



# Hurricane Sandy Inland Water Damage in the NY - NJ Metropolitan Area - A New Perspective on the Nature of Urban Flooding in the Northeast United States

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## Introduction

Hurricane Sandy (2012) resulted in unprecedented water damage from submergence in floodwaters as well as the impacts from water-borne debris. The great damage (more than \$50 Billion) was not only a function of the power of the storm and the great development in the region, but also the unique geologic and topographic factors that amplified surface flooding. The reasons for the greater surface flooding in Hurricane Sandy are the subject of this paper.

Most Sandy flooding reports in New York City attribute all of the damage to salt water surge. However, my field studies, and the photographic and videotape documentation of others, suggest that both fresh water flooding and debris impact were significant components of the damage. In reality, the flooding was not simple submergence, but involved increased fluid forces resulting from the movement of that water.

This article focuses on freshwater flooding and its interaction with the salt water surge at the coast. It examines flooding damage components and considers the mitigation actions needed to reduce future auto and structural losses.

## Nature and Relief of the Land Surface in the Northeast United States

The geology and topography of the coastal areas in the Northeast United States are very different from the rest of the hurricane-prone coasts in the Southeast and Gulf of Mexico regions. In addition, much of the land surface has been paved in northeast urban centers. The Northeast is characterized by mountains and hills rather than the gently sloping coastal plains to the south.

Major factors in the development of flooding conditions are: 1) the nature of the surface (bedrock, sand, and pavement), 2) the rate of rainfall and, 3) the slope of the land surface. Three of New York City's five boroughs (Manhattan, The Bronx and Staten Island) are underlain by relatively impermeable bedrock. The other two boroughs (Queens and Brooklyn) are underlain by glacial sands and a sandy coastal plain on the south shore of Long Island (Figure 1). However, the normal permeable nature of the sandy areas has been greatly reduced by paving.

The bedrock areas of three of the five New York City Boroughs have relief up to a hundred meters (Manhattan, The Bronx and Staten Island). This is the result of differential weathering acting upon the folded metamorphic rocks that underlie New York City. The Manhattan Schist and Fordham Gneiss are resistant

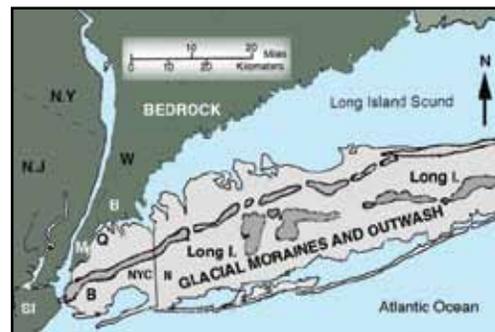


Figure 1. Land surface types in the New York Metropolitan Region.

rocks and ridge-formers, and the comparatively weaker Inwood Marble underlies valleys and some waterways (Figure 2).

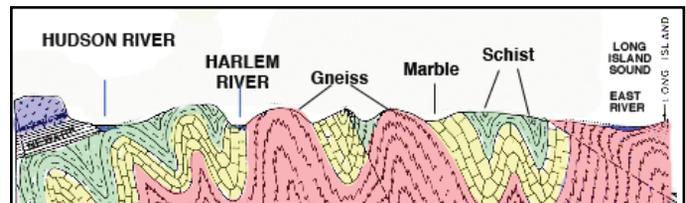


Figure 2. Generalized geologic section through the northern part of New York City. The actual geology of the city is highly complex because of multiple tectonic events. This generalized cross section emphasizes how differential weathering has created the present relief. Source: Geology Department, City College of N.Y.

Building of New York's extensive street grid (north-south avenues and east-west streets) in the early part of the 19<sup>th</sup> century resulted in lowering high areas and filling in low ones (Walsh, 2006). The marked relief of the bedrock in New York City is important because the steeper the land surface, the faster is the surface water flow velocity. In northern Manhattan and the Bronx, the relief is so marked that it requires long staircases for people to move from the low areas to the high areas. A number of intermittently passable (to autos) "stepped streets" (Walsh, 2006) are required for people to walk from the low to high areas of the northern Bronx and Manhattan (Figure 3).

