony Brook University, Stony Brook, NY
4/15/2013-4/16/2013	Integrating an Understanding of Resilience Across the Levels of Resilience	The Infrastructure Security Partnership	The Thayer Hotel, Westpoint, NY
4/15/2013-4/17/2013	Introduction to Coastal Foundation Design and Construction for Design Professionals; FEMA Best Practices for Flood and Wind Mitigation	FEMA Building Science and FEMA New Jersey Joint Field Office	Rutgers CAIT Auditorium, Piscataway, NJ
4/21/2013	New York at Risk: On the Waterfront	AIA NY	Center for Architecture, New York, NY
4/23-4/25 5/1-5/2	Structural Response of NYC Buildings to Sandy	ASCE Metropolitan Section - Structures Group	Bruno Walter Auditorium, New York Public Library
5/10/2013	Beyond Waterproofing New York - A Designed Response	City College of New York's Spitzer School of Architecture	New York, NY
5/16/2013	Superstorm Sandy: A Live Town Hall - What worked. What didn't. What's next.	WNET/THIRTEEN, NJTV, WLIW21 (Long Island), other tri-state media organizations	-
5/22/2013	The Hurricane Sandy Route 35 Emergency Repairs / Rehabilitation	ASCE Metropolitan Section - Infrastructure Group	Polytechnic Institute of NYU, Brooklyn, NY
5/23/2013	Restoring New Jersey's Beaches for a more Resilient Future	The Jersey Shore Partnership, Inc.	Ocean Place Hotel, Long Branch, NJ
6/4/2013	Three presentations: (1) Homeland Security Information Network (HSIN); (2) NYU Langone Medical Center Sandy evactuation; (3) Changes to NYC storm evacuation zones	General Society of Mechanics and Tradesmen (Hosted by NYC OEM / FDNY)	Geneal Society Headquarters, New York, NY
6/6/2013	Multidisciplinary Assessment of Building System Response to Superstorm Sandy	NYIEC Technical Conference	NYC School Construction Headquarters, Queens, NY
10/7/2013	Lifting Houses above the Flood Plain	Structural Engineers Association of New York (SEAoNY)	Polytechnic Institute of NYU, Brooklyn, NY
10/17/2013	A Stronger, More Resilient New York	ASCE Metropolitan Section - Coasts, Oceans, Ports & Rivers Committee	Helen Mills Theatre, New York, NY
10/24/2013	Engineering Resilient Cities through the Vision of Children: Commemorating One Year Since Hurricane Sandy	EERI / General Society of Mechanics and Tradesmen	Geneal Society Headquarters, New York, NY
11/12/2013	Hurricane Sandy, One Year Later: Lessons Learned and New Standards - Technical Session	SAME NJ, Philadelphia and NYC Posts and The Infrastructure Security Partnership	Joint Base McGuire-Dix-Lakehurst, NJ

An effort towards resiliency that brought a different spin to the engineering approach towards resiliency using the ideas and creativity of children was organized by the New York – Northeast (NYNE) chapter of the Earthquake Engineering Research Institute (EERI) in collaboration with the Society of Mechanics and Tradesmen at the one year anniversary of Sandy. The event showcased art by students from The Gateway Schools' Center for Educational Enrichment, in Manhattan, and PS 39 on Staten Island (Figure 8.1). This community gathering gave engineers the opportunity to learn from the children's creative and intelligent perspectives about resiliency as well as exchanging ideas among themselves. The effort was embraced by all major engineering organizations of New York who offered to be outreach partners for the event, including the American Society of Civil Engineers (ASCE), the American Council of Engineering Companies (ACECNY), the Structural Engineers Association of NY (SEAoNY), the Multidisciplinary Center for Earthquake Engineering Research (MCEER), and the Urban Green Council.

Figure 8.1 Artwork by The Gateway Schools' Center for Educational Enrichment, in Manhattan, and PS 39 on Staten Island (EERI event 10/24/13).

The artwork consisted of 14 oversized plywood panels depicting the arc of the devastation of the hurricane and the subsequent rebuilding and renewal of the affected communities. Expertly facilitated by the notable NYC sidewalk artist, Hani Shihada, these panels tell the whole story of the storm through the eyes of children, providing a fascinating view from a previously unexplored angle.

In further recognition of their outstanding cooperation and collaboration as evidenced by this project, the New York City Council honored both Gateway's Center for Educational Enrichment and PS 39 with an official Proclamation, formally presented at City Hall on October 30th, 2013.

