TR-2933

Street Scale Modeling of Storm Surge Inundation along the New Jersey Hudson River Waterfront

Alan Blumberg, Thomas Herrington, Larry Yin, and Nickitas Georgas

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Executive Summary

A new, high-resolution, hydrodynamic model that encompasses the urban coastal waters and coastal flood plain of New Jersey along the Hudson River waterfront opposite New York City has been developed and validated. 3.1m model grid resolution combined with high-resolution LiDAR elevation datasets permit a street by street focus to inundation modeling. The waterfront inundation model (NJWIM) is a sECOM model application, nested into a larger New York Bight sECOM model (NYHOPS), itself nested to an even larger Northwest Atlantic sECOM model (SNAP). Robust wetting and drying of land in the model physics provides for the dynamic prediction of flood elevations and velocities across land features during inundation events. NJWIM was forced by water levels from the NYHOPS hindcast of Hurricane Sandy. The hindcast utilized Sandy over ocean wind field and atmospheric pressure data, offshore wave and tidal boundary forcing, atmospheric heat fluxes, and interior streamflow data. Validation against 56 water marks and 16 edgemarks provided via the USGS and through an extensive crowd sourcing effort consisting of photographs, videos and personal stories shows that the model is capable of computing overland water elevations quite accurately. The correlation coefficient (R^2) between the water mark observations and the model results is 0.92. The standard deviation of the residual error is 0.07 m. The simulated water levels at 78% of the data measurement locations have less than 20% error. Water levels in excess of 2 m above ground were predicted quite well.

Comparisons to the 16 flood edgemarks suggest that the model was able to reproduce flood extent to within 20 m. This remarkable agreement between the model results and the observations is due to the robust wetting and drying physics of sECOM, the high resolution, accurate digital terrain map assembled for this study, the fine resolution used in the model and the high fidelity forcing functions brought to this study. Because the model was able to capture the spatial and temporal variation of water levels in the region observed during Hurricane Sandy, it was used to identify the flood pathways and suggest where flood preventing interventions could be built. The model is now being used to assess various flood preventing interventions and could serve as part of a forecast system for the next meteorological event.

Assessment of the flood pathways revealed that a majority of the inundation experienced along the Hudson River waterfront of Hudson County can be attributed to three main entry points – the Morris and Long Slip Canals, and Weehawken Cove. Constructing flood mitigation structures at these critical entrance points should eliminate the majority of storm surge related flooding experienced in Hudson County during Hurricane Sandy. Model simulations with flood interventions located at the north and south side of Hoboken, at Long Slip Canal, at Morris Canal, and along the Jersey City Hudson River were examined individually and in combination. Results indicate the all storm surge flooding can be eliminated in Hoboken and northwest Jersey City through the construction of north and south floodwalls, and the filling of the Long Slip Canal. The Morris Canal floodwall analysis indicates that a significantly greater volume of floodwater will enter Jersey City from the south across Liberty State Park than from the Canal itself. An extension of the floodwall along the canal west to the Hudson County Light Rail line is required to prevent the flooding of the southwest portion of Jersey City.

Contents

Introduction

Coastal storms are among the world's most costly and deadly disasters, with strong winds, floodwater inundation, and coastal erosion capable of damaging and disabling infrastructure. Increased damage from coastal flooding is one of the most certain impacts of the future with storm surges coming on top of rising sea levels, and with the potential for intensified storms and increased rainfall in the Northeast United States [*Walsh et al. 2014*]. Sea level rise is expected to accelerate over the 21st Century, primarily due to increasing expansion of warming seawater and accelerated melting of land-based ice sheets. A conservative estimate of 30-60cm for New York City (NYC) by 2080 will change a 100-year flood event to a 30-year flood event; the latest localized projections show a 25% chance of sea level rising more than a meter over this period [*Horton et al. submitted*]. Storm climatology changes can have a similarly large impact of reducing return periods [*Lin et al.* 2012], and recent evidence suggests this has been occurring and will continue over the next several decades in the North Atlantic due to both regional reductions in aerosol emissions [*Villarini and Vecchi* 2012] and atmospheric warming [*Grinsted et al.* 2013].