These marked elevation differences are less apparent in the heavily developed lower half of Manhattan. However, some

large-scale relief changes in lower Manhattan have survived development. As a child growing up in the Bronx (Bronx County), I remember the water torrents that would pour down those long stairs (Figure 3) in a heavy summer afternoon rain-fall. The limited capacity of New York City’s combined sewers would cause the surface waters water to pool in the low areas.



Figure 3. “Stepped streets” connecting low and high points in northern Manhattan.

Paved surfaces in urban areas are totally impermeable and surface discharge increases rapidly. Where sloping surfaces are paved, the velocity of the floodwaters can be appreciable. (Figure 6).



Figure 6. Fresh water flash flooding in an urban area.

New York City has grown considerably by filling in the margins of its waterways (Nevius and Nevius, 2009). Walsh (2005) identified 45,500 acres of land filled since colonial times. Major landfilling in the southern boroughs of New York City occurred between 1924 and 1957 (Figure 7). These filled lands have subsided due to compaction, and were major sites of both fresh water (rain) and salt-water flooding during Hurricane Sandy.

### Why is Hurricane Flooding Greater in the Northeast?

Sandy’s landfall 100 miles to the south of the city resulted in relatively low rainfall in New York City (Halverson and Rabenhorst, 2013). However, most hurricanes making landfall closer to the city are accompanied by higher rainfall. If the rainfall rate exceeds the rate of ground surface infiltration, the excess water will flow downhill across the surface and pool in the low areas. The prevalence of bedrock, rather than sediment, at the surface, greatly increases the flash flooding potential in the Northeast (Figure4).

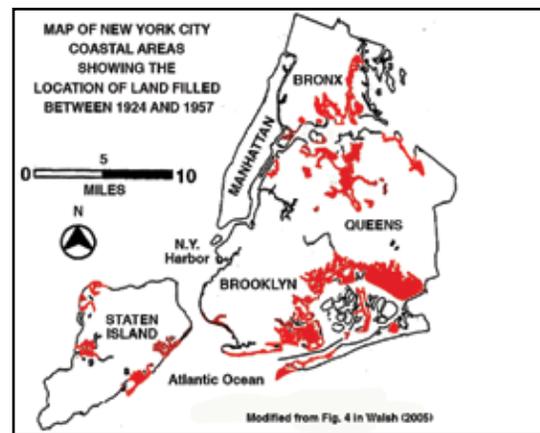


Figure 7. Areas in southern New York City that were filled for waterfront development between 1924 and 1957. Modified from Walsh (2005).

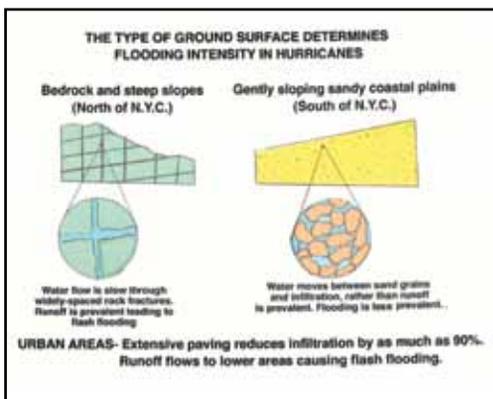


Figure 4. The differences in water infiltration in bedrock and sand areas.

### Fresh Water Flooding

New York City is far different from what it was in colonial times. The recently completed Mannahatta Project (Sanderson, 2012) has given us a detailed picture of the massive hydrologic and topographic changes that have taken place in 300 years of development (Figure 8).

Southernmost waterways were filled as the small (in 1800) city grew northward. All the former streams in Manhattan were filled by the middle of the nineteenth century during development of the innovative street grid system (east-west

In an urban area, concrete and asphalt can cover from 20% to 90% of the land surface. The extent of paved surfaces versus open vegetated areas in the N.Y. -N.J. metropolitan region can only be appreciated in a satellite view (Figure 5).