9 LOOKING INTO THE FUTURE

The intensity and scope of damage observed in the aftermath of Hurricane Sandy are unprecedented. Economic impact in New York and New Jersey alone was estimated to be on the order of $34 billion (Blake et al. 2013). The storm provides an urgent reminder of the vulnerability of our coastal communities and mega-cities to major flooding and damage and highlights how increased urbanization worldwide, combined with climate change, exposes urban centers to extreme weather events at increasing frequency. Recent reports indicate that the frequency of such storms could increase in the future. For example, a severe rain event struck Toronto in the summer of 2013, causing significant flooding around the city and to underground infrastructure, including tunnels.

Sandy initiated discussion among professionals from a variety of disciplines, including civil infrastructure planners, engineers, architects and environmental scientists. Questions considered include: should we build large-scale barriers to prevent storm surges from flooding an urban area? Will these barriers shift the flooding problem to other areas? Should we allow coastal areas to flood and enhance the resiliency of the infrastructure by hardening them in place so that functionality can be restored within a short period of time, or attempt to retreat from vulnerable areas through managed buyout programs? Most current codes and regulations do not address the big-picture issues of resiliency and sustainability from a geotechnical engineer’s perspective.

While individual resiliency-enhancing measures may be adopted as necessary on a local scale, improving resiliency in dense urban areas often requires collaboration across multiple agencies, jurisdictions, owners, operators, and the public, due to the interconnectedness of infrastructure systems (which was clearly illustrated by the effects of Hurricane Sandy described herein). Improving sustainability can require even greater collaboration, as sustainable solutions are typically regional in scope.

Short-term solutions are needed to retrofit or rebuild, with the main concern being the safety of the communities and continuation of everyday life. Meanwhile, the long-term challenge for the geotechnical engineering profession is to translate the intents of resiliency and sustainability into quantifiable terms and incorporate them in a performance based engineering framework which considers life cycle costs.

Today, jurisdictions and communities that were affected by Hurricane Sandy are working intensely to meet the dual challenges of sustainability and resiliency. Their plans rely heavily on geotechnical solutions in the short term, and provide an opportunity for the geotechnical community to be involved in long-term planning. The Federal Emergency Management Agency (FEMA) issued new Advisory Base Flood Elevation Maps for NJ and NY based on Sandy available at www.region2coastal.com/sandy/abfe as well as new guidelines for construction and rehabilitation of building foundations in flood zones (FEMA 2013). The new guidelines require, among other measures, first floors raised above base flood elevation using piles, piers, or foundation walls; proper anchorage of building structures to foundations to resist flotation; and open foundations or breakaway walls to prevent unbalanced loading on foundation walls (Figure 9.1). The Mayor of NYC issued an order for flood-resistant design, referencing the new FEMA maps. The Governor of NJ has also adopted the new FEMA standards for construction along the NJ coastline as announced on January 24, 2013.

The importance of geotechnical engineering to resilient and sustainable urban design is exemplified by the ambitious plan announced by the Mayor of NYC to protect the city from future storms (NYC Special Initiative for Rebuilding & Resiliency 2013, available at: www.nyc.gov/html/sirr/html/report/report.shtml).

