Validating the HAZUS Coastal Surge Model for Superstorm Sandy

by

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List of Abbreviations

ARA - Applied Research Associates

CAT - Category of Hurricane (Range: 1 to 5)

CSM - Coastal Surge Model (HAZUS)

DEM – Digital Elevation Model

DHS - Department of Homeland Security

EOHW - Envelopes of High Water

ET – Extra-Tropical

FEMA - Federal Emergency Management Agency

FL - Flood Model (HAZUS)

GBS - General Building Stock

GIS - Geographic Information Systems

HAZUS - Hazards US

HSIA - Hurricane Sandy Impact Analysis

HU - Hurricane Model (HAZUS)

HWM - High Water Marks

IDW- Inverse Distance Weighting

MEOW - Maximum Envelope of Water

MOM - Maximum of MEOWs

MOTF - Modeling Task Force

NED - National Elevation Dataset

NHC - National Hurricane Center

NHP - The National Hurricane Program

NOAA - National Oceanic and Atmospheric Administration

NYC - New York City

NYOEM - New York Office of Emergency Management

NYCOEM - New York City Office of Emergency Management

NWS - National Weather Service

P-Surge - The probabilistic approach (P-Surge)

SF - Safety Factor

SLOSH - Sea, Lake, and Overland Surges from Hurricanes

SWAN - Simulated Waves Near-shore

UDG - User-Defined Depth Grid

USACE - U.S. Corps of Army Engineers

USGS - U.S. Geological Survey

Abstract

Several recent hurricanes along the eastern United States seaboard have resulted in catastrophic flooding: Hurricane Katrina (2005), Hurricane Irene (2011), and Hurricane Sandy (2012). In addition to their disastrous effect on life and property, protracted utility outages from flooding are expensive and disruptive to recovery. Utilities could be less vulnerable to flooding if company assets were protected better in advance, based on the models of predictable storms surges. The Federal Emergency Management Agency (FEMA) is tasked with hazard mitigation and response through the United States, for floods among other perils. FEMA's HAZUS [Hazards US] software included modules for predicting flood extents in response to stream discharges (inland) and coastal surges. The National Oceanic and Atmospheric Administration (NOAA) also makes predictions of storm surges via its SLOSH [Sea, Lake, and Overland Surges from Hurricanes] maps. Both HAZUS and SLOSH rely on geographic information systems (GIS) technology. This study compares the FEMA HAZUS and NOAA SLOSH model predictions against direct flood measurements for the Hurricane Sandy "Superstorm" that damaged extensive areas of New York and New Jersey beginning on October 29th, 2012. Focus is placed on differences in predicted vs. observed flood inundation for key utility asset and infrastructure locations, especially in flood hazard zones. For Superstorm Sandy, SLOSH produced more accurate flood predictions than HAZUS for New York City.

Chapter 1: Introduction

Flooding is a predictable, recurrent natural hazard throughout the world. Floods alone cost the nation an average of $8.2 billion (NWS 2013); the overall economic consequences, including indirect[1] losses such as time off work, retail sales, and lost production may have more impact, and are harder to estimate (Kliesen 1994; Hallegatte 2014). Social infrastructure along with cultural and personal effects, some irreplaceable, are also damaged or destroyed by floods; the human pain and suffering is incalculable.

Floods cannot be avoided, but for every conceivable reason they should be mitigated. A dollar spent on mitigation is repaid four times over in dollars not spent on response and recovery (Rose et al. 2007; FEMA 2014). Floods generally are more predictable than earthquakes, wildfires, volcanic eruptions, and other natural hazards precisely because they do recur, and their magnitude at various recurrence intervals has been extensively studied in many locales (Bell 2003). Thus, it is possible to estimate flood risks and protect against them.

Although floods occur throughout the U.S., two regions are particularly prone to them: the Midwest, from riverine flooding (on the Missouri, Ohio, and Tennessee rivers); and the Atlantic seaboard, from coastal flooding (throughout the Gulf of Mexico and from Florida to Maine), primarily caused by hurricanes. (The Pacific coast is relatively immune to hurricane-induced floods.) Much of the damage from hurricanes is caused by storm surge, the *run-up* of ocean water onto land.

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[1] Direct losses: building damages, bridge collapse, loss of lives. Indirect losses: commuter disruptions, loss of local tax revenues, reduced tourism (SOURCE: Adapted from Brookshire and McKee (FEMA, July 1992), p. 282.)

Over the past twenty years, a spate of large Atlantic hurricanes has caused large damages (Table 1). The U.S. government reaction, in addition to essential response and recovery, has been to improve hurricane prediction, with the goal of facilitating evacuations and relocations when needed as well as mitigating future damages.

Table 1. Costliest U.S. Atlantic hurricanes (NOAA 2014)

Rank	Hurricane	Season	Damage ($ billions)
1	Katrina	2005	$108
2	Sandy	2012	$71.4
3	Ike	2008	$29.5
4	Andrew	1992	$26.5
5	Wilma	2005	$20.6
6	Irene	2011	$15.6
7	Charley	2004	$15
8	Ivan	2004	$14.2
9	Rita	2005	$10
10	Frances	2004	$8.9

One predictive approach, SLOSH [Sea, Lake and Overland Surges from Hurricanes] has been championed by National Oceanic and Atmospheric Administration (NOAA); this is based on fluid-dynamics modeling, but generally pre-computed for an ensemble of historic/typical storms and presented statistically to avoid the vagaries of individual storms. A second predictive approach, HAZUS [Hazards US], has been developed by FEMA; this too is based on fluid-dynamics modeling - exactly the SLOSH model in fact - but does focus on a specific storms and their impacts in specific coastal locales, and also incorporates economic and social dimensions (damages to building and impacts on human activities).

This thesis directly compares the SLOSH and HAZUS approaches in a re-analysis of the Hurricane Sandy ("Superstorm Sandy") event of November 2012, which caused about $20 billion in direct damages in the New York City (NYC) area (City of New York 2014). Because of the magnitude of these damages, which were to some extent anticipated, FEMA deployed its Modeling Task Force (MOTF) to install flood sensors just in advance of storm and afterward prepare a "ground-truth" study of the extent of flooding from Sandy. Their study, the Hurricane Sandy Impact Analysis (HSIA), makes it possible to do a three-way comparison of SLOSH vs. HAZUS vs. reality, in this important case.

NYC also experienced flooding due to heavy rainfall and storm surge from Hurricane Irene in 2011, just a year before Hurricane Sandy. In reaction, my employer, Consolidated Edison (Con Ed), a major utility company operating in New York and New Jersey, had already begun to prepare for storm surge and flooding to protect its essential assets: power generating stations and distribution substations (City of New York 2013). As a substation engineer, I was exposed to methods of flood prediction that are highly regarded, such as SLOSH. Using geographic information systems (GIS), I overlaid SLOSH on aerial imagery creating maps of the major electric substations in flood-prone areas.

These updated flood maps proved vital in responding to Hurricane Sandy in 2012, and helped during the early phases of the storm. Notwithstanding significant outages and damages that occurred, the highest-risk utility infrastructure was significantly protected with the resources available. However, Hurricane Sandy over-topped Con Ed’s preparations, which in many instances consisted of sandbags, plywood and other temporary barriers to protect the utility’s critical facilities (City of New York 2013). Con Ed also shut down three entire networks preemptively (Bowling Green and Fulton in Lower Manhattan and Brighton Beach in Brooklyn) and de-energized feeders where flooding appeared imminent at key underground vaults. To prevent need for such shutdowns in future, additional *storm hardening* measures are being developed to protect utility assets in flood-prone areas, for example elevating substations and building perimeter flood barriers, doors, gates, etc. – an expensive operation (Con Ed 2013).

Because of the costs involved with both over- and under-preparation for inevitable future hurricane flooding in NYC, closer analysis of the accuracy of prediction methods, including storm surge, becomes important. NOAA's SLOSH analyses are largely reactive, based on an ensemble of prior hurricane events. However, it is evident (Table 1) that weather, including hurricanes, is becoming more dramatic (Shepard et al. 2012; Knutson et al. 2010). Accordingly, a proactive method of storm surge prediction is desirable. In this thesis, I examine HAZUS as that method.

My hypothesis is that a dynamic, spatially detailed hurricane model can provide better results than SLOSH statistics. Hurricane Sandy provided a ready opportunity to test this hypothesis because 1) the storm has been studied in detail by many others (City of New York 2014; USACE 2013) and 2) additional verification is available from Con Ed's coastal power facilities (Con Ed 2013, 24, Table 1) that are distributed around NYC, some of which did not escape flooding.

Chapter 2: Background

Hurricanes are large, violent, ocean-borne storms combining low pressure, high winds, torrential rain, and abnormal pile-ups of water onto land, known as *storm surge*, i.e. "water pushed onto shore" (Figure 1). Similar to tsunamis, storm surges come on-shore in a matter of minutes, quickly inundating coastal areas and precluding orderly response, or even evacuation.

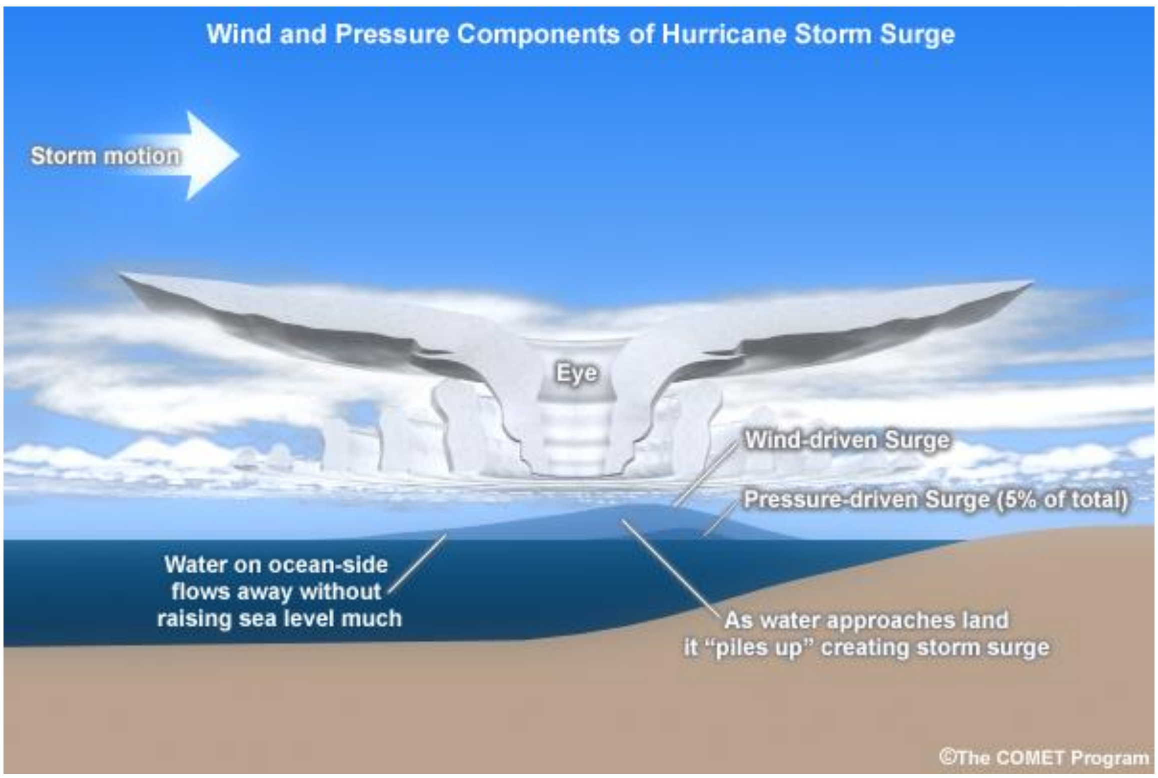


Figure 1. Hurricane Components for Storm Surge (NOAA)

In the Hurricane Katrina event of August 2005, the storm surge was 24-28 ft., overtopping levees and burying New Orleans in water. More than 1800 people died in that storm, most by drowning. During late August 2011, Hurricane Irene spent its energies along a series of landfalls from North Carolina to New York. Because Irene's storm surge was small, only 47 people died.

When storm surge and high tides coincide, the combination, known as *storm tide* (Figure 2) can be immensely destructive. Hurricane Sandy, during late October and early November 2012, produced a storm tide of 8-14 ft. in New York City (NYC) for protracted periods, causing unprecedented damage to the city's complex infrastructure (bridges, tunnels, subways) and power distribution systems (City of New York 2013). Sandy was responsible for at least 147 direct deaths[2], 72 of which occurred outside NYC (Blake et al. 2013).

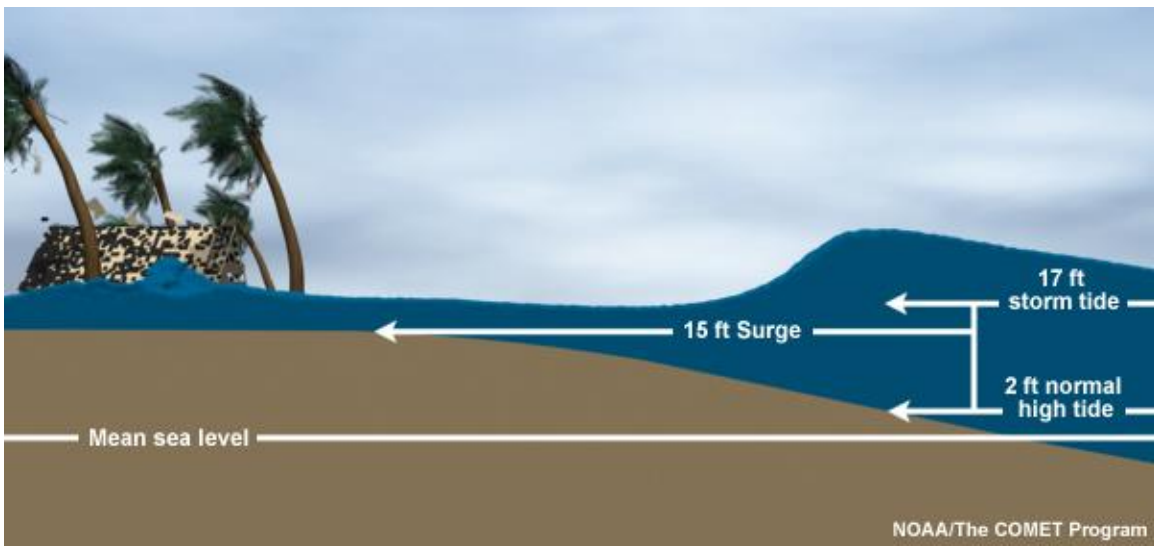


Figure 2. Storm Surge and Tide (NOAA)

Low-lying urbanized coastal areas, such as New Orleans and New York City, are obviously the most at risk to surge from hurricanes; they are also the slowest to drain from flooding induced by the surge, which increases the flood damage. River estuaries are also

[2] Deaths occurring as a direct result of the forces of the hurricane are referred to as "direct" deaths. These include those persons who drowned in storm surge, rough seas, rip currents, and freshwater floods. Direct deaths also include casualties resulting from lightning and wind-related events (e.g., collapsing structures). Deaths occurring from such factors as heart attacks, house fires, electrocutions from downed power lines, vehicle accidents on wet roads, etc., are considered "indirect" deaths (Blake et al. 2013).

susceptible to surges, and in addition may be swelled by rainfall from the storms. For example, during Hurricane Sandy, parts of the Hudson and East Rivers flooded into areas of Manhattan and Bronx, which are several miles inland.

Hurricanes

Hurricanes originate in the Southern Atlantic Ocean during the warmest months of year, late summer through fall. Hurricane *strength* is categorized on a five-level scale, the Saffir-Simpson Hurricane Wind Scale (NWS 2013), according to peak wind speed, from CAT 1 (74-95 mph winds) to CAT 5 (157 mph+).

Hurricanes form when warm, so-called extra-tropical (ET) water pushes north into cooler surrounding water. Latent heat energy fuels the storm (Phillips 2003): evaporation from the ET warm pool drives moist air aloft, causing an area of low pressure. As the moist air rises, it spreads, cools, and eventually condenses in the storm bands, dumping water back down in areas of higher pressure. Cyclonic (counter-clockwise) circulation of the system occurs because of the Coriolis[3] force. The storm as a whole migrates northeastward, driven by the trade winds, often in unpredictable spurts. However, it may suddenly detour to the West, because prevailing winds may not be strong enough to steer the hurricane in assumed direction making a path erratic (Netting 2003). When the storm encounters land, its source of energy is removed, and it quickly dissipates.

Hurricanes are characterized by bands of intense thunderstorms swirling around a relatively quiet, often rain-free, "eye" at the center. A cross-section through a hurricane

[3] The Coriolis effect explains the paths of winds in the atmosphere. In the Northern Hemisphere, winds pass from high-pressure systems to low-pressure systems on the right making storms, such as Hurricane Katrina, appear to swirl counter-clockwise. (http://education.nationalgeographic.com/education/encyclopedia/coriolis-effect/?ar_a=1)

(refer to Figure 1) shows the eye as a core of low atmospheric pressure, surrounded by rings of higher pressure. Because of the low central pressure, sea-water mounds up there; the storm's peripheral winds push other, larger mounds of water. As the storm migrates, ocean swells and sometimes breaking waves are produced.

If the storm makes landfall, its mounded-up water is suddenly driven on-shore in a tangible event, i.e. storm surge. Regular tidal processes can either reduce or enhance storm surge by several feet, depending on the phase of the tides and the time of landfall.

Coastal geomorphology, vegetation (or lack of it), and build-up (including levees and sea-walls) all affect storm surge, too. Within an embayment, surge may be further concentrated, whereas at a cape, it is spilled away. A gentle slope permits longer, deeper run-ups, whereas the steep slope results in breaking waves, which can significantly damage lower elevation buildings near the coast and in open bays, even without flooding.

NOAA's SLOSH Model

Surge modeling is an art (Jelesnianski, Chen, and Shaffer 1992). In 1992, NOAA's National Weather Service (NWS), through its National Hurricane Center (NHC), began to predict storm surges on the U.S. Eastern Seaboard using a computer model called SLOSH [Sea, Lake and Overland Surges from Hurricanes] for the purpose of forecasting storm surge height well before a hurricane makes landfall (Jelesnianski, Chen, and Shaffer 1992). SLOSH essentially evolved from earlier models developed in the late 1960's and early 1970's, notably SPLASH [Special Program To List Amplitudes of Surges From Hurricanes] (Jelesnianski 1972). SLOSH is a fluid-dynamics code for predicting surge <u>in response</u> to hurricanes, not the hurricanes themselves.

SLOSH estimates storm surge based on a hurricane's track, wind, pressure, forward speed/intensity; tidal effects can be included. However, SLOSH does not include rainfall amounts in its predictions (Melton et al. 2010; NWS 2010); nor does it account for wind-blown waves. SLOSH accuracy is generally ±20% of the peak storm surge (NWS 2010). For example, if the predicted storm surge is five feet, then the observed peak should be within four to six feet.

The NHC uses SLOSH to predict storm surge for both emergent and hypothetical hurricanes on the basis of historical ones (NWS 2010). In the latter case, the predictions can be verified from water depth gauges and/or high water marks (HWM), such as inundation lines left on trees or structures, observed the field. SLOSH's prediction/ verification history is systematically updated every few years, thus adapting to changes in hurricane behavior over time.

Reflecting the importance of coastline geometry and bathymetry, SLOSH considers 37 separate basins (Figure 3) along the U.S. Eastern seaboard. Basins are centered on susceptible features such as coastal inlets, low-lying topography, population centers, and ports (NWS 2013). SLOSH basins are modeled radial grids, varying from ~1x1 km cells at the coast to ~2x2 km and more offshore, i.e. quite different from GIS rasters.