Figure 5. Satellite view of the New York-New Jersey metropolitan region showing paved and open areas (Source: NASA).

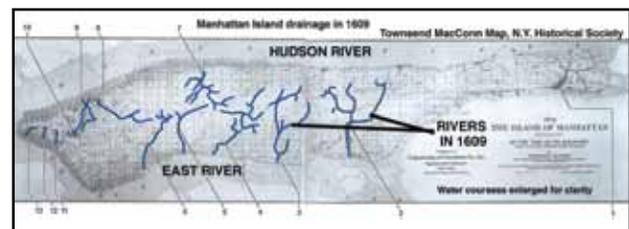


Figure 8. The island of Manhattan was well drained in colonial times. (Source: New York Historical Society).

streets and north-south avenues). With the streams gone and more and more of the city paved over, there are now very few places for rain to infiltrate into the ground.

New York City is no stranger to crippling freshwater flooding by summer convective storms and nor'easters. The December 1992 nor'easter illustrated that even moderate storms can cause significant flooding, especially if they occur during a high tidal cycle (Cole et al. 2008). On August 27, 1999, three inches of rain in two hours submerged low points on arterial highways and flooded the subways creating major transport problems (New York Times, 1999). Another nor'easter in 1994 caused freshwater flooding that closed the FDR Drive along the East River. Low points were flooded by as much as four feet of water, which stranded about 50 cars and required SCUBA divers to rescue some of the drivers! (National Weather Service, 1994).

In 2011, Upper New York State and New England sustained catastrophic flooding during Hurricane Irene. The flooding resulted from orographic rainfall that occurred as Irene moved over the mountains of the Northeast (Coch, 2012a). There was considerable flooding in New York City as well (Coch 2012b). The glacial moraines of Long Island (Figure 1) were sufficiently high to initiate a detectable increase in rainfall (Coch, 2012a).

Coch (1994, 2012b) speculated on the effects of a very wet hurricane passing across the New York-New Jersey Metropolitan Area on a coast-normal track. Hurricane Sandy made the demonstration. After Hurricane Sandy, I reviewed numerous photos of street flooding in areas located at the inland edge of the salt-water incursion. Based on personal familiarity with those areas, I realized that the flood levels there were somewhat higher than predicted by Sandy's surge levels alone (Figure 9).



Figure 9. Abnormally high flood waters near the East River in southeast Manhattan.

How could higher-than-average flood levels be achieved during hurricanes and tropical storms? My hypothesis is illustrated in Figure 10. In hurricanes, where fresh water meets salt water, there would be a zone of anomalously high water at the junction (Figure 10).

I am inferring that the difference in predicted and actual flood levels resulted from fresh water additions to the water column because flood levels were higher than predicted by salt-water surge level predictions alone. However, this is only an inference. Conducting salinity and water depth sampling of floodwaters at various stages in a future urban hurricane landfall could add substance to the hypothesis. However, it may be difficult to get volunteers for such a study.

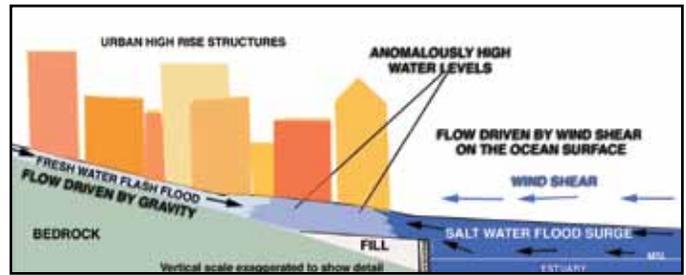


Figure 10. During Hurricane Sandy, gravity-driven fresh water met wind-driven salt water to create an anomalously high water level at the junction.

## Flood Velocities

Examination of videotapes shows that Hurricane Sandy flooding, in many cases, was not just a simple gradual submersion in quiet waters. In that case, structures would be simply subjected to the mass of the rising water. However, vehicles clearly exhibited collisions with each other (Figure 11) in waters that were being driven down slope by gravity (freshwater) and hurricane winds that were driving a salt-water surge inland.