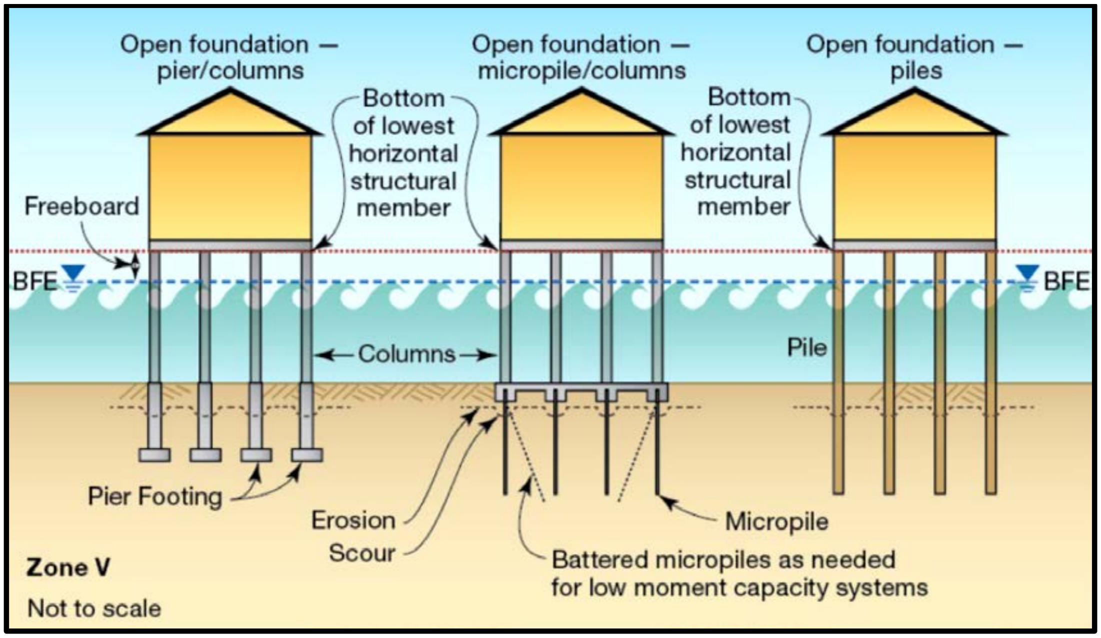


Figure 9.1 Examples of NFIP-compliant foundations in Zone V where bottom of lowest horizontal structural member is located above the BFE. (FEMA, 2013).

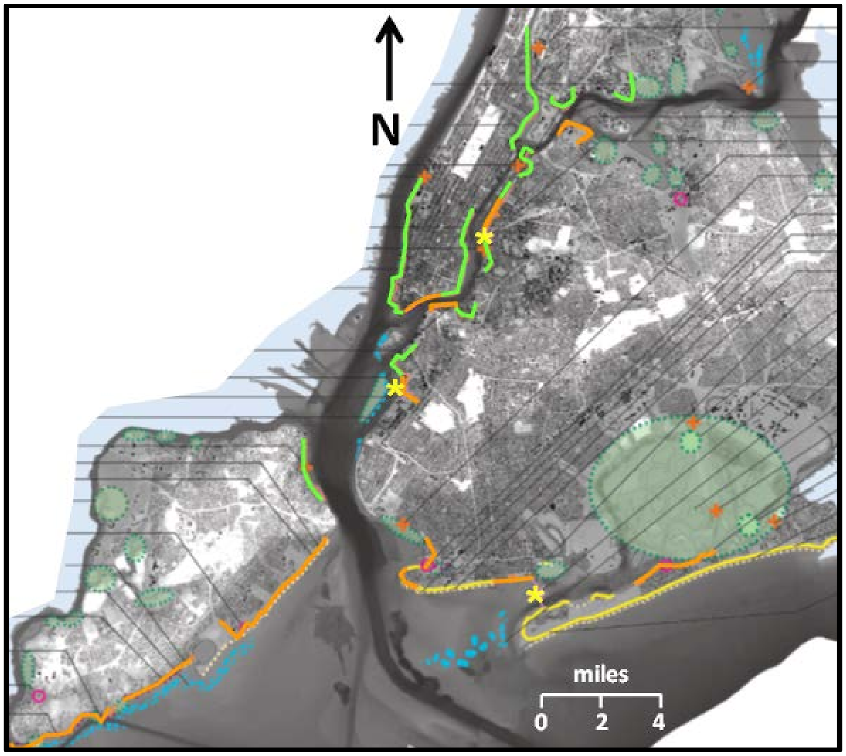


Figure 9.2 NYC Mayor's Comprehensive Coastal Protection Plan, indicating proposed: (i) orange lines - bulkheads, revetments, or levees; (ii) yellow lines - dunes; (iii) green lines - Integrated Flood Protection System; (iv) yellow asterisks - local surge barriers; (v) blue dots - offshore breakwaters; (vi) green shaded areas - wetlands (ref: NYC Special Initiative for Rebuilding & Resiliency, 2013).

The Mayor’s plan, Figure 9.2, proposes “traditional” geotechnical solutions such as raised bulkheads, armor stone revetments, and levees along some 24 miles of shoreline. It also features more novel solutions such as construction of dunes along some 18 miles of shoreline, an additional 18 miles of “Integrated Flood Protection System” (a hybrid system including terraced berms, benches, park walls, and deployable floodwalls), construction of offshore breakwaters, wetlands, living shorelines, reefs, and three local storm surge barriers.

There is a continued emphasis on installation of engineered shore protection systems, which protected several communities along the NJ and NY coastline. Smart growth strategies are also being employed with increased emphasis on programs such as Blue Acres allowing homeowners or landowners that are in flood plains to sell their land to the state for conversion to open space (www.state.nj.us/dep/greenacres/blue_flood_ac.html).