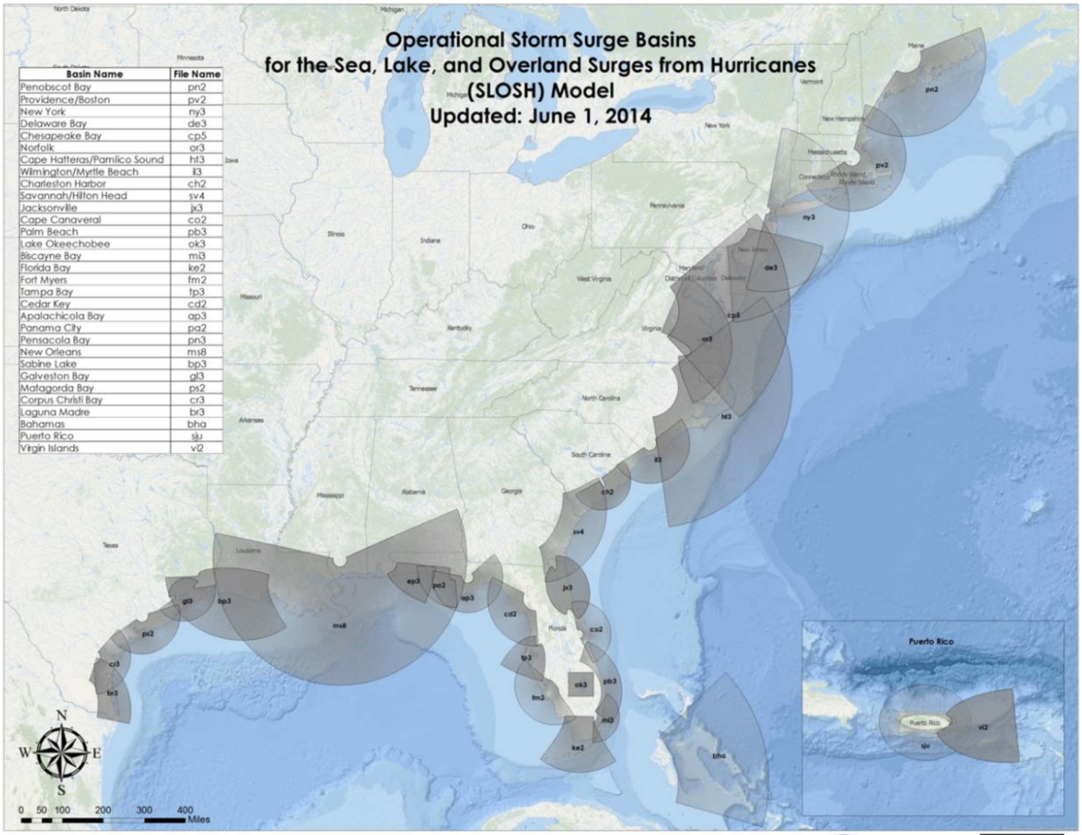


Figure 3. SLOSH Basins (NOAA)

Based on SLOSH, storm surge *potential* can be reasonably well correlated with hurricane strength, in each basin. The SLOSH basin definitions have been continuously updated[4] over the last 20 years, as actual storm surges from hurricanes have been recorded. Again, it is noteworthy that larger storms and bigger storm surges seem to be occurring (Shepard et al. 2012; Knutson et al. 2010).

SLOSH utilizes three prediction methods, designated deterministic, probabilistic, and composite. The deterministic method forecasts storm surge based on a "perfect"

[4] Six basins per year

forecast, which is never the case in an emergent storm. However, this method is useful with historical storms for which meteorological details have been retained (NWS 2013). The probabilistic method, denoted P-Surge, incorporates histories from several past storms closely matching the track, intensity, and size of an emergent one. The composite method utilizes a Monte Carlo approach, running several thousand hypothetical scenarios for the emergent storm as P-Surge candidates. NHC regards the composite method as best, because it takes into account uncertainty in forecast predictions.

The composite method separates further into two sub-methods. The "Maximum Envelope of Water" (MEOW) calculates the maximum water depth reached in each basin cell at any point in time during a modeled storm (NWS 2010). The NHC has pre-calculated the MEOW for a variety of storm scenarios, i.e. hurricane category, forward speed and direction, etc. The "Maximum of MEOWs" (MOM) reports the super-maximum water depth reached in each basin cell across all modeled storm scenarios in each basin. Ten MOMs are available per basin, one per storm category (CAT 1 to CAT 5) at each of two tide levels (low and high).

TU Delft's SWAN Model

Winds blowing over the ocean generate waves, which are amplified during storms. Because of Holland's exposure to the stormy North Sea and its large, low-elevation coastal areas, wind-blown waves are a persistent hazard. The Technical University of Delft (TU Delft) developed the SWAN [Simulating Waves Near-shore] model specifically to address storm-borne waves. In addition to surface winds, SWAN takes into account sea-bottom geometry and ocean currents. SWAN is accessible at <http://www.swan.tudelft.nl>.

SWAN employs a spectral wave model utilizing a variable-size grid to capture wave mechanics. The grid used is coarser in the open ocean, and made progressively finer toward shore (FEMA 2012a; TUDelft 2013), similar to that in SLOSH composite predictions.

SWAN can model both deep-water and near-shore waves, or be restricted to near-shore waves only (FEMA 2012d). Deep-water waves, which form in the open ocean and progress relentlessly toward shore, are large, primarily transverse (up and down) waves. Near-shore waves are smaller, longitudinal (back and forth) waves; these are responsible for most of the breaking and crashing water along coasts, which so is intensively destructive.

Figure 4 demonstrates the use of SWAN in a general circulation model of wind-generated waves around Long Island leading into New York Harbor, developed by the Computer Hydraulics Laboratory from the University of Notre Dame <http://www3.nd.edu/~coast/projects.html#top>. Noteworthy are the flow patterns: northwesterly on the South shore of Long Island, turning almost directly West in the NYC area (boxed).

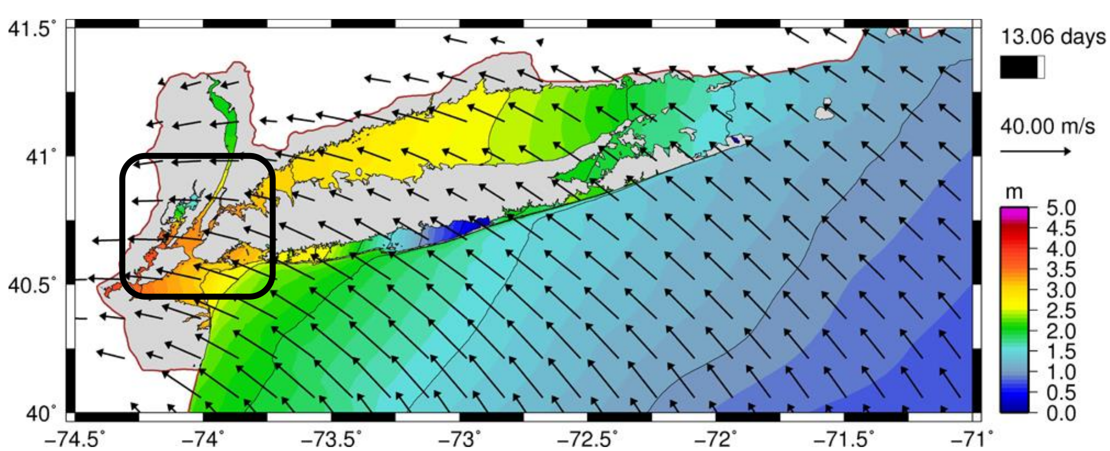


Figure 4. SWAN Wave/Circulation Model (Notre Dame)

FEMA's HAZUS Model

FEMA, an agency of the Department of Homeland Security (DHS), has progressively developed its HAZUS meta-model as a risk assessment program for estimating potential losses from a trio of natural hazards: earthquakes, floods, and hurricanes. HAZUS' results are used by "local, state, regional officials and consultants to assist [in] mitigation planning and emergency response and recovery preparedness" (FEMA 2012b, 1-1).

HAZUS employs a deterministic, GIS-based modeling methodology exclusively. Largely stand-alone models are built-in for earthquake, flood, and hurricane hazards. In response to the modeled hazards, through a system of engineering-oriented *damage functions*, HAZUS estimates physical damage to infrastructure (roads, pipelines, etc.), building stock (both commercial and residential structures), as well as economic losses and social impacts (lost jobs, business interruptions, and repair and reconstruction cost, temporary shelter requirements, displaced households, etc.) (FEMA 2013).

HAZUS recognizes three levels of hazard analysis. Level 1 is the default "out of the box" estimate obtained from minimal hazard parameters applied to a national inventory of building stock, essential facilities (hospitals, police and fire stations, schools), transportation and other lifelines (energy, water, sewer, etc.). Level 2 improves loss estimates based on more detail about the hazard conditions and/or updated local inventories of buildings and other infrastructure. Level 3 is the "top of the line" estimate, involving specifics of the hazard, details of individual buildings, advice of subject matter experts, etc.

The HAZUS Flood model (designated FL) assesses damage and losses from flooding, which may be either riverine or coastal. The HAZUS Hurricane model (HU) assesses damage and losses from high winds and associated rain, which may also cause flooding. Thus, the FL and HU models are frequently used together with regard to hurricane hazards.

A recent HAZUS addition is the Coastal Surge Model (CSM), which estimates storm surge effects in coastal communities, specifically by incorporating SLOSH and SWAN together[5] with the FL and HU models. Coastal surge is defined as storm surge plus tide, in essence an estimated version of storm tide (FEMA 2012c). CSM predictions are approached through HU first, FL second, as wind and rain strongly affect the near-shore environment and water run-up. Care is taken to avoid double counting. For example, hurricane winds may damage a building that floodwaters also damage.

Hurricane winds generate large waves that increase water run-up during these storm events. In HAZUS, SWAN is used in conjunction with SLOSH in CSM to model wind-generated waves in coastal regions and inland waters. For the Atlantic seaboard, SWAN's deep-water modeling area is preset (Figure 5). Deep-water waves can add run-up pulses of several feet to coastal surge. Near-shore waves add a further amount of run-up atop both coastal surge and deep-water waves, if included. Because of HAZUS' relatively coarse spatial scale, only SWAN's near-shore option is recommended for use with the CSM.

[5] Both the NOAA SLOSH and the TUDelft SWAN codes have been adapted to run within HAZUS.

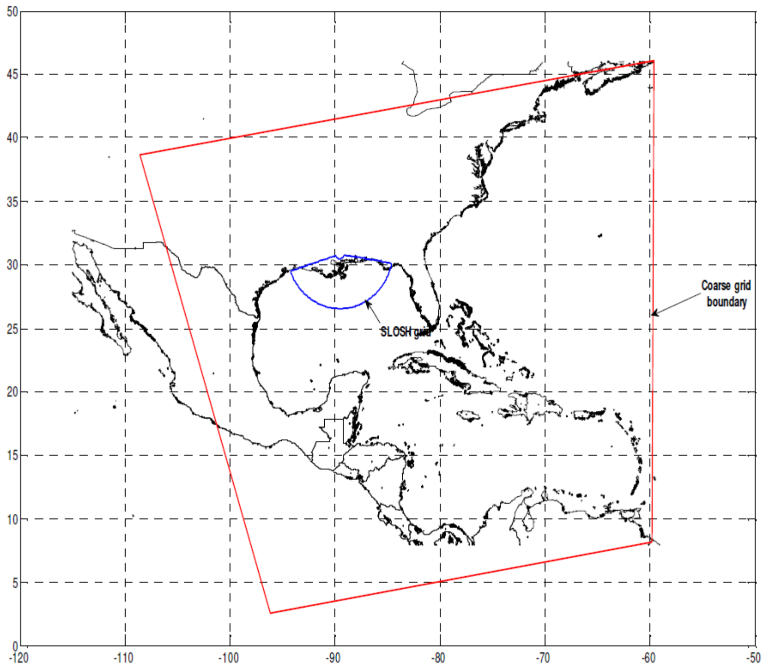


Figure 5. Northwest Atlantic Grid Domain (FEMA 2012c)

Hurricane Sandy

Hurricane Sandy ("Superstorm Sandy", hereafter simply Sandy), the subject of this study, was a "no pushover" hurricane, but certainly not the most intense on record for NYC. Sandy, a CAT 1 storm in the U.S., produced sustained winds of 70+ mph, with a lowest pressure 940 mbar; however, it was historically large with a radius of 175+ miles of hurricane force and 500+ miles of tropical storm force winds that covered most of the Eastern seaboard for several days (Figure 6) (Aon Benfield 2013). Sandy was super-destructive because of its unprecedented, protracted storm surge.

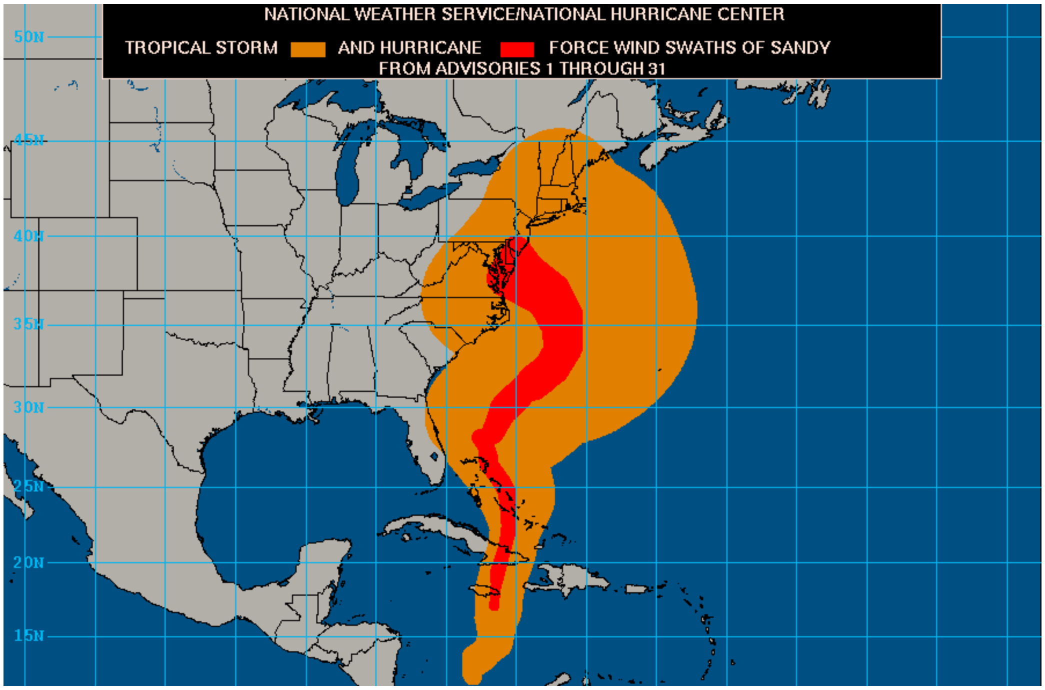


Figure 6. Surface wind field of Hurricane Sandy (NWS/NHC)

Sandy, became a CAT 1 hurricane on October 24th, 80 miles south of Jamaica, and made its first landfall there (Figure 7) (Blake et al. 2013). Increasing in strength, Sandy became a CAT 3 hurricane, causing havoc in Cuba before declining back to CAT 1 when it passed the Bahamas. While over the Bahamas, Sandy grew considerably in size but decreased to below hurricane strength. After the Bahamas, Sandy headed to the U.S. northeast, meanwhile increasing in speed and strength again to a CAT 1 once more.

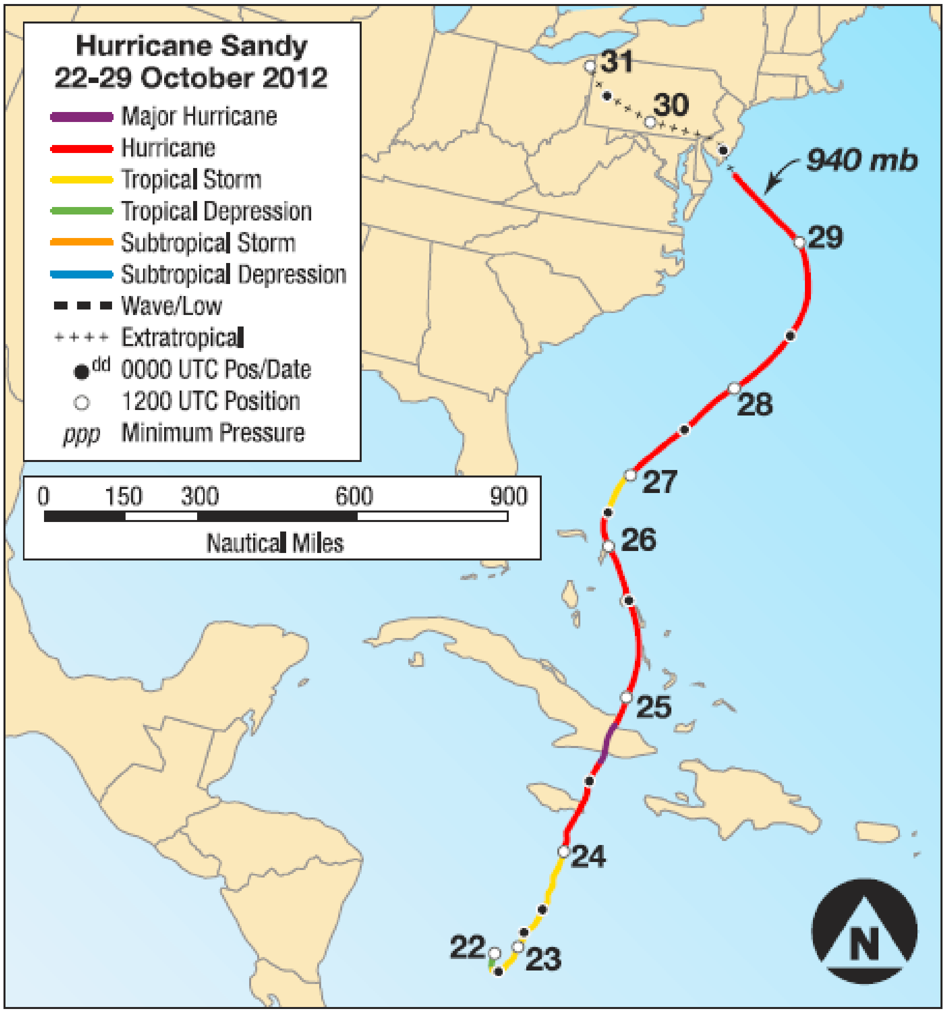


Figure 7. The Path of Hurricane Sandy (NOAA)

From the outset, Sandy was not a typical hurricane: it had a larger than normal radius of maximum winds, 100 (vs ~60) nautical miles, and stronger winds located in the western part (vs northern) side of the storm (Blake et al. 2013). Near North Carolina Sandy appeared to weaken but it encountered an anomalous blocking pattern over the North Atlantic preventing it from going out to sea. Early on the morning of October 29th, Sandy re-encountered the warm waters of the Gulf Stream, which caused it to re-intensify, achieving a forward speed of 20 kt. and a peak wind speed of 85 kt. Thereafter, Sandy, consistently a CAT 1 storm, made landfall in Brigantine, New Jersey at about 2330 UTC, with sustained winds of about 70 kt. and gusts up to 90 kt. (Figure 7) (Blake et al. 2013; Eisner 2012). Sandy slowed down after landfall and continued in a west-northwest direction toward northeastern Ohio. On October 31st, Sandy weakened considerably and finally fizzled out in Ontario, Canada.

Loss of life from Sandy was the largest for any hurricane on the Eastern U.S. seaboard since Hurricane Agnes in 1972 (Tennis 2013). (Hurricane Katrina was a Gulf Coast storm.) Staten Island, was labeled as “Ground Zero” by media; 21 direct deaths were reported in that borough alone.

The devastation caused by Sandy in the five-borough New York City (NYC) area was unprecedented (City of New York 2013). The property damage and number of people impacted (not killed) by Sandy far exceeded those of Hurricane Katrina (Eisner 2012). Power outages interrupted the lives of 800,000 customers, equating to over two million people in NYC. Many customers were without electricity for up to 17 days after the storm.