Figure 11. Car collisions caused by flowing floodwaters. The flow in this case was from left to right.

Wind-driven waves formed on floodwaters in lower Manhattan (Figure 12). Fixed structures such as doors, windows and walls will fail under the force of wind-driven waves, unless suitably reinforced.



Figure 12. Wind-driven waves of Hurricane Sandy in lower Manhattan.

## Flood Damage Mitigation

A wide range of projects has been proposed to limit future flooding damage in New York City. Some are limited in area and cost, and deal with protecting only critical facilities such as power plants, roadways, and transit entrances.

Other concepts deal with protecting whole sections of the city. One large-scale proposal is to build a series of massive surge barriers within New York Harbor (Hill, 2012). My objections to this mitigation proposal are presented in Coch (2012c). In this paper I will concentrate on mitigation measures for fresh water flooding in the Northeast. The problem of coastal surge and wave action will be discussed elsewhere.

As discussed above, major storms and hurricanes in New York City have closed many arterial highways, such as the FDR Drive and the Belt Parkway, by flooding across low segments of the roadway. These low areas are known as “choke points.” Once a choke point develops, that route is useless for subsequent transport. Choke points most commonly develop as a result of saltwater flooding or combinations of saltwater and freshwater flooding, which was common during Hurricane Sandy. However, freshwater alone has created choke points in past New York City hurricanes (Figure 13). The photos in Figure 13 illustrate freshwater flooding in the Borough of Queens. These areas are underlain by glacial sands (Figure 1) with a high infiltration rate; however, the flooding areas are surrounded by paved surfaces that limit infiltration. This is the essence of urban freshwater flooding.



Figure 13. Examples of freshwater flooding causing choke points in New York City in past hurricanes. **A.** Flooded cars in an underpass on Queens Boulevard after Hurricane Connie (August 11-14, 1955.) **B.** Flooded cars at a choke point on the Belt Parkway in Laurelton, Queens from Hurricane Diane (August 17-20, 1955).

Choke points are serious impediments to both evacuation and post-storm relief efforts. These vulnerable areas can be protected either by raising the level of the roadways or building floodwalls. It is vital that the floodwalls are of adequate strength to resist flood pressures and high enough that their tops exceed any past flood levels.

Massive street flooding may be infrequent, but in a major coastal urban center such as the New York City metropolitan area, the consequences can be catastrophic. It is vital to protect critical structures such as hospitals and power plants. During Hurricane Sandy, street flooding destroyed the lower levels of two major hospitals along the East River. Millions of dollars of diagnostic medical equipment was destroyed in hospital basements and the patients had to be transferred to other facilities at higher elevations. Manhattan was plunged into darkness during Sandy when the floodwall was overtopped in Con Edison’s 14<sup>th</sup> Street generating plant. Power was cut

to avoid equipment damage. The flooding of this one power facility cut the power to most of lower Manhattan (Figure 14). Tens of thousands of people were trapped for days in high-rise buildings without electricity.



Figure 14. Blackout caused by the failure of the 14<sup>th</sup> Street Con Edison power facility. The lighted area in the lower left is Battery Park City, which had an independent power source.

Over 250,000 vehicles were destroyed by flooding in Hurricane Sandy (D. Hermanek, personal communication 2013). Removing the damaged and flooded vehicles to concentration centers was a major logistical task (Figure 15).



Figure 15. Damaged vehicles at the Calverton N.Y Executive Airport concentration center on Long Island. This was only one of several such centers in the N.Y.-N.J. Metropolitan Region (Courtesy of International Auto Auctions Inc.)

New York City is an area with high topographic relief. A simple solution to flooding damage to vehicles is to move them to higher areas, just as we do for inhabitants of frequently inundated areas. There will be abundant parking spaces in inland commercial areas when the hurricane makes landfall.