On a national level, President Obama’s Hurricane Sandy Rebuilding Task Force has launched Rebuild by Design (www.rebuildbydesign.org/), an international design competition for rebuilding damaged communities that will be resilient in future storms (Civil Engineering Magazine, January 2014). In August 2013, following submissions from 15 countries, 10 teams that include planners, engineers, architects, and academics, were selected as finalists. In spring 2014 the winner will be chosen and funded by the US Department of Housing and Urban Development disaster recovery grants, and by public and private sectors. This effort has brought the Sandy rebuilding issue from a local to national and international levels.

The above developments highlight how Hurricane Sandy has catalyzed a shift in future planning of metropolitan areas towards resilient yet sustainable designs against extreme natural events. Geotechnical solutions clearly are, and will continue to be, at the core of these plans. The time is right for the geotechnical engineering community to lead the transition from legacy systems to resilient and sustainable designs, before the next disruptive event occurs.

10 REFERENCES

- American Institute of Architects New York (AIANY) (2013). “Post-Sandy Initiative: Building Better, Building Smarter: Opportunities for Design and Development.” May, 44pp.
- Blake E.S, Kimberlain, T.B, Berg, R.J, Cangialosi, J.P, and Beven, J.L. II (2013). “Tropical Cyclone Report, Hurricane Sandy (AL182012) 22029 October 2012, available since February 12 at www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf
- Brenner, A., JMT Engineering. Private communication. Lawrenceville, NJ (2012)
- Brick Township Bulletin (2006). bulletin.gmnews.com/news/2006-01-05/Front_page/015.html , accessed February 1, 2013.
- Climate Central (2013). “Hurricane Sandy’s Untold Filthy Legacy: Sewage.” www.climatecentral.org/news/11-billion-gallons-of-sewage-overflow-from-hurricane-sandy-15924, accessed May 30, 2013.
- Coastal Research Center (2013). New Jersey Coastal Composition. The Richard Stockton College of New Jersey, accessed January 31, 2013.
- Construction Equipment Guide, www.constructionequipmentguide.com/Bridge-Over-Barnegat-Rises-to-New-Heights/5631/ , accessed February 1, 2013.
- Dahigrean, Paul B. (1977). Geology of Monmouth County in Brief, New Jersey Department of Environmental Protection, August
- Dike, Paul A. (1987). Geology of New Jersey, Glassboro State College.
- Eschenasy, D. (2013). “Structural Response of NYC Buildings to Sandy.” ASCE Metropolitan Section Structures Group Seminar, NY Public Library for the Arts at Lincoln Center, April 23 – May 2.
- FEMA (2013). “Foundation Requirements and Recommendations for Elevated Homes: Hurricane Sandy Recovery Fact Sheet,” May
- Gibbs, L.I. and Holloway, C.F., co-chairs (2013). “Hurricane Sandy after Action: Report and Recommendations to Mayor Michael R. Bloomberg.” New York City Mayor’s Office, May

- Godfrey, P.J. (1976). "Barrier Beaches of the East Coast," Oceanus, 19:5:27-40.
- Google Inc. (2013) Google Earth, [map]. www.google.com/earth/index.html (generated November, 2012 through January, 2013).
- Hill, D. (2014) "Fighting back," Civil Engineering Magazine (January 2014).
- Johnson, C. (1982). Historic and Geomorphic Evidence of Barrier Dynamics and the Origin of the Sunken Forest, South Shore of Long Island, NY, M.S. Thesis, University of Massachusetts, Amherst, Dept. Geology & Geography, 190 pp
- Jogan, Brenda M. H. (1978). Geology of Atlantic County in Brief, New Jersey Department of Environmental Protection, June
- Kaufman, S., Qing, C., Levenson, N., and Hanson, M. (2012). Transportation During and After Sandy, Rudin Center for Transportation, NYU Wagner Graduate School of Public Service, November 2012, 36pp.
- Kenward, A., Yawitz, D, and Raja, R. (2013). "Sewage Overflows from Hurricane Sandy." Climate Central, April 2013, Princeton, New Jersey, April
- Khinda, J.S., editor (2013). ASCE Met Section Infrastructure Group Seminar: "Impact of Sandy's Storm Surge on NY/NJ Infrastructure" Polytechnic Institute of NYU, Brooklyn, NY, April 8-9
- Leatherman, S.P., ed. (1979). Barrier Island Handbook, National Park Service Cooperative Research Unit, Environmental Institute, Univ. Massachusetts, Amherst
- Lucey, Carol S. (1971). Geology of Bergen County in Brief.New Jersey Department of Environmental Protection. August 1971.
- Mantoloking and Super Storm Sandy (2012). www.mantoloking.org/wp-content/uploads/2012/11/cm111912.pdf, Mantoloking Borough Town Council Meeting, Nov. 14, 2012.
- McMaster, Robert L. (1954). "Petrography and Genesis of the New Jersey Beach Sands," Geological Series