Inundation was a major factor in Sandy’s impact in NYC. Its worst-case tidal surge – Sandy made landfall at high tide with a full moon – caused higher than anticipated water levels and unexpected damages far inland. Significant parts of NYC, especially lower Manhattan, were, and are, vulnerable to flooding because of their low elevation; much of that area is built on fill (Figure 8). Tidal surge as low as 6 ft. destroyed homes, knocked-out power, damaged power substations, and flooded transportation routes, thereby making evacuations all the more difficult (Figure 9, Figure 10).

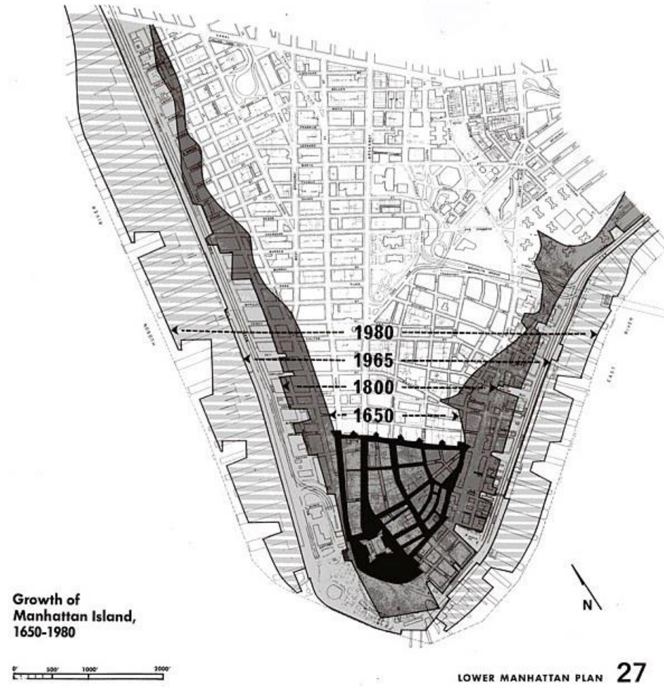


Figure 8. Lower Manhattan Landfill (David A. King Web site)

Figure 9. Lower East Side Manhattan, NY (from Blake et al. 2013)

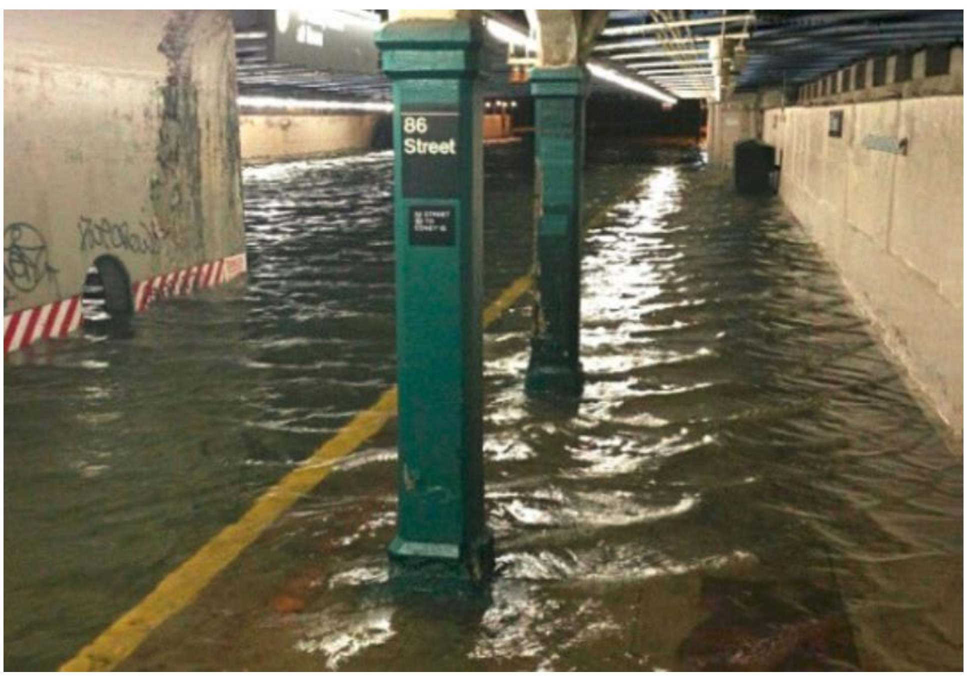


Figure 10. Lexington Avenue Subway Station (from Blake et al. 2013)

Sandy's storm tide exceeded all records (Figure 11), trumping those of Hurricane Irene in 2011 (City of New York 2013). Its highest storm surge measured by a National Ocean Service (NOS) tide gauge in New York was 12.65 ft. above high-tide, measured in Kings Point, on the north shore of western Long island. Staten Island reported a high storm surge of 9.65 ft.; and 9.40 ft. was recorded in Battery Park, the southernmost part of Manhattan (Blake et al. 2013). Table 2 summarizes the storm tide range for various neighborhoods in the New York City area.

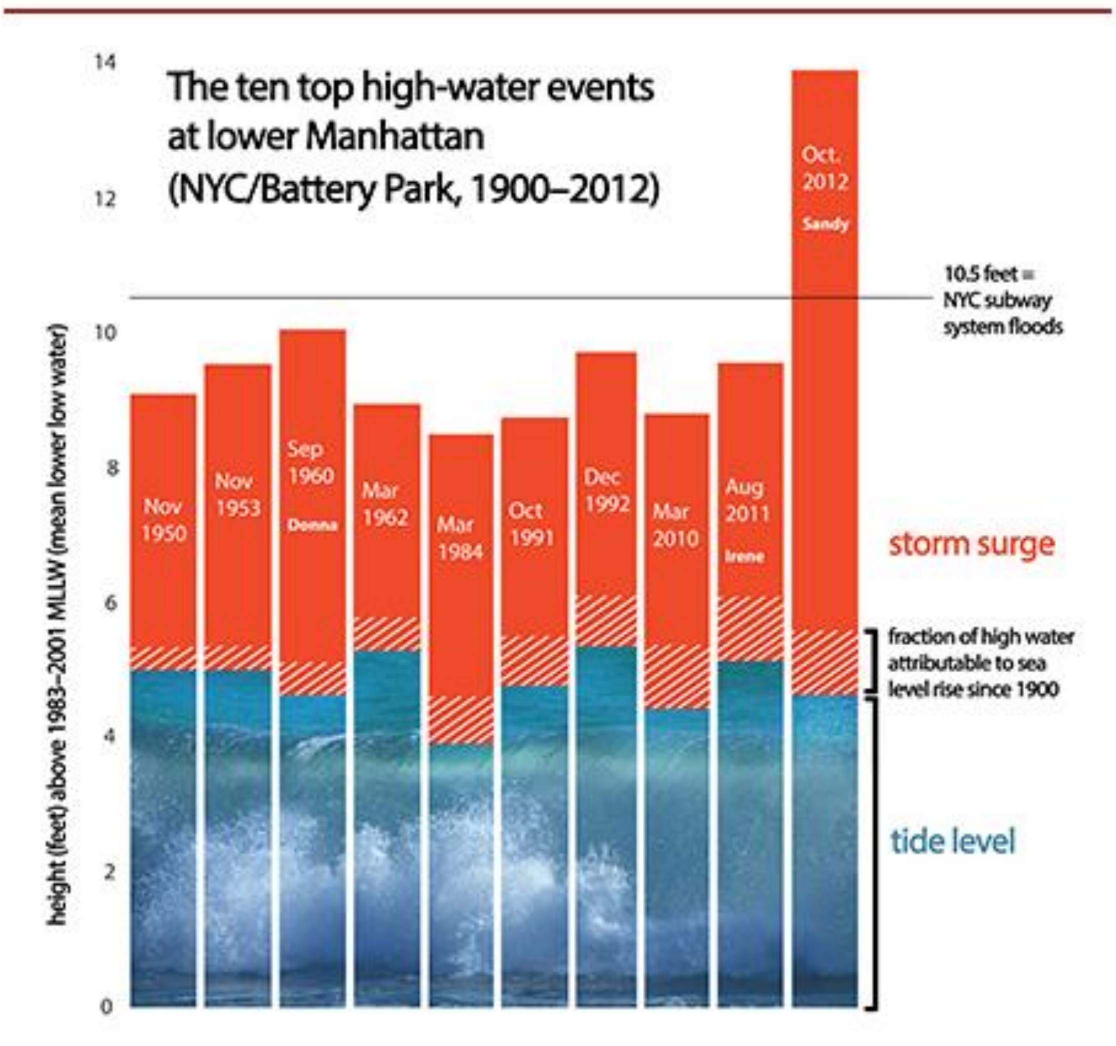


Figure 11. Storm Surge in NYC, 1900 to 2012 (Henson 2012)

Table 2. Storm Tide above ground levels for NYC and surrounding area

Neighborhood	Storm Tide (Range in ft.)
Staten Island and Manhattan	four to nine
Brooklyn and Queens	three to six
Bronx and Westchester	two to four
Long Island (Western)	three to six
Hudson River Valley	three to five

The New York City Office of Management and Budget estimated total damages from Sandy in NYC proper - just the five boroughs - to be $19 billion (Blake et al. 2013). Altogether, 305,000 homes were destroyed, making it the largest storm-related outage in NYC history. According to the Metropolitan Transit Authority (MTA), Sandy was also the worst disaster in its 108-year history causing an additional $5 billion in damages to the subway system, with persistent flooding in eight tunnels that took numerous subway lines out-of-service for weeks after the storm (refer to Figure 10). All waterfronts in NYC were affected, particularly in low-lying neighborhoods. The East River on the Manhattan side, where a major electric power generating station (East River) and East 13th St. distribution substations are located, was severely flooded (refer to Figure 9), causing equipment to malfunction and preventing re-electrification up to 12 days[6]. The New York Stock Exchange closed for two days, its longest period of closure since the Blizzard of 1888.

However, a few days before Hurricane Sandy, the inundation predicted for the tri-state area[7] (Figure 12) was minor, less than half of what eventually occurred. Many pre-storm preparations were minor, too – and quickly overwhelmed. Predictions themselves are often victims of unforeseen natural forces.

[6] Twelve days after Sandy, 98 percent of impacted customers had restored power.
[7] New York, New Jersey, Connecticut

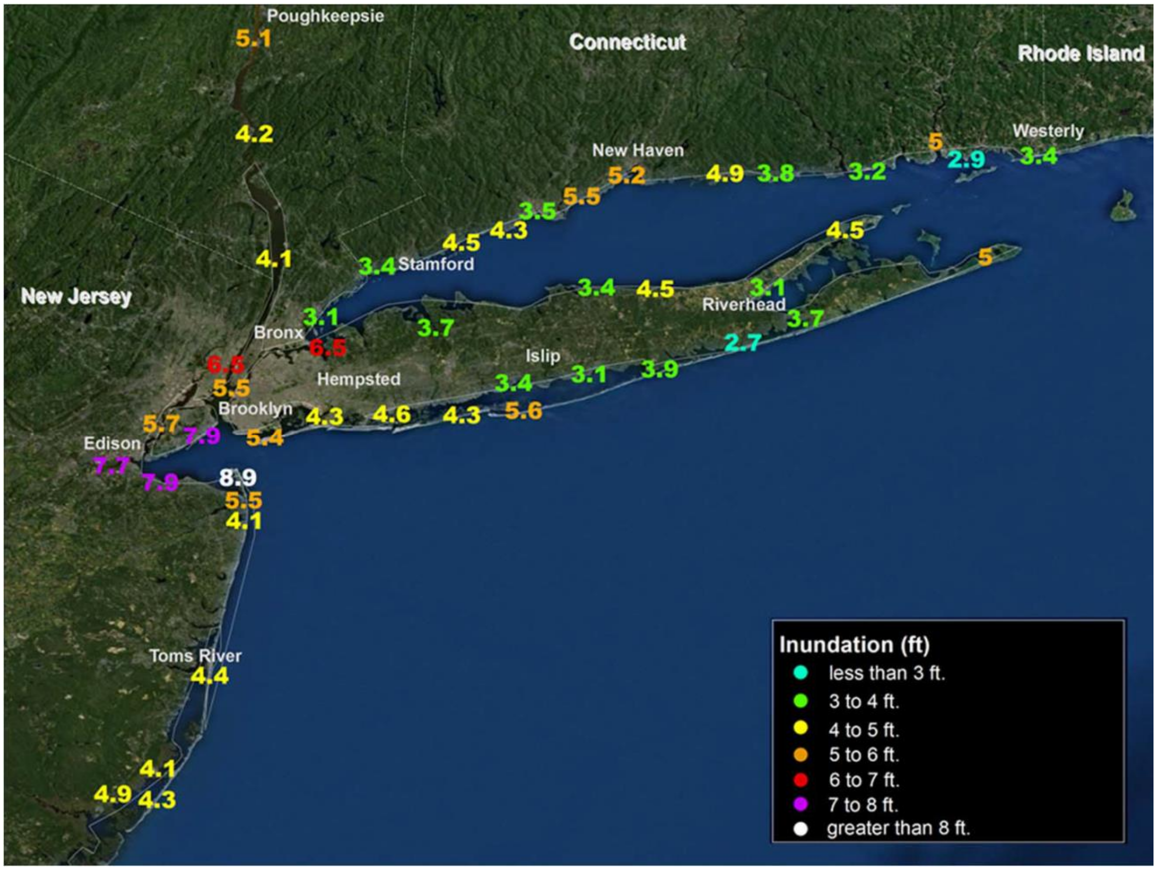


Figure 12. Estimated inundation – NJ, NY, CT (from Blake et al. 2013)

Hurricane Sandy Impact Analysis (HSIA)

The FEMA Modeling Task Force (MOTF) is a group of hazard experts and GIS professionals from government, academia and industry that is "on standby" to model risk from natural disaster events (MOTF 2013). The MOTF is deployed on demand to analyze hazards and model their impacts before, during, and after events.

In the case of Hurricane Sandy, which was recognized as a potentially huge hazard long before its landfall, MOTF was assigned to the New York / New Jersey metro area for close to three weeks (Figure 13). In late 2012, the MOTF was further tasked to define the extent of flooding from Hurricane Sandy based on a variety of direct measurements and observations. The MOTF work came to be known as the Hurricane Sandy Impact Analysis (HSIA) (MOTF 2013).

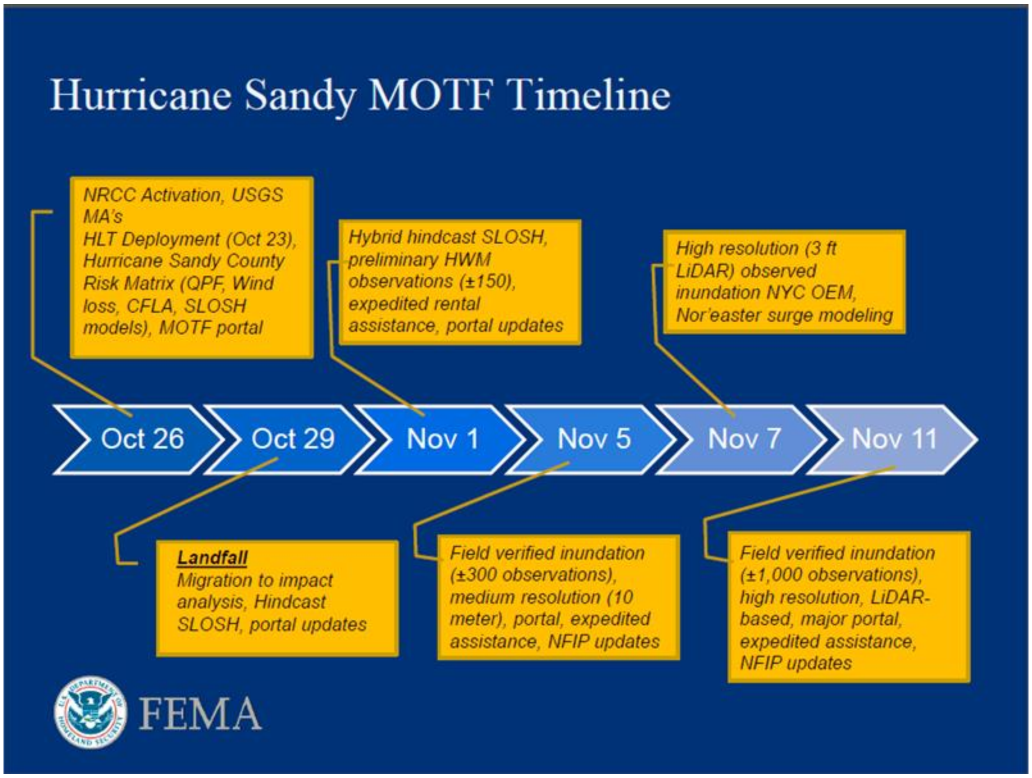


Figure 13. MOTF Timeline (FEMA)

As part of HSIA, the MOTF integrated data from a range of sources, the most important being high-water marks (HWMs) observed in the field and surge-senor data provided by the USGS. Immediately after an event, HWMs are identifiable from water lines found on trees and structures, and debris, depicting the highest elevation of the floodwaters. Such HWMs are progressively erased with recovery efforts and the passage of time (O'Brien 2014; MOTF 2013).

USGS supplied surge-sensors also capture temporal data about floodwater arrival and retreat, together with maximum water depth, estimated by the pressure applied from the force of the storm surge. Surge sensors are temporarily installed on posts or structures before a storm and removed after to extract their recorded data (Longenecker 2014).

The HSIA workup has been used and verified by several other groups, including a $25 million study by USACE (USACE 2013). The MOTF data are acknowledged as accurate to 1/10 ft. vertically and 1 m horizontally, in data rich areas. Further evidence is provided by the 319,000+ buildings in NYC, which were verified by FEMA inspectors has having suffered some sort of flood damage, i.e. water reached them to some degree; however, this data is not publicly posted, for reasons of privacy.

In summary, the MOTF work represents the best possible “ground truth” for Hurricane Sandy, which is well documented in the HSIA report (MOTF 2013), included as Appendix A in this thesis.

Chapter 3: Data and Methods

This study compares the outputs of HAZUS combined hurricane and flood model runs for Hurricane Sandy, both with and without coastal surge, against: 1) predicted flood inundation based on historical storm statistics, and 2) measured flood levels at selected locations. Primary data inputs to the HAZUS modeling were topography of the NYC region together with meteorology of Sandy's evolution through time. A high-accuracy flood-depth grid prepared by the FEMA MOTF was also used.

Study Region

The greater New York City (NYC) region comprises five boroughs (which are also New York State counties) as shown in Figure 14. Over time, some of the borough boundaries have become somewhat contorted. For example, Manhattan (New York County), originally just the island by that name, now includes a small spur at the North, Marble Hill, which at one time was part of Manhattan but because of the Harlem Ship Canal (1895) became part of mainland North America. Similarly the dockyards at the Brooklyn Bridge Park, across the East River otherwise known as Brooklyn (Kings County) according to the U.S. Census belong to Manhattan. These contortions cause problems for modeling.

Figure 14. The Five Boroughs, NYC (Britannica)

Topography of NYC Region

The USGS makes available the National Elevation Dataset (NED), providing continuous bare-earth, i.e. without buildings or vegetation, topography of the conterminous U.S. and outlying areas at various resolutions[8]. NED is available through National Map (USGS 2015), which automatically prepares a section of this topography clipped to a bounding-box (longitude/latitude coordinates). A high-resolution, NED product is available over most of the NYC region.

[8] Typically 1 arc-second (30 m) and ⅓ arc-second (10m).

For this study, experiments were conducted with two NED resolutions: 30 meters and 10 meters. Each NED download is an ArcGIS GRID, immediately usable within HAZUS as its digital elevation model (DEM) in the flood module. HAZUS contains code to clip DEMs to its study region, in this case, the five boroughs of NYC.

Figure 15 depicts a topographic map of NYC rendered in HAZUS. Low-lying areas, shown in yellow-to-orange tones, typically along estuaries, bays, or the Atlantic Ocean itself, are all susceptible to storm surge flooding.