Hundreds of thousands of Northern New Jersey residents live on land within range of a 5 m hurricane storm tide, and – with peak water levels of 3.5-4.5 m above mean sea level in Raritan Bay and Newark Bay – Hurricane Sandy flooded many of these neighborhoods. Hurricanes have made direct hits on the New Jersey - New York City metropolitan area four times over the last 400 years, including 1693, 1788, 1821, and 1893, and will likely do so again [*Scileppi and Donnelly* 2007]. Moreover, sea level rise of 1 m will mean that a severe extra-tropical storm (a "nor'easter") will lead to flooding levels nearly as bad as Sandy or the historic hurricanes; The worst nor'easters (e.g. 1992) have an annual probability of occurrence of one in twenty and cause maximum water levels of about 2.0-2.5 m above normal [*Orton et al.* 2012a].

The NJ Hudson River Waterfront cities of Hoboken, Jersey City, Weehawken and Bayonne (Hudson Waterfront) are among the most populous cities in NJ. These four cities are located on the smallest footprint of any of the top 100 most populous cities in the United States. They lie across the Hudson River from Lower Manhattan and are bordered by water on two sides – with the Hudson River and Upper New York Bay on the east, and the Hackensack River and Newark Bay on the west (Figure 1). They are served by the densest mass transit systems in the State of New Jersey, and are home to the 12th largest downtown in the United States. The cities have much of their land within the new draft FEMA 1%-flooding-probability-per-year (“100-year”) flood zone, yet many of the buildings are high rises, with steel beams into the bedrock or attached row houses and brownstones that generally cannot be raised. As a result, the Hudson waterfront is an excellent example of an urban coastal region that is badly threatened by sea level rise and storm surges.

During Hurricane Sandy, all four cities were severely impacted. For example, in Jersey City about 75% of the population lost power, with many residents not having gas and electricity restored for more than a week. 2,500 residents sought shelter due to lack of power, water, and heat. With 50,000 people living in one square mile, Hoboken is the fourth most densely populated municipality in the US. Many of its residents were without power for nearly two weeks after the storm. Sandy crippled the Port Authority Trans-Hudson line (PATH), a 24-hour subway which last year ferried 76.6 million passengers between Manhattan and New Jersey. The entire system was out for two weeks. A link to the World Trade Center was out for four weeks, and the Hoboken line restored service months later. All repairs and projected costs to the PATH system are expected to ultimately exceed $700 million. The costs associated with Hurricane Sandy in Jersey City alone could easily approach $100 million, and the cost associated with damages to city-owned property and equipment alone is estimated at approximately $23 million.

Here, a modeling analysis is carried out with the overriding goal of predicting the inundation likely to occur from a storm surge event. An accurate model will improve the capacity of Hoboken, Jersey City, Weehawken and Bayonne to adapt to coastal flooding from storms and a rising sea level. It is important that we consider these four adjoining cities together in the analysis because it is likely that a protective measure in one city may adversely affect its neighboring city.

Figure 1. The Hudson River Waterfront Study Area

Literature Review

The simplest flood model in use today is “bathtubbing” – a method in which flood waters are assumed to spread out horizontally to cover all land areas of equal or lower elevation. A more advanced version of bathtubbing considers hydraulic connectivity (*NOAA Costal Services Center 2012*), removing unrealistic pools in the inner low land areas caused by blindly comparing the heights between the ground and the extended water surface.

Hydrodynamic inundation models, although more complex and more costly in computation, are able to capture the flooding/drying physics and yield more meaningful results.