- Metropolitan Transit Authority (2013). “Rebuilding the Rockaways after Hurricane Sandy: The Recovery,” accessed May 21, 2013 www.mta.info/nyct/service/RebuildingRockawaysAfterHurricanSandy.htm
- New Jersey Department of Community Affairs (2013). “Community Development Block Grant Disaster Recovery: Action Plan,” State of New Jersey, approved by HUD: April 29
- NJ Task Force 1 (2012). Trenton, NJ. Private communication
- NJDOT (2012a). “Hurricane Sandy Damage Assessment,” NJDOT - Structural Evaluation and Bridge Management, December 4
- NJDOT (2012b). “Route 35 over Cheesequake Creek Reconstruction to Resume.”
- www.state.nj.us/transportation/about/press/2012/092712.shtm, accessed 1/29/2013
- New York Building Congress (2013). “Risk and Resiliency after Sandy,” June
- NYC Department of Buildings (2013). “Rebuilding NYC after Hurricane Sandy: A Guide to New Code and Zoning Standards for Industry Professionals,” ongoing (updated June 2013).
- NYC Panel on Climate Change (2013). “Climate Risk Information 2013: Observations, Climate Change Projections, and Maps.” PlaNYC / The City of New York Mayor Michael Bloomberg, June
- NYC Special Initiative for Rebuilding and Resiliency (SIRR) (2013). “A Stronger, More Resilient New York.” PlaNYC / The City of New York, June
- North American Tunneling Journal (2012). “News: Hurricane Recovery at the Harbor Siphon.” December 2012 ed. (5).
- North American Tunneling Journal (2012). “After the Storm.” December 16-19
- Ocean County Engineering Department (2012). Presentation on Superstorm Sandy, November 28.
- O'Neill, J.M. Passaic Valley Sewerage Commission's Newark sewage plant could be hampered for weeks. NorthJersery.com. 11/15/12.

- Piazza, G. (2013). "Hurricane Sandy, Rapid Response Firsthand." Cover Story, The Magazine of the Deep Foundations Institute, Special DFI Issue: Hurricane Sandy: Lessons Learned. May/June 2013
- Press of Atlantic City (2012), "Debris from Hurricane Sandy Testing Landfills," www.pressofatlanticcity.com/communities/eht/debris-from-hurricane-sandy-testing-landfills/article_689c8964-4af7-11e2-8f86-0019bb2963f4.html?photo= , accessed January 15, 2013.
- Psuty, N.P. and Ofiara, D.D. (2002). Coastal Hazard Management: Lessons and Future Directions from New Jersey, Rutgers Univ. Press, New Brunswick, NJ.
- Rebuild by Design (www.rebuildbydesign.org/)
- Reid, J.H. General Contractor (2011). Marine Construction Project List, www.jhreidgc.com/2011/proj_mc_manto.html#, accessed 2/1/13.
- Rodin, J. and Rohatyn, F. G., co-chairs (2013). "Recommendations to Improve the Strength and Resilience of the Empire State's Infrastructure." NYS 2100 Commission, February
- Ship Bottom Municipal Code (2012)
- Tamaro, G.J., Kaufman, J.L., and Azmi, A.A. (2000). "Design and Construction Constraints Imposed by Unique Geologic Conditions in NYC," DFI 25th Annual DFI Meeting and 8th International Conference, October 5-7, New York City
- Tanski, J. 2012 (revised). Long Island's Dynamic South Shore — A Primer on the Forces and Trends Shaping Our Coast, New York Sea Grant. 27 pp.
- USGS (2012). Hurricane Sandy Storm Tide Information
- US Department of Agriculture, Soil Conservation Service (1978). Soil Survey of Atlantic County, NJ.
- US Dept. of Agriculture, Soil Conservation Service (1989), Soil Survey of Ocean County, NJ.
- US Dept. of Agriculture, Soil Conservation Service (1995), Soil Survey of Bergen County, NJ.

- US Army Corps of Engineers (1974). Shore Protection Manual, Coastal Engineering Research Center (CERC), FT. Belvoir, VA, Parts I, II, and III.
- USACE Philadelphia District. YouTube. http://www.youtube.com/watch?v=CWxlVvJLdpU. 11/16/12.
- WOBM (2012). wobm.com/route-37-bridge-opens-to-barrier-island-residents, accessed January 29, 2013