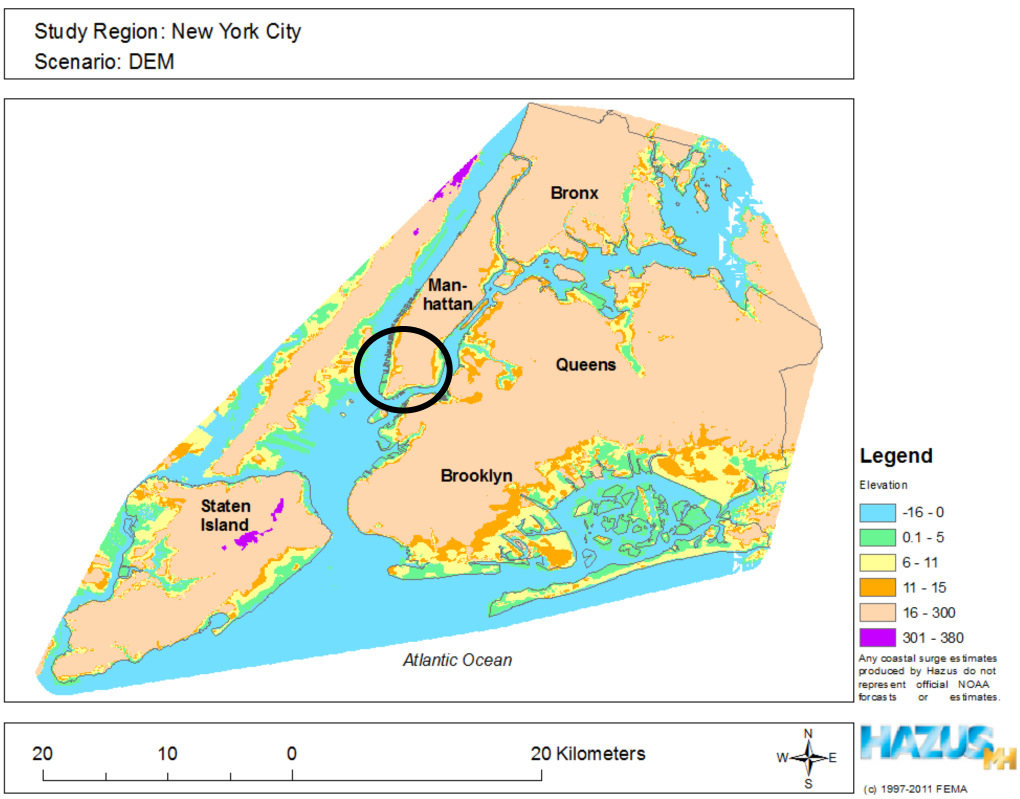


Figure 15. Topography of NYC

Manmade areas of NYC, created via landfill, are especially at risk. Downtown Manhattan, the largest landfilled area of NYC (circled in Figure 15), has been expanded several times over the last 300-400 years, as detailed in Figure 8. All the South end of Manhattan was severely impacted by Hurricane Sandy, as were other coastal regions in NYC: Southern Queens, Southern Brooklyn, and Staten Island (City of New York 2013; City of New York 2014).

Meteorology of Hurricane Sandy

The National Hurricane Program (NHP), a joint activity of FEMA, NOAA, and U.S. Corps of Army Engineers (USACE), makes available their so-called Hurrevac (hurricane evacuation) files[9] detailing the evolution of hurricanes. Hurrevac files are archived at (Hurrevac 2015). Each Hurrevac file contains reports of weather forecasts and observed meteorological data including hurricane track (location), storm radius and central pressure (mbar), magnitude of winds and other details. Figure 7 depicts the progress of Hurricane Sandy during the critical period 30 Oct - 1 Nov 2012, as encoded in its Hurrevac file. Hurrevac files must be downloaded manually. HAZUS then ingests these files directly into the HU model, using them to reconstruct the track and meteorology of a particular storm.

Predicted Flood Inundations

NOAA's SLOSH is the foundation of HAZUS Coastal Surge Model's (CSM) estimation of storm surge for hurricane events along the U.S. Atlantic coast, including both Gulf and Eastern seaboards. HAZUS includes an implementation of SLOSH, which is run deterministically based on either a Hurrevac file or a hypothetical storm in Hurrevac format.

[9] Atlantic Storm File Path: http://data.hurrevac.com/STMFiles/Atlantic/ (For Sandy look up "s_2012.stm")

Separate from HAZUS, NOAA also makes available its prepared SLOSH predictions at <http://www.nhc.noaa.gov/surge/slosh.php>. The deterministic forecast, including so-called Envelopes of High Water (EOHW), is only provided 36 hours before anticipated landfall, when track and speed are reasonably well set. For this study of Hurricane Sandy actual meteorological data directly input into HAZUS was used.

The probabilistic forecast (P-Surge) is reported as an "exceedance" above mean sea level (NGVD29[10]): the expected storm surge heights that have only a one-in-ten chance of being exceeded. For Hurricane Sandy, a 7-13 ft. exceedance was reported in the most exposed areas of Manhattan, Brooklyn and Queens (Figure 16).

[10] An old vertical datum, generally ~1 ft. higher than the modern datum NAVD88, used by HAZUS.

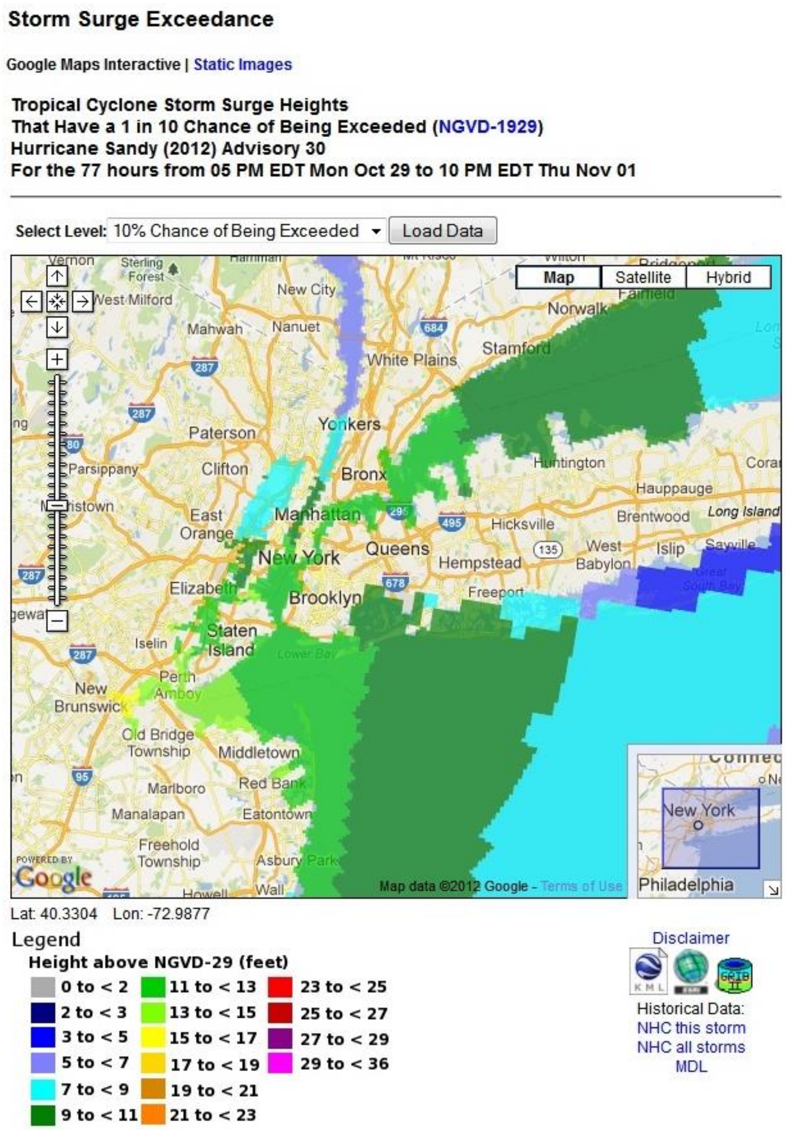


Figure 16. Storm Surge Exceedance, 10% likelihood[11] (NOAA)

The composite forecast, expressed in MEOWs and MOMs, is shown in Figure 17. For Hurricane Sandy, only ~10 ft. of storm surge was predicted around Manhattan, Brooklyn and Queens. The greatest, ~13 ft. storm surge was confined to the apex of Long Island Sound and lower Staten Island. In actual fact, these situations were reversed.

[11] To estimate total water levels, add this value to the tide height at the time of peak surge.

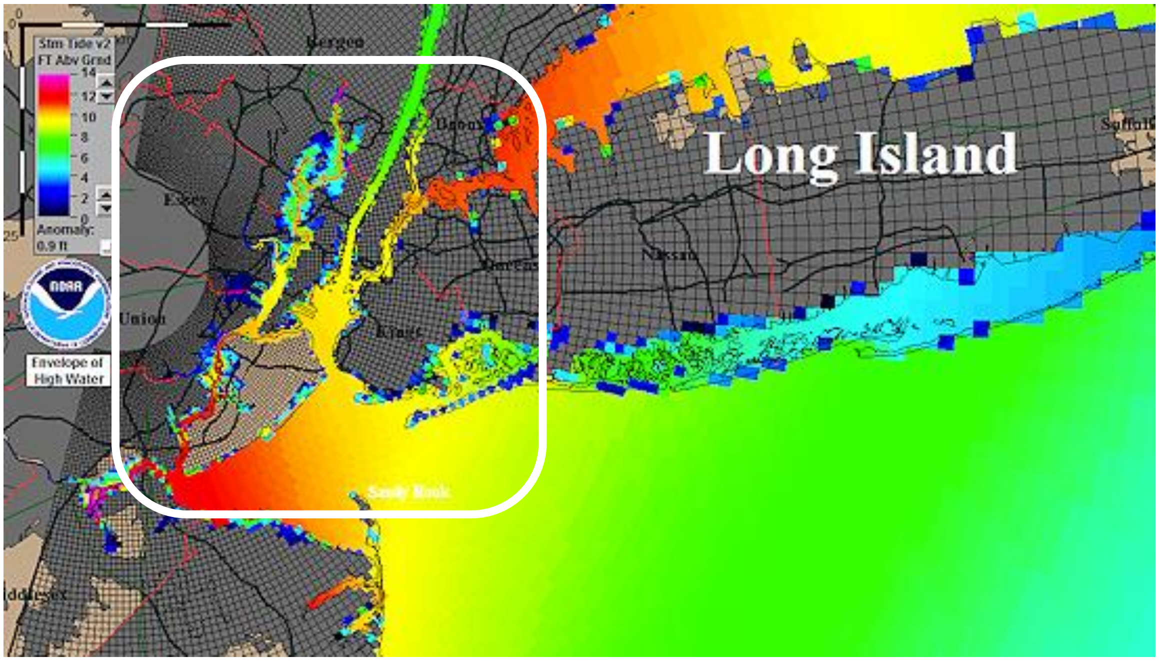


Figure 17. SLOSH Model for Hurricane Sandy (from Forbes et al. 2014)

Prior to Hurricane Sandy, USACE had also prepared a worst-case, CAT 1 storm surge prediction for NYC, based on the composite SLOSH MOMs, as shown in Figure 18. The USACE prediction was also undersized.

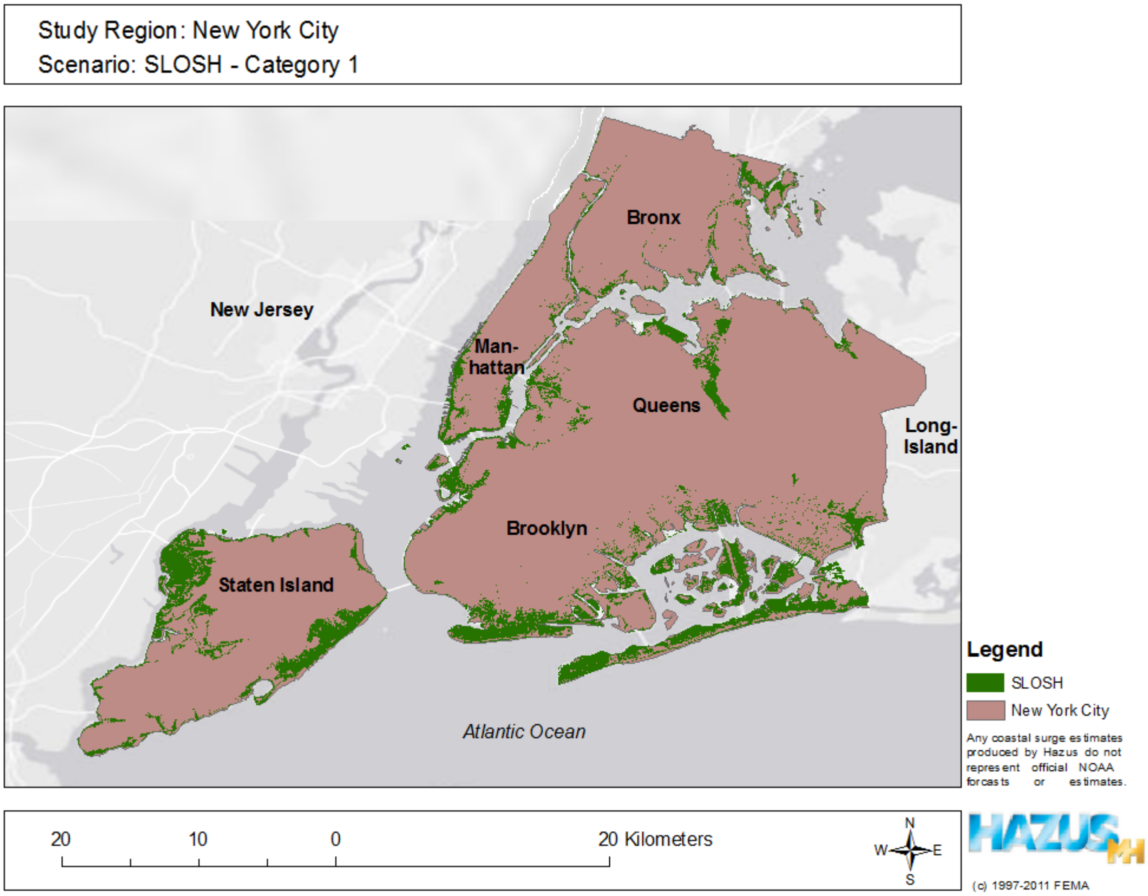


Figure 18. SLOSH Cat 1 Worst Case, NYC (USACE)

HAZUS Coastal Surge Model

As described above, the HAZUS Coastal Surge Model (CSM) combines NOAAs' SLOSH and TUDelft's SWAN, in an enhanced, deterministic prediction that includes the effects of wind-blown waves. Actual tide can also be incorporated in a simplified way: as the predicted tide 1-2 days before the storm. Thus, the HAZUS prediction can be for tidal surge, in fact, not simply storm surge. HAZUS does not compute tidal conditions within CSM; rather, the user directly enters the tide conditions expected in advance of the storm, i.e. as if a storm were not present. Figure 19 and Figure 20 present schematically CSM processing.

Within CSM, use of SWAN is an option; and SWAN itself presents two sub-options, near-shore waves only or both deep-water and near-shore waves. Starting from the HU model, the options are presented as shown in Figure 20.

When SWAN is in use, storm surge analysis is performed via SLOSH for a period of simulation time (nominally 15 minutes) and then suspended. The new water-level data from SLOSH are then passed to SWAN, and the wave model is advanced for the same fixed period of simulation time. The near-shore breaking wave stresses from SWAN are then passed back to SLOSH for the next time period, and simulation continues until the hurricane passes through and beyond the study region (FEMA 2012a)

Because of SWAN's relatively coarse scale for deep-water waves (see Figure 5), only the near-shore option is recommended for use with the CSM. In addition, SWAN is compute-intensive. As a practical matter for this study, the entire five-borough NYC study region could not be modeled at once in HAZUS using SWAN; rather each of the boroughs had to be run separately.

HAZUS models all use a *plate carree* (longitude and latitude, WGS 84) horizontal grid, with elevations in feet (NAVD 88), while SLOSH and SWAN are both use a polar grid and older datum (NGVD 29) for the New York ('ny2') basin. Grid and datum conversions are a fertile source of error in making HAZUS FL, SLOSH, and SWAN interoperate.

Modeling the hurricane and coastal surge hazards together avoids double-counting damages caused by the hazards separately. However, the combined "wind and flood" scenario estimates do not allow determination of the percentage of losses that are attributable to wind or flood alone (FEMA 2012c).

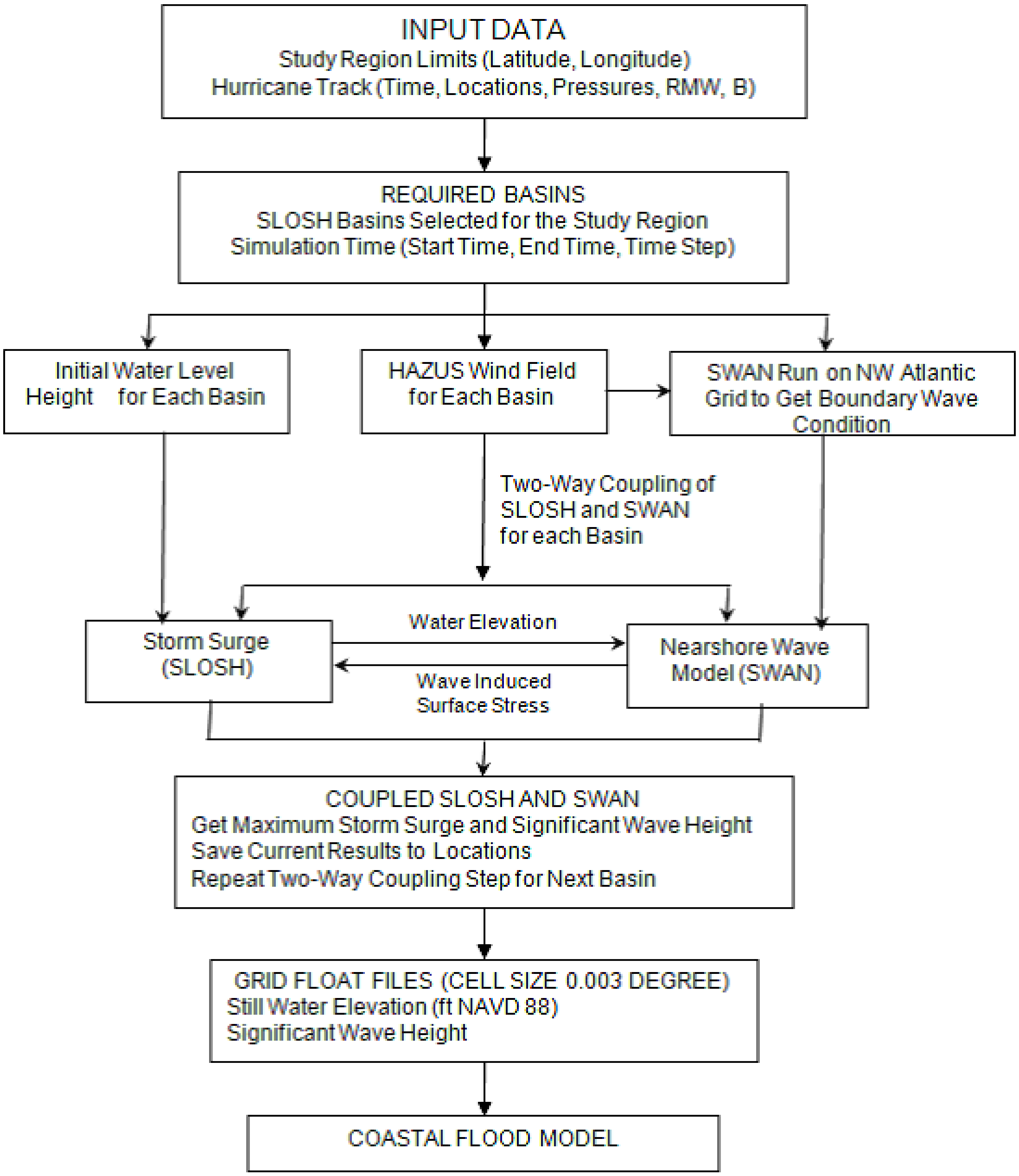


Figure 19. Storm Surge/Wave Model Flow Charts (HAZUS)

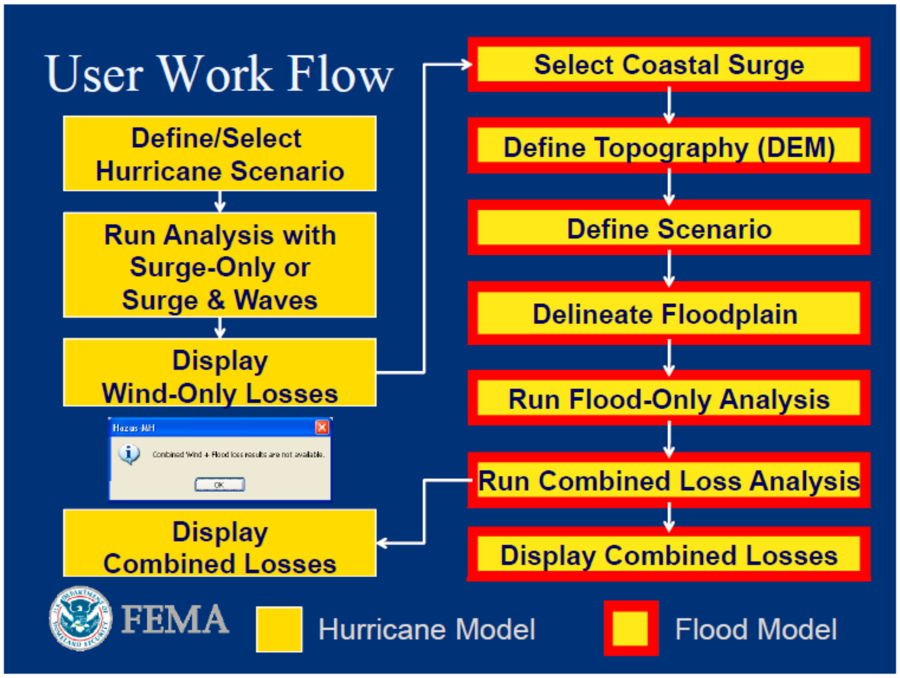


Figure 20. CSM – User Work Flow (from Lavelle 2012)

Measured Flood Levels

During Hurricane Sandy, because of the storm's size and anticipated impacts, the FEMA MOTF was assigned to the New York / New Jersey metro area for close to three weeks (Figure 13). Included in the MOTF's Hurricane Sandy Impact Analysis (HISA), of particular importance to this thesis, were its delineation of the floodwater boundary and associated depth-grid, both utilized in the CSM.