The Wetting and Drying (WD) algorithm is one of the most important components of a storm surge model. The algorithm used here is based on the Princeton Ocean Model (POM) of Blumberg and Mellor (1987) as modified by Oey (2006). The algorithm, dynamically determines whether a grid is wet or dry and accordingly includes or removes it into or from computation. It balances the trade-offs among computational costs, physical authenticity and realistic results.

Modeling inundation in coastal cities and towns has been an attractive task due to the comparatively higher importance imparted by population density and social functions. Several studies by Villanueva and Wright (2006), Fewtrell et al. (2008), Sanders and Gallegos (2008), Schubert et al. (2008), Gallegos et al. (2009), Gallien and Sanders (2011), Schubert and Sanders (2012), Gallien et al. (2013), and Wang et al. (2014) have involved applications for urban settings using high-resolution LiDAR and local elevation survey data. As overland friction is important, Wang and Christensen (1986) have used models to determine the values of Manning's *n* friction coefficient for various building sizes, densities and configurations.

Two recent studies highlight the progress in simulating real cases. The Jan 10, 2005 flood event in Newport Beach, CA was simulated (Gallien et al. 2013) by a regional model CoSMoS (Barnard et al. 2009) fusing a local Godunov-type finite volume model BreZo, which was developed on the basis of a series of papers (Begnudelli and Sanders 2006, 2007; Sanders 2007, 2008; Begnudelli and Bradford 2008; Sanders and Gallegos 2008). The model grid is unstructured, consisting of about 500,000 cells, with various resolutions ranging from 3.5 m to 300 m strategically assigned to different parts of the domain; its bathymetric and topographic data were from LiDAR and Real Time Kinematic GPS (RTK-GPS) surveys.

The other real case simulation was the inundation model of New York City during Hurricane Sandy (Wang et al. 2014). They used a regional model, SELFE (Zhang and Baptista 2008) as forcing for a local scale inundation model, UnTRIM, which was based on a series of papers by Casulli (Casulli and Cheng 1992; Casulli and Walters 2000; Casulli 2009; Casulli and Stelling 2011). The UnTRIM WD algorithm is of the element removal type; its model grid consists of a 200m-by-200m-resolution square base grid with embedded bathtubbing 5m-by-5m-resolution subgrids. Bathymetry was from NOAA surveys and coastal relief models and the land topography was from USGS LiDAR surveys and the Open NYC Building Inventory.

In general, the methods to validate flood inundation models are horizontal inundation area comparison, High Water Mark (HWM) comparisons, tidal gauge time series comparison, and time-stamped water mark comparisons. As Medeiros and Hagen (2013) described in their paper, quality data are scarce. For the Newport Beach, CA model, Gallien et al. (2013) used 85 digital photographs in combination with eyewitness accounts to determine the flood extent. Wang et al. (2014) used primarily USGS maps based on their Hurricane Sandy Mapper to make comparisons. The comparisons are only somewhat useful because those maps are not very accurate.

New Jersey Waterfront Inundation Modeling System

The New Jersey Waterfront Inundation Model (NJWIM) is an sECOM model application, nested into the larger New York Bight sECOM model (NYHOPS), which is itself nested to an even larger Northwest Atlantic sECOM model (SNAP, Figure 1). sECOM (Blumberg *et al* 1999, Georgas and Blumberg 2010) is a three dimensional, free surface, hydrostatic, primitive equation estuarine and coastal ocean circulation model. Prognostic variables include water level, 3D circulation fields (currents, temperature, salinity, density, viscosity, and diffusivity), significant wave height and period. It is a successor model to the ECOM/POM combination that is in use by almost 3000 research groups around the world with over 1000 papers having been published with them as the modeling engine (Blumberg and Mellor 1987). Its operational forecast application to the New York / New Jersey Harbor Estuary and surrounding waters (NYHOPS) is found online (http://www.stevens.edu/maritimeforecast) dating back to 2006 (Bruno *et al* 2006, Fan *et al* 2006, Georgas *et al* 2009a, Georgas 2010), and includes forecasts of chromophoric dissolved organic matter and associated aquatic optical properties through coupling to an RCA-based water quality model (Georgas *et al* 2009b).