## CONCLUSION

Review of photographic and videotape data, plus field observations, have provided a new perspective on the nature of hurricane flooding in a densely developed urban coastal center. The role of fresh water flooding has been underestimated in paved, northern urban centers underlain by bedrock. The confluence of gravity-driven fresh water and a wind-driven salt-

water surge can create anomalously high water levels where the two meet. Water damage is not simply the result of static pressure from slowly rising waters, but the additional forces resulting from movement of those waters. Structural surfaces (doors, bulkheads, floodwalls) must be reinforced to resist the total force of the static water column and its motion.

Understanding the mechanics of coastal flooding and applying appropriate mitigation can significantly reduce hurricane induced flooding in urban areas. Hurricane Sandy has shown that massive urban flooding may be infrequent but it will have great consequences in the bedrock urban centers of the Northeast. Sea level is rising at a rate of about a foot per century in the greater NYC Metropolitan Area (Rosensweig and Solecki, 2001) and the flooding problem will only increase with time. We must start the necessary planning to reduce flooding damage in urban areas.

## References

- Coch, N.K. 2012a, Hurricane Irene (2011)-A Hydrological Catastrophe in the Northeast U.S., *The Professional Geologist*, Sept/Oct, p. 47-52.
- Coch, N.K. 2012b, Hurricane Irene-Lessons for the Northeast, Geological Society of America, Abstracts with programs, V.44, n.2, p. 51.
- Coch, N.K., 2012c, Hurricane protection in New York City-Now is not the time for Multiple Surge Barriers, *Jour. of Coastal Research*, V. 28, n.2, p. 324-331.
- Coch, N.K., 1994. Hurricane Hazards in the Northeastern United States. In: Finkl, C. (ed.), *Coastal Hazards — Perception and Susceptibility*, *Journal of Coastal Research*, Special Issue No. 12, pp. 115–147.
- Cole, B., Buonaiuto, F., Bowman, M., Wilson, R., Flood, R., Hunter, R., Mintz, A., Hill, D., 2008, New York City's Vulnerability to Coastal Flooding, *Bull. Amer. Meteorol. Soc.* June, p. 829-841.
- Halverson, J.B. and Rabenhorst, T. 2013, Hurricane Sandy-The Science and Impacts of a Superstorm, *Weatherwise*, March/April p. 14-23.
- Hill, D., 2012, The Lessons of Katrina, Learned and Unlearned, *Journal of Coastal Research*, V.28, N.2, p. 324-331.
- National Weather Service, Eastern Region, 1994, The Great Nor-easter of December 1992, *Disaster Survey Report*, 59 pp.
- Nevius, N and Nevius, J. 2009, *Inside the Big Apple - A Streetwise History of New York City*, Free Press, New York City 294+ p.
- New York Times, 1999, Surprise Deluge Cripples Morning Rush in New York, August 1, 1999, p.1.
- Rosensweig, C and Solecki, W., Eds., 2001, *Climate Change and a Global City: The Potential Consequences of Climate Variability and Change-Metro East Coast*, Columbia Earth Institute, 224p.
- Sanderson, E.W., 2009. *Mannahatta — A natural history of New York City*, City. New York: Abrams, 352p.
- Walsh, D.C., 2005, Reconaissance mapping of landfills in New York City, *Groundwater* V.33, n.4, p. 387-399.
- Walsh, K. 2006, *Forgotten New York-Views of a Lost Metropolis*, Collins Reference, New York City, 373 p.

## Acknowledgements

Dr. Patrick Brock, Queens College, helped in increasing my understanding of the complex geology of New York City. Carol A. Coch (U.S. Army Corps of Engineers NAD-retired) provided valuable editorial assistance. Allan McDuffie, U.S. Army Corps of Engineers-retired) has taught me a lot about the nature of flooding in New York City. Donald Hermanek, Insurance Auto Auctions, provided details on the disposal of damaged cars. Gary Conte, U.S. Weather Service, Bohemia, NY, provided information on rainfall during Hurricane Sandy. Meagan Lenna was of great assistance in the production of this manuscript.

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