The HSIA utilized high-water marks and storm surge sensor data, geolocated using GPS with a horizontal accuracy of ~10 feet, to create a floodwater surface using the Inverse Distance Weighting (IDW)[12] tool in ArcGIS. Among the commonly used spatial interpolation

[12] Inverse Distance Weighted estimates cell values in a raster dataset that weights samples points as the distance a point is from the cell being evaluated. The closer the sample point is to the cell the higher the weight applied to the calculation of the cell's value and vice versa.

methods, IDW was preferred in this case because it "draws for the data", i.e. creates no artifacts. This surface was intersected with the 10m DEM for NYC, to produce a floodwater boundary (also made available as shapefile). Based on this boundary, flood-depth grids were developed by subtracting from the flood-level the underlying topography for NYC. In fact, two topographic DEMS were considered: the first from the New York Office of Emergency Management (NYOEM), at 3 m (horizontal) resolution; and the second from the New York City Office of Emergency Management (NYCOEM), at 1 m resolution.

The NYCOEM flood-depth grid together with the flood surface elevation produce the user-defined depth grid (UDG)[13] used for some aspects of this study. This final UDG has been used and verified by several other groups, including USACE, which confirms its accuracy to 1/10 ft. vertically and 1 m horizontally, in data rich areas. The HSIA flood boundary in comparison with SLOSH (CAT 1) is depicted in Figure 21.

[13] Final version was made available on the HSIA MOTF FTP site as of February 2013

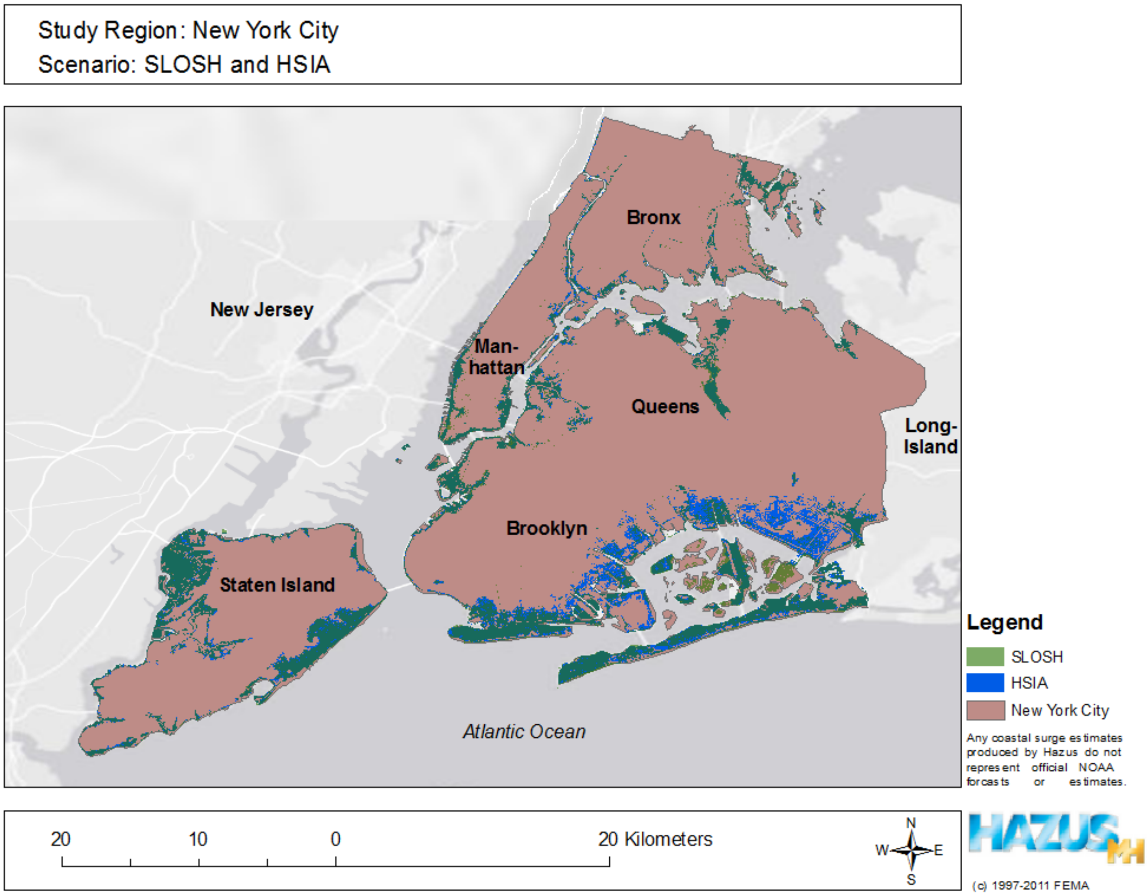


Figure 21. SLOSH vs. HSIA, NYC

HAZUS Model Runs

This study focused on the extent and depth of the floodwaters, as modeled by CSM for Hurricane Sandy, and directly validated against the HSIA study. Further direct confirmation was provided by Con Ed (2013) and NYOEM (2013) reports of flooding to electrical power substations.

Altogether, twelve CSM runs were completed for this study. Each run began with the HU model, which generated the wind field, then progressed with the CSM as appropriate. The first two runs, covering all of NYC, allow evaluation of the effects of spatial resolution.

The remaining ten runs (two sets of five runs each) allow evaluation of the CSM, including wind-blown waves with and without a deep-water wave component via SWAN. Owing to the compute-intensity of SWAN, as mentioned before, the entire study region could not be run at one time, but instead had to be run borough-by-borough and reassembled, significantly increasing the human effort involved. Table 3 summarizes these model runs.

Table 3. HAZUS Modeling Scenarios

Scenario	Region	DEM	Coastal Surge Options
1	All of NYC	30 m	No-Waves
2	All of NYC	10 m	No-Waves
3 - 7	5 Boroughs Individually	10 m	Near-Shore only
8 - 12	5 Boroughs Individually	10 m	Deep-Water & Near-Shore

Flood-related damage to buildings was also examined, although without validation. Additional damages were widely reported to transportation and utility "lifelines", but were not incorporated in this study, due to HAZUS' requirement of a user-defined inventory of complex assets to model such damages meaningfully.

Some anecdotal evidence of was provided by the extent of utility outages, which lasted up to three weeks. Overall, Hurricane Sandy caused more than four times as many customer outages as the previous worst storm in Con Ed's history (Con Ed 2013). Within four days after Sandy's departure, most of the Con Ed's customers who lost power had their power restored. However, critical substations in lower Manhattan, in particular the power station located at East 14th street, had been damaged extensively. The 12-foot wall protecting the transformer was breached by the 14-foot storm tide resulting in a series of network (power) shutdowns, for all of downtown Manhattan and up to 34th street, which lasted about five days (Con Ed 2013). Across NYC storm tide varied in height because of topography and location. The Battery (Lower Manhattan) experienced flooding over 11 ft. relatively lower than the 14 ft. seen in the Lower East Side (E. 14th street) (USGS 2013; Henson 2012).

Chapter 4: Results

The results presented below compare the CSM predictions for Hurricane Sandy in three ways: first, amongst themselves, to assess the effects of scale (30m or 10m DEM), and the contributions of waves (none, near-shore only, or deep-water and near-shore); second, against the stochastic SLOSH predictions, which apply to a generic storm; and third to "reality" as established in detail by the HSIA (ground-truth) for this storm.

In all cases, the area and perimeter of the flooded area are taken as proxy for flood damage. The depth of floodwater and duration of flooding is not considered. The detailed shape of the flooded area, which certainly affects the spatial distribution damage, particularly in low-lying areas, is also not considered in any quantitative way, but only graphically. Differences in perimeter are quite visible.

Figure 22 shows the CSM baseline "out of the box" scenario, without waves, for the entire NYC area (i.e. as a single study region), using a 30m (1 arc-second) DEM and a pre-surge tidal height of 1.46 feet. Only a very minor reduction in flooded area, from 36.92 mi^2 to 36.90 mi^2 (0.05%) resulted from using a 10m (1/3 arc-second) DEM, which took almost ten times longer to complete.

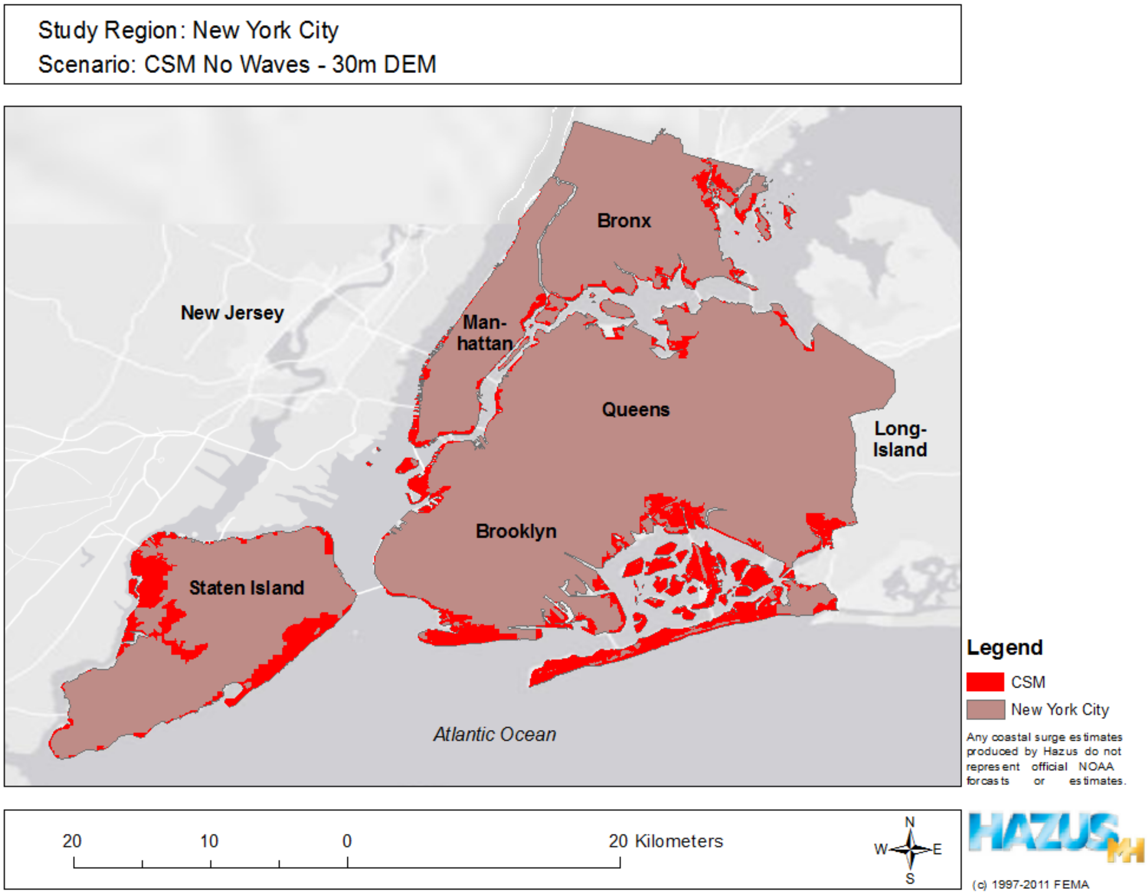


Figure 22. CSM baseline, NYC, no waves, 30m DEM

Figure 23 compares the same CSM baseline case (red) against the SLOSH prediction (green) and the HSIA ground-truth (blue) for Manhattan. Transparency is applied so that discrepancies between the flooded regions can be visualized. Specifically, rust (red+green) represents agreement between CSM and SLOSH, and violet (red+blue) represents agreement between CSM and HSIA. Obviously, significant areas of both agreement and disagreement exist across the three predictions, although details are difficult to discern at the small scale. Major Con Ed generating stations and distribution substations affected in

Sandy, as reported in (Con Ed 2013), are also shown along with other power utilities (Figure 23).

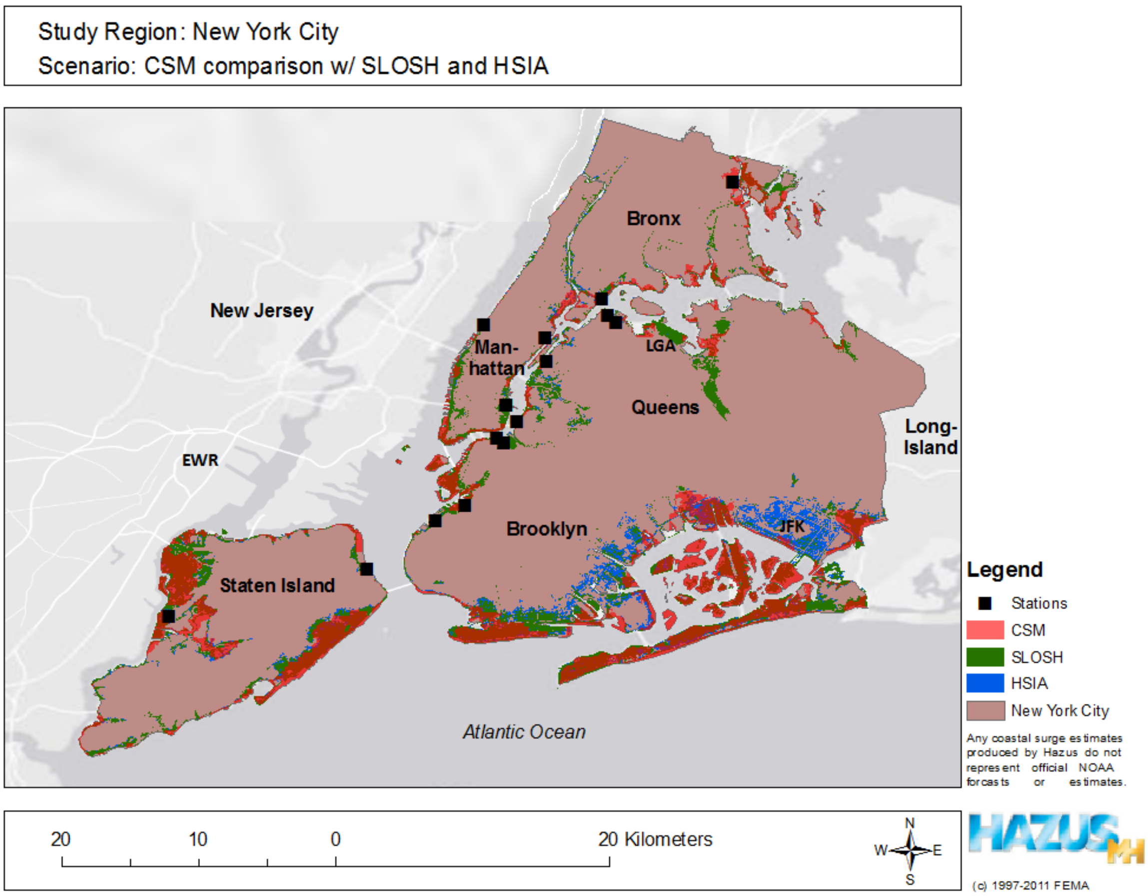


Figure 23. CSM Baseline vs. SLOSH and HSIA

CSM scenarios involving waves could not be run for the entire NYC study area, apparently owing to array size limitations in HAZUS; rather, these were run for the five boroughs (each a county of New York state) as separate study areas. To obtain the most detailed results, all runs were made with the 10m DEM. Results are shown in Table 4, in comparison to SLOSH and HSIA for the individual boroughs, which were obtained by ArcGIS geoprocessing (as both SLOSH and HSIA considered NYC as whole).

Curiously, the sum of the CSM no-waves scenarios for the individual borough study areas (33.61 mi²) does not closely match the CSM no-waves scenario for NYC as a whole (36.90 mi²). The reason for this large (~10%) discrepancy is unknown.

Table 4. Summary of inundation by three methods, NYC

Map	Scenario	CSM	SLOSH [14]	HSIA[15]
N Y C	no-waves	36.90	40.23 (+9.0%)	46.90 (+27.1%)
Manhattan	no-waves	1.17	2.54 (+116.4 %)	2.49 (+112.2%)
	near-shore only	1.43	2.54 (+77.6%)	2.49 (+74.1%)
	deep-water & near-shore	1.46	2.54 (+74.0%)	2.49 (+70.5%)
Bronx	no-waves	2.98	2.58 (–13.2%)	2.54 (–14.8%)
	near-shore only	2.98	2.58 (–13.2%)	2.54 (–14.8%)
	deep-water & near-shore	3.36	2.58 (–23.2%)	2.54 (–24.4%)
Brooklyn	no-waves	8.60	8.89 (+3.3 %)	11.63 (+35.3%)
	near-shore only	9.01	8.89 (–1.3%)	11.63 (+29.1%)
	deep-water & near-shore	17.24	8.89 (–48.4%)	11.63 (–32.5%)
Queens	no-waves	13.82	13.12 (– 5.1%)	16.59 (+20.0%)
	near-shore only	14.56	13.12 (– 9.9%)	16.59 (+13.9%)
	deep-water & near-shore	21.94	13.12 (– 40.2%)	16.59 (–24.4%)
Staten Is.	no-waves	7.04	9.95 (+ 41.3%)	11.09 (+57.5%)
	near-shore only	7.56	9.95 (+31.6%)	11.09 (+46.7%)
	deep-water & near-shore	8.89	9.95 (+11.9%)	11.09 (+33.9%)

The CSM flood predictions vary dramatically and erratically depending on the scenario. For NYC as a whole, CSM under-predicts SLOSH by 9% and HSIA ("truth") by a whopping 27%. These are significant differences, specifically in the later.