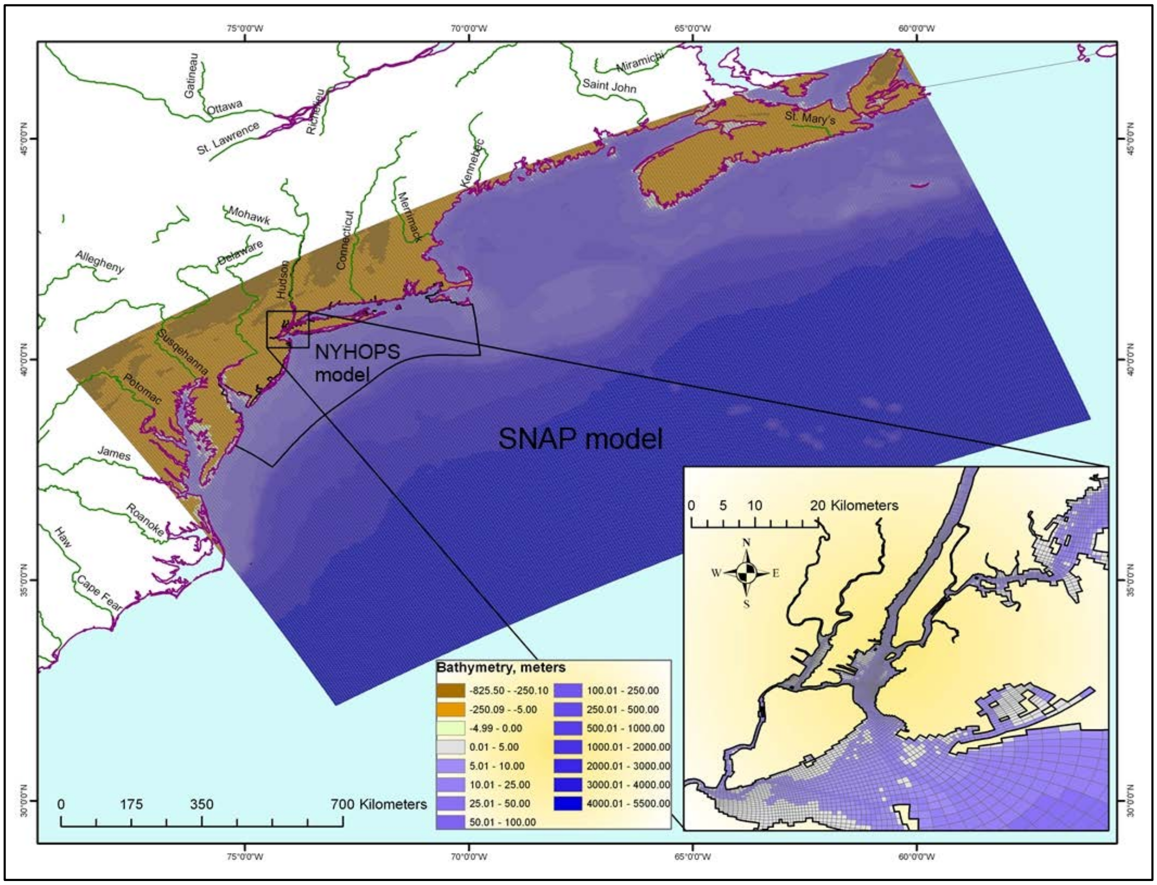


Figure 2. Stevens Northwest Atlantic Prediction (SNAP) model domain, showing the New York Harbor Observing and Prediction System (NYHOPS) model nested within it. The New Jersey Waterfront Inundation Model is itself nested within NYHOPS.