[14] Difference of 3.15 mi² in total flood area (SLOSH) compared to the total of the borough flood areas because of different boundaries between HAZUS & SLOSH/HSIA.
[15] Difference of 2.56 mi² in total flood area (HSIA) compared to the total of the borough flood areas because of different boundaries between HAZUS & SLOSH/HSIA.

- In Manhattan, CSM under-predicted by comparison to both SLOSH and HSIA in all scenarios. Lower Manhattan is a particular trouble-spot. Curiously, the scenarios with waves were significantly worse than without.
- In Bronx, CSM over-predicted by comparison to both SLOSH and HSIA in all scenarios, and still missed the inundation on the west coast of the Bronx entirely. In the areas that CSM predicted, the inundation seems to be deeper than in the other methods.
- In Brooklyn, results are mixed: without waves, CSM under-predicted by comparison to both SLOSH and HSIA; with waves, it over-predicted SLOSH, but fell on both sides of HSIA.
- In Queens, the results are even more troubling: without waves, CSM over-predicted SLOSH slightly but under-predicted HSIA; with waves, its predictions increased, as expected, and eventually exceed both SLOSH and HSIA.
- Finally, for Staten Island CSM again under-predicted both SLOSH and HSIA in all scenarios; with waves, its predictions improved somewhat.

As flooding in Manhattan was the most mis-predicted by HAZUS as well as the most severe, that borough was examined in greater detail. Figure 24 shows the baseline scenario in small multiples for Manhattan alone[16] in comparison to SLOSH (left side) and HSIA (right side) using the same color conventions as Figure 23. The inset maps focus on Lower Manhattan, where some of the worst flooding occurred. Despite the small scale, blocky "gaps" in the HAZUS predictions are clearly shown. Along the East River on the southeast side of Manhattan, HAZUS missed the flooding entirely, although it is evident in both SLOSH and HSIA. Similarly, the middle section of the docks on the west side of Manhattan is missed. However, as the CSM scenarios intensify, from no-waves to near-shore waves to deep-water & near-shore waves, its predictions improve, i.e. are better aligned with SLOSH and HSIA.

[16] For completeness, Appendix B shows analogous results for all five boroughs.

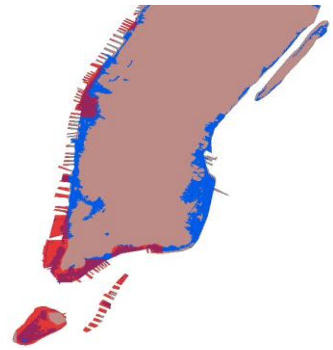
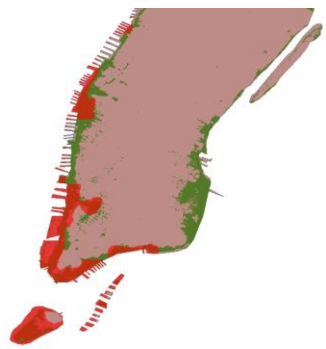
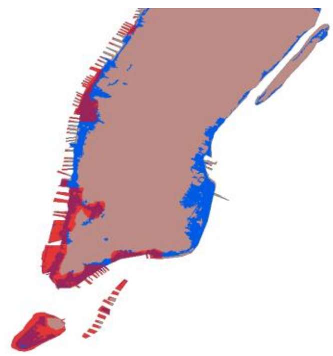
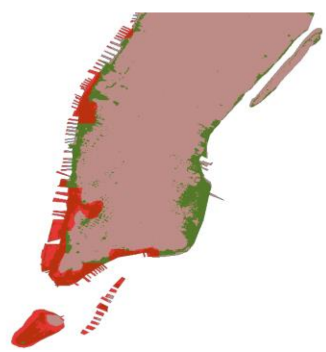
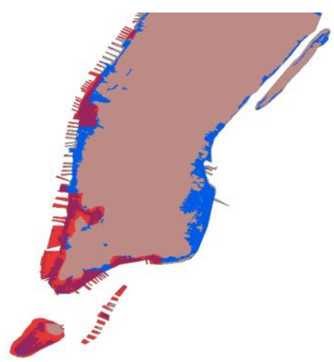
 CSM no-waves vs SLOSH – 1.17 mi^2 + 2.54 mi^2	 CSM no-waves vs HSIA – 1.17 mi^2 + 2.49 mi^2
 CSM near-shore waves vs SLOSH – 1.43 mi^2 + 2.54 mi^2	 CSM near-shore waves vs HSIA –1.43 mi^2 + 2.49 mi^2
 CSM deep-water & near-shore vs SLOSH – 1.46 mi^2 + 2.54 mi^2	 CSM deep-water & near-shore vs HSIA – 1.46 mi^2 + 2.49 mi^2

Figure 24. CSM vs. SLOSH, CSM vs. HSIA, Manhattan

Just south of Manhattan is Governor's Island displaying CSM inundation. Slightly to the south east of southern tip of Manhattan are the Brooklyn Bridge Park docks, a low-lying area which is technically part of Manhattan. The docks are mostly inundated by the CSM, but seem to have been missed entirely by SLOSH and HSIA.

Figure 25 details CSM results for Lower Manhattan with the SLOSH 'ny2' grid[17] superimposed. Each grid cell is ~1km x 1km, although curvilinear in outline, because the SLOSH gird is radial. The elevations of selected grid cells are shown at their centroids: "dry" cells have positive values, "wet" cells negative values. HAZUS determines flooding in CSM from the SLOSH grid. However, a rectilinear pattern in the boundary of CSM's flooded area, shown in red, and <u>not</u> supported by the SLOSH grid, is clearly visible; this is sketched with dashed lines in some places. In addition, curious triangular artifacts of land jut into the lower East River, indicated by the dashed circle. Overall, the blockiness (cells) of the CSM is curious by comparison to the SLOSH grid, and also appears shifted to the West.

[17] The finer 'ny3' is not available in HAZUS 2.1

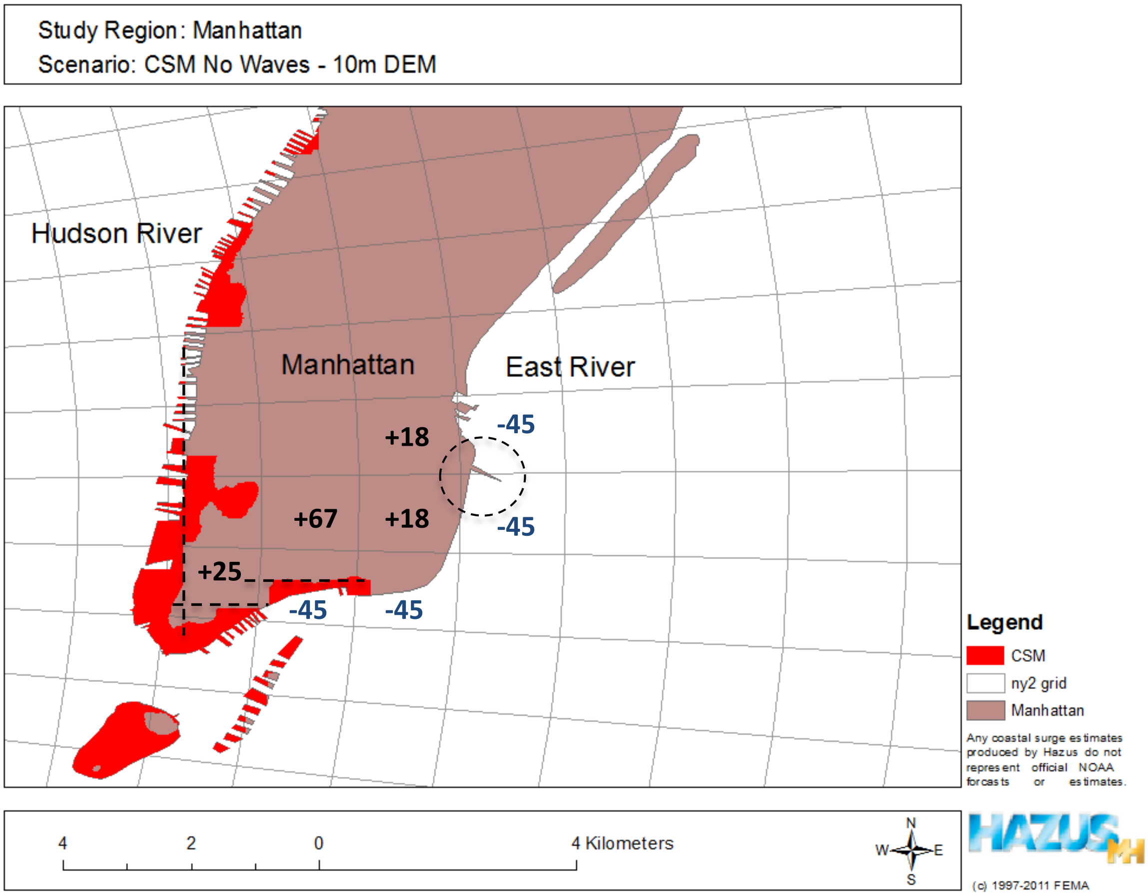


Figure 25. CSM Baseline with SLOSH Grid, no waves

Of course, no prediction is perfect; nor even is an after-the-fact report such as HSIA. During Sandy, Con Ed experienced flooding in eleven of its power generating and distribution facilities (Table 5). At most, CSM predicted six of these and SLOSH predicted ten. However, HSIA only reported nine. In part the reason for these results is that urban flooding, particularly around tall buildings and down streets that behave as tunnels, is quixotic. Still, it appears that CSM is less reliable than SLOSH, at least for New York City.

Table 5. Inundated power substations, NYC

Method	Count
Con Ed (observed)	11
FEMA HSIA (observed)	9
NOAA SLOSH	10
HAZUS CSM	
No-Waves (1 arcsec DEM)	6
No-Waves (1/3 arcsec DEM)	6
Near-Shore only	5
Deep-Water & Near-Shore	5

Chapter 5: Discussion

HAZUS CSM significantly under-predicted the flooding for Hurricane Sandy as shown in Figure 26. The most egregious “gaps” for NYC are marked. Specific problems for Manhattan were presented in detail above, some suggested explanations for which follow.

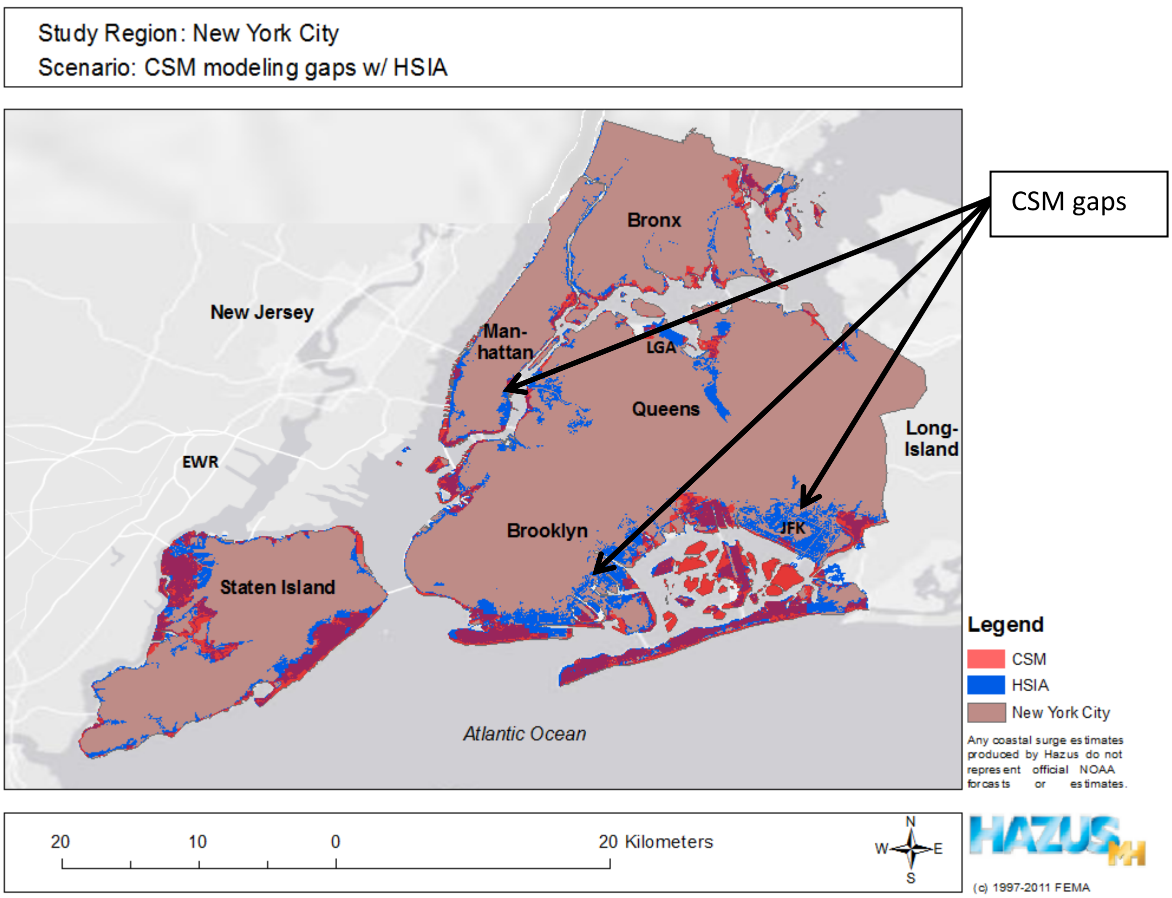


Figure 26. Gaps in CSM Prediction

Individual borough (county) analysis presents a complicated story (Table 4). CSM over-predicted the Bronx, under-predicted Manhattan and Staten Island, and gave mixed results (over and under predictions) for Brooklyn and Queens. The varied results arise primarily from miscalculation of the flood surface geometry, resulting in the egregious "gaps" noted above. Minor differences in administrative boundaries also exist: HAZUS uses the 2000 TIGER data (FEMA 2012a) for its counties, while HSIA used basic ArcGIS default base-maps, which do not account from some real gerrymandering such as the Brooklyn Docks, mentioned previously.

SLOSH basins are defined by radial grids, gradually increasing in cell size outward from the center along a preferred axis, in New York's case from west to east. The older 'ny2' SLOSH basin and grid used in HAZUS 2.1 has coarse grid cells averaging 1 x 1 km in the NYC area. Also 'ny2' utilizes the deprecated NGVD29 vertical datum, which differs by ~1 ft. from the updated NAD88 datum used throughout HAZUS.

Figure 27 depicts the 'ny2' SLOSH grid with average ground elevations (in ft.) for various cells in Lower Manhattan and its adjacent rivers and shores. Positive numbers (black) represent land cells, above sea level, and negative numbers (yellow) represent water cells, below sea level. Note particularly the cells in Lower Manhattan: some positive cells are partially in the Hudson and East Rivers.

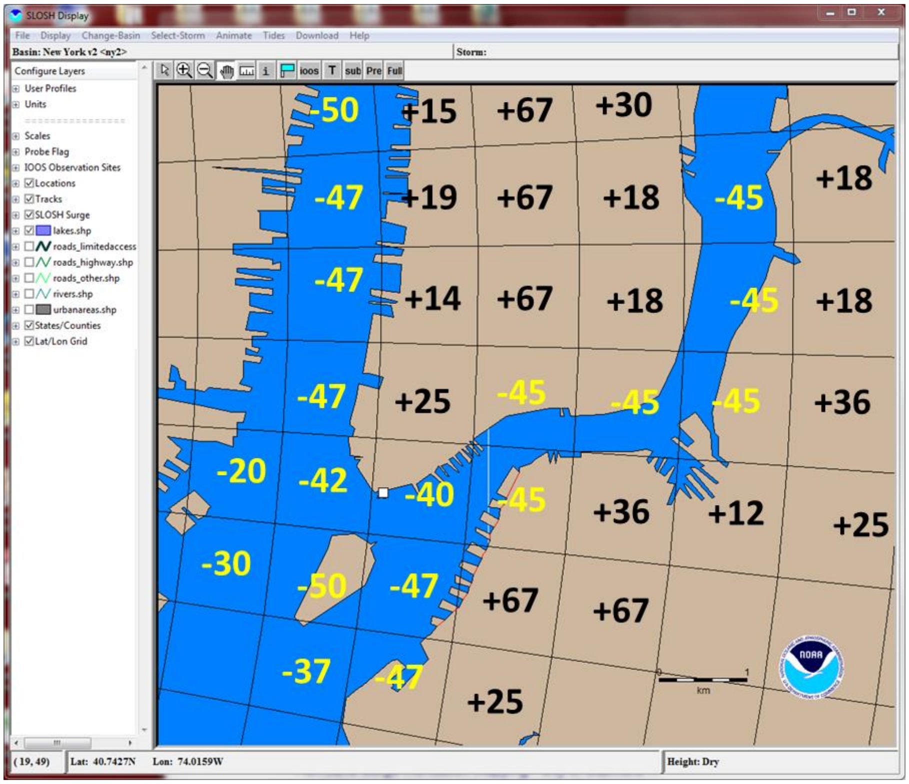


Figure 27. SLOSH 'ny2' basin, with elevations

In addition to the SLOSH model for stillwater elevation, CSM also embeds the SWAN model for wind-blown waves. The ocean surface parameters, stillwater elevation (from SLOSH) and windblown wave heights (form SWAN), are interpolated back to rectangular grids – referred to as "grid float files", or causally the "surge file(s)" – for calculation of flood depths in HAZUS proper. These grids have 0.003x0.003 degree resolution, about 0.25x33 km at the latitude of NYC (~41° N.); consequently the underlying DEM of the land surface is relatively unimportant, as demonstrated by the results in the baseline case for NYC (Figure 22).

Figure 28 shows the surge file (grey blocks) and the SLOSH/SWAN cells (green dots at corners) for the same area and moment in time as Figure 27. There appears to be an error in the radial-to-rectangular grid interpolation, most obvious in the lower East side by the East River (boxed in blue): it is not credible for water to be deeper near shore and shallower in the river. Similar errors appear along the West side piers, opposite Midtown. The reason for these errors is unclear, although they always occur in conjunction with protrusions from the land, i.e. the spurious "dagger" into the East River and the West side "piers". It seems that any block in the grid file that contains land is exempted from interpolation.

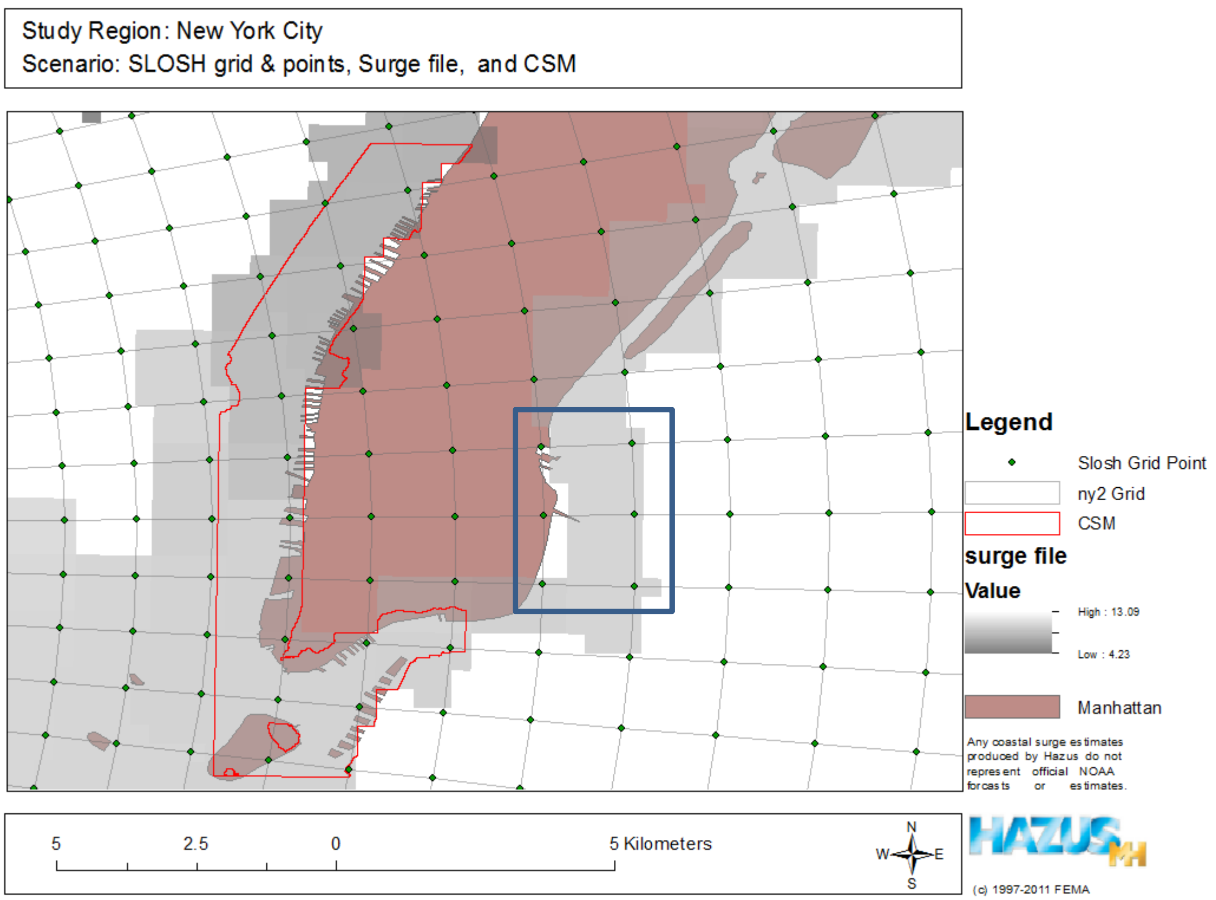


Figure 28. CSM with SLOSH surge (grid & points)

The fundamental problem, however, in CSM's prediction for NYC is the restricted area being modeled (Figure 28, thin red outline), which excludes essentially all of the East

River. The HAZUS Coastal Flood Model, on which CSM is based, automatically derives a default shoreline from TIGER data, which can be modified by DEM-based transects for open coasts. However, in the CSM, the transect modification is unavailable, and it is also impossible to multiple shoreline segments beyond the default. For NYC in particular, the default shoreline curiously cuts through both the West side piers and the Brooklyn docks; it also excludes the East River, where heavy flooding occurred in fact. CSM under-predictions for Manhattan are thus explained.

Similarly, the under-predictions for Staten Island primarily appear on its West shore, Arthur Kill, a tidal strait in between New Jersey and Staten Island. Arthur Kill is not wide enough and deep enough to be considered an active shoreline or transect for the CSM.

Overall, SLOSH did a better prediction of Hurricane Sandy storm tide than CSM. The erratic results obtained with CSM for the five boroughs, under-predictions for Manhattan and Staten Island and over-predictions for Brooklyn, Bronx, and Queens are particularly disturbing. Knowing that a prediction is biased in some way is workable; not knowing if it is biased, and in what way, is not.

Chapter 6: Conclusion

It is clear that a solid method of storm tide/surge prediction is essential in preparing for future, inevitable hurricanes and associated flooding in New York / New Jersey region. In particular, New York City has vast underground utility systems, particularly for electrical distribution, that are susceptible to flood events. Hurricanes Irene and Sandy proved that storm tide/surge events could cause major, extended losses – not just of electricity but of other services (gas, steam, water) as well.

Because electricity is essential both to initial emergency response and to recovery from hurricanes, a power company's major assets, specifically its generating stations and distribution substations, are amongst the "consumers" for accurate flood predictions. Even without electrical outages, the economic burden of storm surge is devastating and it can take weeks, months, or even years (as with Katrina and Sandy) for the community to fully recover from a hurricane event.

Reciprocally, utility companies in particular would benefit from better flood prediction, as the cost of protecting their assets in flood-prone areas is very large. Severe storms, including Hurricanes Irene and Sandy, have cost Con Ed $600 million in damage recovery through 2013. After Sandy, Con Ed began to invest an additional $1 billion over a four-year period (Con Ed 2013) to mitigate future storm damages.

It is an engineering practice to build in a safety factor (SF) of 10% above the actual structural "load", here the expectable floodwater depth. For electrical distribution facilities within the NYC area the safety factor is +2 ft. above the highest estimation of future flooding. If flood predictions can be in error by +/- 5ft, this error factor is meaningless. If the possibility of an outsized flooding is ignored, however, the result can be enormously expensive recovery and repair, as occurred with the Con Ed generating station at E. 13th street, which was flooded by Hurricane Sandy at least 3 ft. above the high-water experienced in Hurricane Irene, just a year earlier (Con Ed 2013; City of New York 2013). The result was much more expensive repair of the station as well as protracted electrical outage for ratepayers.

Of necessity, electrical power stations along with supporting railway and dock facilities are located near or actually in the floodplain (City of New York 2014). These cannot be relocated, only mitigated in place. A solid prediction of flood risks and hence flood mitigations needed are essential to protecting them.

For emergency management purposes, only SLOSH and HAZUS CSM are available prior to a hurricane event. Hurricane mitigation plans, specifically for storm hardening, must be based on such models. NOAA and FEMA personnel are well versed in the operations of their respective models and can help emergency managers with using them. However, the models must give correct results.

Regrettably, despite its more extensive modeling capabilities for wind-blown waves in particular, the CSM in HAZUS 2.1 is currently less accurate than SLOSH. However, FEMA has engaged on HAZUS "modernization" (FEMA 2015) which has the potential to make it better in many aspects. A major impetus for this effort is to allow HAZUS to run in ArcGIS v10.2[18]. On the list of modernizations for CSM are to incorporate the higher-resolution (0.5x0.5 km) 'ny3' vs. 'ny2' SLOSH grid (Figure 29). If internal arrays are limiting CSM to

[18] ArcGIS v10.3, released in December 2014, may be accommodated as well.

small study areas, viz. single boroughs of NYC, they should be expanded. The interpolation errors from the SLOSH/SWAN grids to the HAZUS FL "surge files" obviously need to be fixed. Finally, the "coastline" in CSM should be made more visible, and easily adjustable.

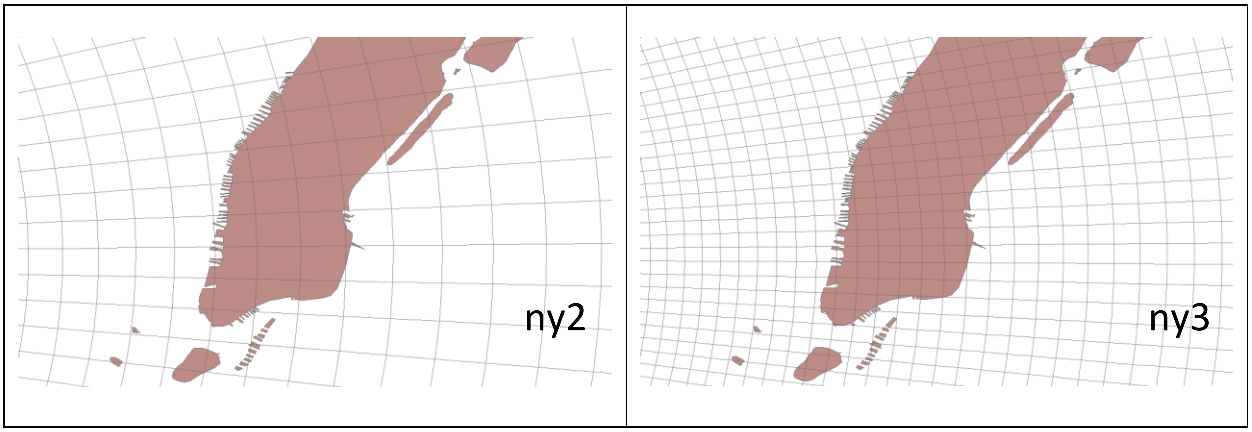


Figure 29. SLOSH 'ny2' vs. 'ny3' basins

Although not part of this study, CSM also has the ability to estimate flood-related damages to so-called essential facilities (hospitals, police and fire stations), lifelines (gas, water, sewer), and transportation systems, all of which are critical to response and recovery in an emergency. Other authors (ABS Consulting 2009; R.M. Towill Corp. / URS Group Inc. Joint Venture 2010; McDonald 2015) have worked extensively in validating these areas.

It will be useful to repeat this study with the new CSM, when available, to validate the improvements that are made.

Appendices

Appendix A. MOTF Overview & HSIA documentation

https://content.femadata.com/MOTF/Hurricane_Sandy/

https://content.femadata.com/MOTF/Hurricane_Sandy/FEMA%20MOTF-Hurricane%20Sandy%20Products%20ReadME%20FINAL.pdf

FEMA Modeling Task Force (MOTF)
Hurricane Sandy Impact Analysis

The FEMA Modeling Task Force (MOTF) is a group of modeling and risk analyst experts from FEMA Regions VIII (Denver) and IV (Atlanta) that may be activated by the FEMA NRCC for Level 1 events in support of disaster response operations. The group consists of individuals with experience in multi-hazard loss modeling and impact assessments, including earthquakes, hurricanes, riverine and coastal floods (surges, tsunamis), winter storms and others. The MOTF plays an important role in coordinating hazard and modeling information from a variety of sources, including other federal agencies, universities, the National Labs, and State and local agencies, to develop consensus for best estimates of impacts before, during, and after events. The MOTF integrates observed information throughout disasters to "ground-truth," verify, and enhance impact assessments.

FEMA MOTF E-mail: FEMA-MOTF@fema.dhs.gov

FEMA MOTF FTP Site: http://184.72.33.183/GISData/MOTF/Hurricane%20Sandy/

Storm Surge Products

Below are links to the FEMA MOTF FTP Site for the latest Hurricane Sandy storm surge data (Final High Resolution – Field-Verified). All products are created from field-verified High Water Marks (HWMs) and Storm Surge Sensor data from the USGS through 14-February 2013. HWMs and Surge Sensor data are used to interpolate a water surface elevation, then subtracted from the best available Digital Elevation Model (DEM), to create a depth grid and surge boundary by state.

State:	**New Jersey**
HWM:	Final Version – February 14, 2013
Projection:	NAD83 (Geographic)
Horizontal:	3-meter (USGS 1/9 Arc-Second NED)
Vertical:	Feet (water depth above ground, NAVD88)
Files:	ESRI Grid (raster, depths)/Shapefile (vector, flood extent)
FTP Link:	NJ_Feb14Final3mSurgeDataClipped.zip

State:	**New York**
HWM:	Final Version – February 14, 2013
Projection:	NAD 1983 State Plane New York Long Island FIPS 3104 Feet
Horizontal:	1-meter (NYCOEM DEM: Richmond, New York, Kings, Queens, Bronx) 3-meter (NYOEM DEM: Bronx, Westchester, Nassau, Suffolk, Queens, Kings, New York, Richmond)
Vertical:	Feet (water depth above ground, NAVD88)
Files:	ESRI Grid (raster, depths)/Shapefile (vector, flood extent)
FTP Link:	NY_Feb14Final3mSurgeDataClipped.zip or NYC_Feb14Final1mSurgeDataClipped.zip

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State:	**Connecticut**
HWM:	Final Version – February 14, 2013
Projection:	NAD83 (Geographic)
Horizontal:	3-meter (USACE DEM)
Vertical:	Feet (water depth above ground, NAVD88)
Files:	ESRI Grid (raster, depths)/Shapefile (vector, flood extent)
FTP Link:	CT_Feb14Final3mSurgeDataClipped.zip

State:	**Rhode Island**
HWM:	Final Version – February 14, 2013
Projection:	NAD83 (Geographic)
Horizontal:	3-meter (USGS 1/9 Arc-Second NED)
Vertical:	Feet (water depth above ground, NAVD88)
Files:	ESRI Grid (raster, depths)/Shapefile (vector, flood extent)
FTP Link:	RI_Feb14Final3mSurgeDataClipped.zip

Hurricane Sandy Composite Surge/Precipitation/Wind Map: County Impact Assessment

A composite of surge, wind, precipitation and snow impacts are used to assess impacts for each County. Surge is the primary driver of the severe impacts as a result of Hurricane Sandy and the relative impact assessment is summarized as follows:

Very High:	Greater Than 10,000 of County Population Exposed to Surge
High:	500 - 10,000 of County Population Exposed to Surge, or Modeled Wind Damages > $100M, or High Precipitation (>8")
Moderate:	100 - 500 of County Population Exposed to Surge, or Modeled Wind Damages $10 - $100M, or Medium Precipitation (4" to 8") (Yellow)
Low:	No Surge Impacts or Modeled Wind Damages < $10M, or Low Precipitation (<4")

Population and Household Exposure values are derived by area weighting using the high resolution field-verified surge extents for New Jersey, New York, Connecticut, and Rhode Island and 2010 census blocks. All other coastal state exposure numbers are based off of the interim low resolution surge extent and 2010 census blocks.

Critical Infrastructure Exposure values are derived by a point based intersection method between the infrastructure and the surge extent. The high resolution field-verified surge extent was used for New Jersey, New York, Connecticut, and Rhode Island, while the interim low resolution surge extent was used in North Carolina, Virginia, Maryland, Delaware, and Massachusetts. Critical infrastructure includes:

1. **Police Stations** – Homeland infrastructure geospatial data inventory assembled by NGA in partnership with the Department of Homeland Security (DHS), 2012
2. **Fire Stations** – Homeland infrastructure geospatial data inventory assembled by NGA in partnership with the Department of Homeland Security (DHS), 2012 and New Jersey Division of Fire Safety (NJ only)
3. **Schools** – Homeland infrastructure geospatial data inventory assembled by NGA in partnership with the Department of Homeland Security (DHS), 2012, New York State Department of Education (New York City only) and New Jersey Department of Education (NJ only)
4. **Hospitals** – Homeland infrastructure geospatial data inventory assembled by NGA in partnership with the Department of Homeland Security (DHS), 2012, New Jersey Department of Health (NJ only)
5. **Communication** – Homeland infrastructure geospatial data inventory assembled by NGA in partnership with the Department of Homeland Security (DHS), 2012 (data set includes AM Antennas, Antenna Structures Registrants, Cellular Towers, FM Antennas, Internet Exchange Points, Internet Service, Provider, IT Locations Portals, Land Mobile Broadcast Service, Land Mobile Commercial Service, Land Mobile Private Service, Microwave Service Towers, Paging Service Transmitters, TV Digital Station Transmitters, and TV NTSC Station Transmitters)
6. **Chemical** – Homeland infrastructure geospatial data inventory assembled by NGA in partnership with the Department of Homeland Security (DHS), 2012 (data set includes Chemical Industries, Nitrogenous Fertilizer Plants, Pharmaceutical Manufacturing, and Phosphatic Fertilizer Plants)
7. **Waste Water** – Homeland infrastructure geospatial data inventory assembled by NGA in partnership with the Department of Homeland Security (DHS), 2012
8. **Electrical** – Homeland infrastructure geospatial data inventory assembled by NGA in partnership with the Department of Homeland Security (DHS), 2012 (data set includes Substations, Electrical Generation Plants, and Electric Generating Units)
9. **Oil and Gas** – Homeland infrastructure geospatial data inventory assembled by NGA in partnership with the Department of Homeland Security (DHS), 2012 (data set includes Biodiesel Plants, Lubricating Oils and Grease Plants, Natural Gas Processing Plants, and Oil Refineries)

In areas experiencing snow, precipitation ranks are defined as:

- <1" Low
- 1 - 2" Medium
- >2" High

In areas experiencing rain, precipitation ranks are defined as:

- <4" Low
- 4 - 8" Medium
- >8 High

Quantitative Precipitation Forecast (QPF) provided by NWS- HPC http://www.hpc.ncep.noaa.gov/qpf/qpf2.shtml (October 30, 2012) Wind and surge loss potential estimates are based on Hazus MH modeling. Potential Hazus wind losses are estimated using Advisory 34, 1700 EDT, October 30. Surge losses are based on FEMA’s Coastal Flood Loss Atlas.

Structure Debris Estimates

FEMA's Modeling Task Force utilized common methods from USACE and FEMA's Hazus program to develop debris estimates for Hurricane Sandy. The methodology is as follows:

1. Building damage levels were assigned as:
   a. Affected was defined as Total Full Verified Loss (FVL) >$0 to $5K, ImageCat imagery classified as Affected, or water depth >0 to 2 feet = 2.05 tons of debris per 1,000 sq feet based on IA Inspector estimate of Building Area
   b. Minor was defined as Total Full Verified Loss (FVL) >$5 to $17K, ImageCat imagery classified as Minor, or water depth >2 to 5 feet = 4.1 tons of debris per 1,000 sq feet based on IA Inspector estimate of Building Area
   c. Major was defined as Total Full Verified Loss (FVL) >$17K, ImageCat imagery classified as Major, or water depth >5 feet = 6.8 tons of debris per 1,000 sq feet based on IA Inspector estimate of Building Area
   d. Destroyed was defined as Destroyed = Yes by the IA inspector, or ImageCat imagery classified as Destroyed = (6.8 + 6.5 + 25) tons of debris per 1,000 sq feet based on IA Inspector estimate of Building Area
2. Based on: http://www.dep.state.fl.us/waste/quick_topics/publications/shw/recycling/candd/cdconversionformula.pdf we converted the demolition debris from tons to cubic yards using 1 cubic yard = 0.24 tons of debris.

FEMA Individual Assistance (IA) Household Inspection Damage Totals

When a household applies for Individual Assistance (IA), FEMA inspectors conduct field inspections of damaged properties. FEMA inspectors estimate the amount of Personal Property (contents) Full Verified Loss (FVL), Real Property (home) FVL and a sum of both is reported as Total FVL. The numbers of damaged applicant households are reported using the following categories from Total FVL.

Household damage classification:

1. **Affected** – Total Full Verified Loss (FVL) greater than $0 to $5,000
2. **Minor** – Total Full Verified Loss (FVL) $5,000 to $17,000
3. **Major** – Total Full Verified Loss (FVL) more than $17,000
4. **Destroyed** – If indicated by IA inspector

Customers without Power-State Summaries

Estimated customers without power summarized from Oak Ridge National Laboratories (ORNL) analyses of latest Advisory: https://pas.ornl.gov/geoserver.

USNG: Risk Matrix

This process involved identifying urban, suburban and rural 1x1km and 10x10km USNG grid cells, and attributing each with surge estimates, precipitation estimates, as well as Hazus estimated wind losses.

USGS Provisional Storm Tide/Storm Surge Data: http://bit.ly/Tu0NV8

In preparation for Hurricane Sandy, FEMA mission assigned the USGS through existing interagency partnership to have USGS technicians deploy non-transmitting storm tide sensors and wave height sensors along with real-time rapid deployment streamgages (RDGs) along the Northeast coast. Prior to, during, and following the storm, these sensors and gages provided real-time situational awareness of storm surge flooding. These sensors are currently being retrieved and surveyed.

The data will be made available on the FEMA MOTF GeoPlatform and the USGS Hurricane Sandy Mapper. The mapper provides location information, site photos and data for storm tide and inland flooding. Data will be made available as soon as possible following the storm.

For more information on the USGS efforts during Hurricane Sandy, please visit http://water.usgs.gov/floods/events/2012/sandy/.

FEMA Coastal Flood Loss Atlas (CFLA):

The FEMA Coastal Flood Loss Atlas is a compilation of risk, vulnerability, and loss estimations developed in conjunction with SLOSH Maximum of Maximum (MOM) hurricane storm surges for Category 1-5 storms. The SLOSH MOM data is a key component of local evacuation zone delineations, and is based on simulations of thousands of hypothetical storm intensities and approach directions (i.e. MOM do not represent any specific storm or track). Thus, the SLOSH MOMs provide a basis for maximum-of-maximum storm surge losses for mitigation planning and disaster operations planning. More information about the CFLA can be found on the FEMA GeoPlatform: http://bit.ly/PSO958.

Description Last Updated: 18-April 2013 1600 MDT

FEMA Modeling Task Force (MOTF) Hurricane Sandy Products README Data file

FEMA GeoPlatform: http://www.fema.maps.arcgis.com
FEMA MOTF GeoPlatform: http://bit.ly/XvhSmA
FEMA MOTF E-mail: FEMA-MOTF@fema.dhs.gov
FEMA MOTF FTP Site (product download): http://184.72.33.183/GISData/MOTF/

11/12/2012 7:40 PM - CT_Nov07Interim10mSurgeData.zip: Our interim product based on mission assigned field verified USGS HWM data, USGS surge sensor data and 10 meter NED DEM, through 07 November 2012.

11/14/2012 7:55 PM - CT_Nov11Interim3mSurgeData.zip: Our interim high resolution product based on mission assigned field verified USGS HWM data, USGS surge sensor data and USACE 3 meter DEM, through 11 November 2012.

11/8/2012 2:08 AM - EastCoast_Nov01Sandy30mInterimSurgeData.zip: Our interim low resolution product based on mission assigned field verified USGS HWM data, USGS surge sensor data and USGS 30 meter DEM, through 01 November 2012. This datasets extent covers all of the east coast impacted by Hurricane Sandy.

11/8/2012 1:59 AM - InundatedSchools_Depth.zip: Our latest schools dataset with potential depth at structure information attached.

01/10/2013 12:38 AM - NJ_Interim3mSurgeData_unclipped.zip: Our interim product based on mission assigned field verified USGS HWM data, USGS surge sensor data and 3 meter NED DEM, through 11 November 2012. This dataset has not been clipped to the county boundaries.

11/12/2012 7:45 PM - NJ_Nov07Interim10mSurgeData.zip: Our interim product based on mission assigned field verified USGS HWM data, USGS surge sensor data and 10 meter NED DEM, through 07 November 2012.

11/15/2012 4:21 AM - NJ_Nov11Interim3mSurgeData.zip: Our interim product based on mission assigned field verified USGS HWM data, USGS surge sensor data and 3 meter NED DEM, through 11 November 2012.

11/8/2012 1:59 AM - NJNYCT_Oct31NoreasterSurgeData.zip: A low resolution (30 meter) estimate of surge inundations for the Nov 6, Nor' easter using NOAA's ET (ExtraTropical) surge model.

12/11/2012 11:42 PM - NY_3m_InterimHighRes_HWMSS1111_unclipped.zip: Our interim high resolution product based on mission assigned field verified USGS HWM data, USGS surge sensor data and NYOEM (New York Office of Emergency Management) 3 meter NY3 SLOSH Basin DEM, through 11 November 2012. This dataset has not been clipped to the county boundaries.

11/12/2012 7:40 PM - NY_Nov07Interim10mSurgeData.zip: Our interim product based on mission assigned field verified USGS HWM data, USGS surge sensor data and 10 meter NED DEM, through 07 November 2012.

11/15/2012 5:04 AM - NY_Nov11Interim3mSurgeData.zip: Our interim high resolution product based on mission assigned field verified USGS HWM data, USGS surge sensor data and NYOEM (New York Office of Emergency Management) 3 meter NY3 SLOSH Basin DEM, through 11 November 2012.

12/27/2012 1:03 AM - NYC_1m_InterimHighRes_HWMSS1111_unclipped.zip: Our interim high resolution product based on mission assigned field verified USGS HWM data, USGS surge sensor data and NYCOEM (New York City Office of Emergency Management) 1 meter NY3 SLOSH Basin DEM, through 11 November 2012. This dataset has not been clipped to the county boundaries

11/15/2012 5:29 AM - NYC_Nov11Interim1mSurgeData.zip: Our interim high resolution product based on mission assigned field verified USGS HWM data, USGS surge sensor data and NYCOEM (New York City Office of Emergency Management) 1 meter DEM, through 11 November 2012.

11/16/2012 12:51 AM - RI_Nov11Interim3mSurgeData.zip: Our interim product based on mission assigned field verified USGS HWM data, USGS surge sensor data and 3 meter NED DEM, through 11 November 2012.

11/30/2012 11:26 PM - WaterSurfaceElevations_HWM1111.zip: Interpolated water surface elevations based off of USGS high water marks and USGS surge sensor data through 11 November 2012.

01/14/2013 11:15 PM - ForecastSurgeBoundaries1029-1105.zip: This files contains two (2) surge low resolution forecast storm surge boundaries. 1. Advisory 29 (30-October 2012) Low Resolution – water surface elevations based on the NHC's SLOSH model and a low resolution (30 meter) DEM was used. 2. Interim Low Resolution Corrected 1105 – Our interim low resolution product based on USGS NED 30 meter DEMs and Preliminary HWM observations record under the USGS mission assignment.

02/25/2013 6:69 PM - HurricaneSandyImpactAnalysis_010913.zip: Our Hurricane Sandy Composite Surge/Precipitation/Wind Map: County Impact Assessment include updates of population, households, Individual Assistance applicants and NFIP policies exposed to surge, as well as estimates of $ losses for surge and wind.

04/18/2013 5:04 PM - CT_Feb14Final3mSurgeDataClipped.zip: Our final high resolution products (Storm Surge Boundary and Depth Grid) based on mission assigned field verified USGS HWM data, USGS surge sensor data through February 14, 2013 and USACE 3 meter DEM.

04/18/2013 6:06 PM - RI_ Feb14Final3mSurgeDataClipped.zip: Our final high resolution products (Storm Surge Boundary and Depth Grid) based on mission assigned field verified USGS HWM data, USGS surge sensor data through February 14, 2013 and 3 meter USGS NED DEM.

04/18/2013 5:45 PM - NY_ Feb14Final3mSurgeDataClipped.zip: Our final high resolution products (Storm Surge Boundary and Depth Grid) based on mission assigned field verified USGS HWM data, USGS surge sensor data through February 14, 2013 and NYOEM (New York Office of Emergency Management) 3 meter NY3 SLOSH Basin DEM.

4/18/2013 6:03 PM - NYC_ Feb14Final1mSurgeDataClipped.zip Our final high resolution products (Storm Surge Boundary and Depth Grid) based on mission assigned field verified USGS HWM data, USGS surge sensor data through February 14, 2013 and NYCOEM (New York City Office of Emergency Management) 1 meter NY3 SLOSH Basin DEM.

04/18/2013 5:30 PM - NJ_ Feb14Final3mSurgeDataClipped.zip: Our final high resolution products (Storm Surge Boundary and Depth Grid) based on mission assigned field verified USGS HWM data, USGS surge sensor data through February 14, 2013 and 3 meter USGS NED DEM.

Access and Use Constraints

SURGE IMPACT ASSESSMENTS ARE BASED ON WORST CASE SCENARIOS USING MAXIMUM OF MAXIMUM (MOM) HURRICANE STORM SURGE PER SAFFIR-SIMPSON HURRICANE CATEGORY, WHICH MAY RESULT IN CONSERVATIVE ESTIMATES OF IMPACTS. Please note that no single hurricane will produce the regional flooding depicted in the MOMs or the loss estimations, risk and vulnerability assessments and potential impacts. Instead, the product is intended to estimate the worst case high water values for particular locations for hurricane evacuation planning. Official forecasts and products are provided by the NOAA National Hurricane Center for specific storms based on official watches or warnings, loss estimation and potential impact assessments may be refined and updated as necessary.

Loss estimates or totals only reflect data for affected census tracts/blocks included in the study regions. The estimates of social and economic impacts contained in these reports were produced using Hazus loss estimation methodology software which is based on current scientific and engineering knowledge. There are uncertainties inherent in any loss estimation, hurricane modeling (including storm surge modeling), ground elevation data, and methodologies and techniques. Therefore, there may be significant differences between the modeled results and the actual social and economic losses following a specific storm event. These results can be improved by using enhanced inventory, geotechnical, or observed meteorological data.

User assumes all risk related to the use of this data. FEMA provides this data "as is" and disclaims any and all warranties, whether express or implied, including (without limitation) any implied warranties of merchantability or fitness for a particular purpose, and there are no express or implied guarantees of accuracy of the data. In no event will FEMA or any other Federal Agency be liable to you or to any third party for any direct, indirect, incidental, consequential, special, or exemplary damages or lost profit resulting from any use or misuse of this data.

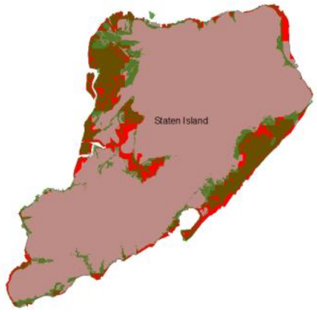
FEMA-MOTF Depth Grid Overview

1. **Advisory 25 - Oct. 28, 2012 (ADV25.zip)** – This was the first set of depth grids that were produced by the MOTF for Hurricane Sandy. Depth grids were produced for coastal areas of North Carolina, Virginia, Maryland, Delaware, New Jersey, New York, Connecticut, Rhode Island, Massachusetts, New Hampshire, and Maine at a 30 meter resolution. The water surface elevation was based off of the National Hurricane Centers Advisory 25 Probabilistic Surge forecast. This advisory corresponds with Hurricane Sandy's maximum intensity.
2. **Advisory 29 - Oct. 29, 2012 (ADV29.zip)** - This was the set of depth grids that were produced by the MOTF for Hurricane Sandy. Depth grids were produced for coastal areas of North Carolina, Virginia, Maryland, Delaware, New Jersey, New York, Connecticut, Rhode Island, Massachusetts, New Hampshire, and Maine at a 30 meter resolution. The water surface elevation was based off of the National Hurricane Centers Advisory 29 Probabilistic Surge forecast. This advisory corresponds with Hurricane Sandy's landfall in New Jersey.
3. **National Hurricane Center's Hindcast - Oct. 31, 2012 (SLOSH_Hindcast.zip)** – This set of depth grids were produced for New Jersey, New York, and Connecticut for Hurricane Sandy, were based off of the National Hurricane Center's Hindcast, or their best model produced storm surge inundation. These depth grids have a 30 meter resolution.
4. **Interim 30 Meter Surge - Nov. 1, 2012 (Interim30m.zip)** – This composite depth grid incorporates data from the NHC's Hindcast, Advisory 29, and preliminary field-verified high water marks. Depth grids have a 30 meter resolution, and were produced for North Carolina, Virginia, Maryland, Delaware, New Jersey, New York, Connecticut, Rhode Island, and Massachusetts.
5. **Preliminary 10 Meter Field-Verified - Nov. 7, 2012 (HWM1107_10meter.zip)** – Depth grids were produced using a preliminary version of the USGS field-verified high water marks, mission assigned by FEMA. The 10 meter resolution depth grids were produced for New York, New Jersey, and Connecticut.
6. **Interim 3 Meter Field-Verified - Nov. 11, 2012 (HWM1111_3meter folder)** - Depth grids were produced using a preliminary version of the USGS field-verified high water marks, mission assigned by FEMA. These high resolution (3m) depth grids were produced for New York, New Jersey, Connecticut, and Rhode Island, as well as a specialized very high resolution New York City depth grid (1m).
7. **Final 3 Meter Field-Verified - Feb. 14, 2013 (HWM0214_3meter folder)** - Depth grids were produced using the final version of the USGS field-verified high water marks, mission assigned by FEMA. These high resolution (3m) depth grids were produced for New York, New Jersey, Connecticut, and Rhode Island, as well as a specialized very high resolution New York City depth grid (1m).

Appendix B. Flood Analyses for Individual Borough - CSM vs. SLOSH and HSIA

 CSM no-waves vs SLOSH – 1.17 mi^2 + 2.54 mi^2	 CSM no-waves vs HSIA – 1.17 mi^2 + 2.49 mi^2
 CSM near-shore waves vs SLOSH – 1.43 mi^2 + 2.54 mi^2	 CSM near-shore waves vs HSIA –1.43 mi^2 + 2.49 mi^2
 CSM deep-water & near-shore vs SLOSH – 1.46 mi^2 + 2.54 mi^2	 CSM deep-water & near-shore vs HSIA – 1.46 mi^2 + 2.49 mi^2

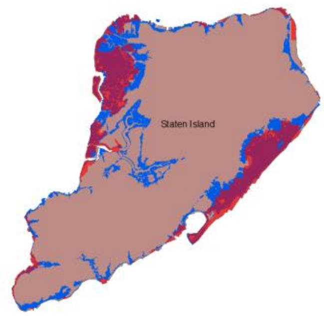
Figure B-1. Manhattan



HAZUS no-waves vs SLOSH – 7.04 mi^2 + 9.95 mi^2

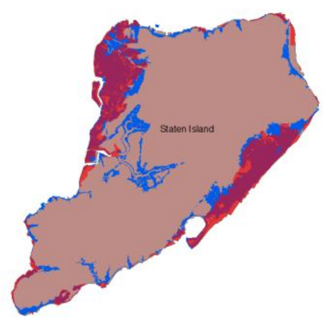
HAZUS no-waves vs HSIA– 7.04 mi^2 + 11.09 mi^2

HAZUS near-shore waves vs SLOSH – 7.56 mi^2 + 9.95 mi^2



HAZUS near-shore waves +HSIA – 7.56 mi^2 + 11.09 mi^2

HAZUS deep-water & near-shore vs SLOSH – 8.89 mi^2 + 9.95 mi^2



HAZUS deep-water & near-shore vs HSIA – 8.89 mi^2 + 11.09 mi^2

Figure B-2. Staten Island

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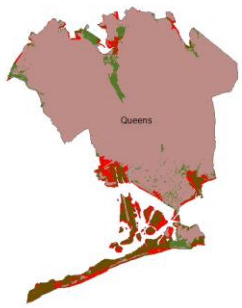
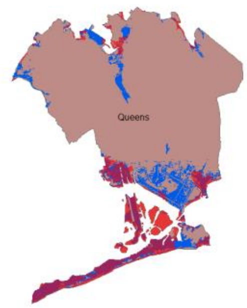
<td>

HAZUS no-waves vs SLOSH – 13.82 mi^2 + 13.12 mi^2</td>
<td>

HAZUS no-waves vs HSIA – 13.82 mi^2 + 16.59 mi^2</td>
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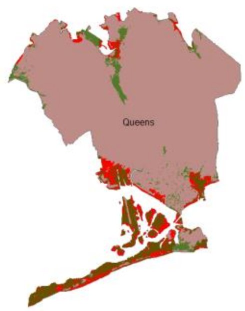
<td>

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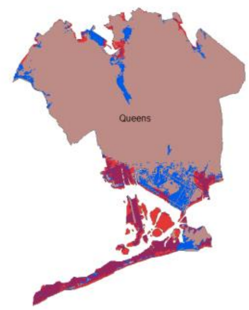
<td>

HAZUS near-shore waves vs HSIA – 14.56 mi^2 + 16.59 mi^2</td>
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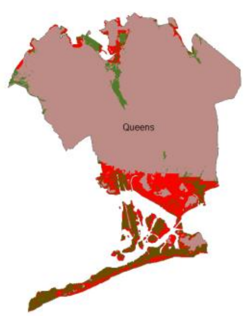
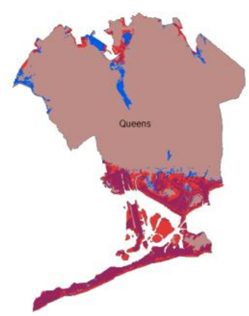
<td>

HAZUS deep-water & near-shore vs SLOSH – 21.94 mi^2 + 13.12 mi^2</td>
<td>

HAZUS deep-water & near-shore vs HSIA – 21.94 mi^2 + 16.59 mi^2</td>
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Figure B-3. Queens

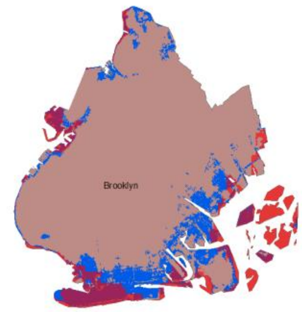
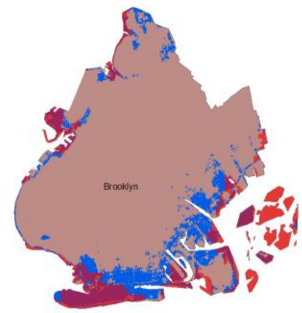
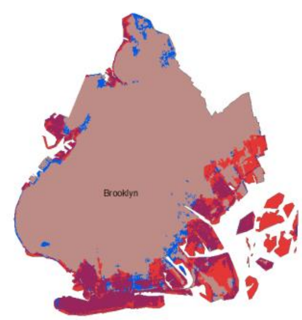
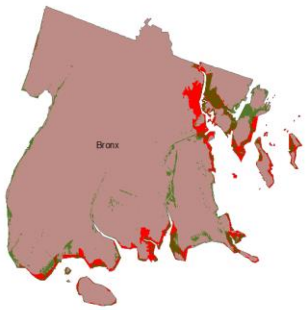
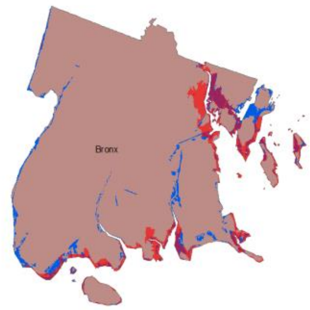
 10m Brooklyn HAZUS no-waves +SLOSH (graphic) – 8.60 mi² + 8.89 mi²	 10m Brooklyn HAZUS no-waves +HSIA (graphic) – 8.60 mi² + 11.63 mi²
 10m Brooklyn HAZUS near-shore waves +SLOSH (graphic) – 9.01 mi² + 8.89 mi²	 10m Brooklyn HAZUS near-shore waves +HSIA (graphic) –9.01 mi² + 11.63 mi²
 10m Brooklyn HAZUS deep-water & near-shore +SLOSH (graphic) – 17.24 mi² + 8.89 mi²	 10m Brooklyn HAZUS deep-water & near-shore +HSIA (graphic) – 17.24 mi² + 11.63 mi²

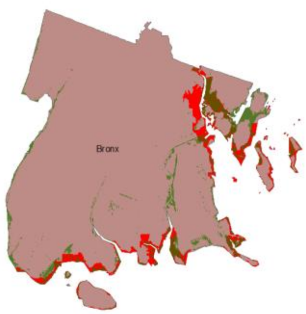
Figure B-4. Brooklyn



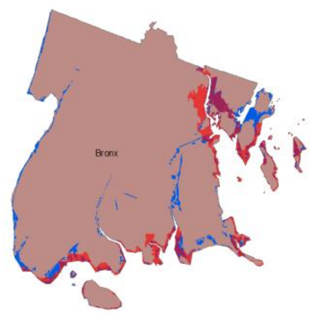
10m Bronx HAZUS no-waves +SLOSH (graphic) – 2.98 mi^2 + 2.58 mi^2



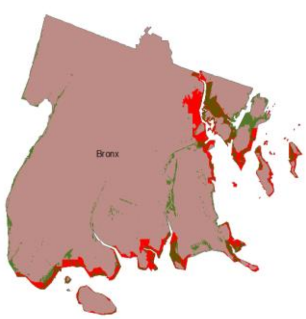
10m Bronx HAZUS no-waves +HSIA (graphic) – 2.98 mi^2 + 2.54 mi^2



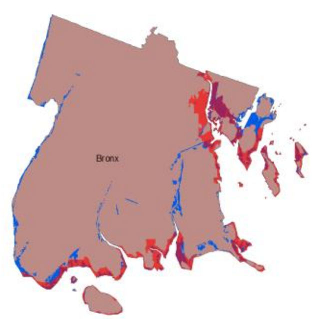
10m Bronx HAZUS near-shore waves +SLOSH (graphic) – 2.98 mi^2 + 2.58 mi^2



10m Bronx HAZUS near-shore waves +HSIA (graphic) –2.98 mi^2 + 2.54 mi^2



10m Bronx HAZUS deep-water & near-shore +SLOSH (graphic) – 3.36 mi^2 + 2.58 mi^2



10m Bronx HAZUS deep-water & near-shore +HSIA (graphic) – 3.36 mi^2 + 2.54 mi^2

Figure B-5. Bronx

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