Important to coastal applications, sECOM includes robust explicit wetting-and-drying of the intertidal zone (Oey 2006, Georgas and Blumberg 2012) precipitation/evapotranspiration and freshwater inflow inputs, and a localized atmospheric heat-flux module that includes both convective and advective air-sea fluxes (Bhushan et al. 2010). Quadratic friction is applied at the bottom based on internally calculated friction coefficients that include wave boundary layer effects (Grant and Madsen 1979, Georgas et al. 2007, Georgas 2010), and at the free surface through assimilation of surface ice cover friction (Georgas 2012).

When run in 3D mode as in NYHOPS, the code employs a mode-splitting technique to integrate in time the barotropic (2D) primitive shallow water equations separately from the baroclinic (3D) advection-diffusion equations that may run on a larger time step. The “external’ barotropic mode time step is restricted by the Courant-Friedrichs-Levy- (CFL-) stability-criterion and is set to 1s in NYHOPS. The “internal’ baroclinic mode can usually converge with a larger time step (10s for NYHOPS), saving computational time. The two time steps are seamlessly integrated with a leap-frog scheme.

In its NYHOPS application to the waters of New York and New Jersey (Georgas *et al* 2009a, Georgas and Blumberg 2010, Georgas 2010), the computational domain is discretized on an Arakawa “C” finite-difference curvilinear grid (147x452 horizontal cells, 15,068 of which are designated as water). The NYHOPS grid (Figure 2) encompasses the entire Hudson-Raritan (New York/New Jersey Harbor) Estuary, the Long Island Sound, and the New Jersey and Long Island coastal ocean. The resolution of the grid ranges from approximately 7.5km at the open ocean boundary to less than 50m in several parts of the NY/NJ Harbor Estuary. In order to resolve coastline features that could not be resolved on the NYHOPS grid cell scale, most notably the NJ Atlantic coast barrier islands, 96 cell interfaces across which transport or mixing is disallowed (“thin dams”) have been defined. In the vertical, the model uses a sigma-coordinate system with bathymetrically-stretched sigma layers to permit better representation of bottom topography. The current vertical resolution of the NYHOPS grid is 10 sigma (bottom-following) layers at depths shallower than 200m, providing forecasts at 150,680 points averaged every 10 minutes.

The New Jersey Waterfront Inundation Model has a constant 6.2 m horizontal resolution. It is quite sufficient to resolve the main avenues in the region which are typically 20m to 25m wide and about 130m long. The cross streets are 14m and about 60m long. The grid and bathymetry are shown in Figure 3. The wetting and drying model’s external time step is 0.1 sec in its 2D barotropic mode. The bottom drag coefficient for the lands areas is taken as 0.025. This is a factor of 10 higher than values used in the offshore waters and as such represents the higher friction from the roads and grassy areas.

The collection and application of bathymetric and topographic data on such small scales were quite involved. A 10 ft (3.1m) resolution Digital Terrain Model (FEMA, 2013) with a vertical accuracy of 0.185m that used LiDAR data as its basis was used as a base map. For the two major urban areas, Hoboken and downtown Jersey City, the building blocks and the places that are deemed resistant to flooding were located based on aerial images from Google Earth and set to infinitely high. Local corrections were included for the piers and for the important area around the NJ Transit terminal in Hoboken, from ground surveying. The relative elevation of the several piers in the region was estimated by measurement tape and the pier elevation was then adjusted according the adjoining street elevations found in the DTM. The NJ Transit area was handled similarly: the heights of the walls and doorways were measured relative to the ground and then adjusted again according to the adjoining DTM street elevations. The bathymetric data of the very nearshore waters was determined using the Jet-Ski-based Stevens Dynamic Underwater Coastal Kinematic Survey (DUCKS) system (Miller et al. 2009). All the bathymetric and topographic data were assembled, quality controlled for consistency by visual inspection, converted to NAVD88 and then placed on a 3.1m rectangular grid for use with the modeling. The bathymetric and topographic data are shown on Figure 3,

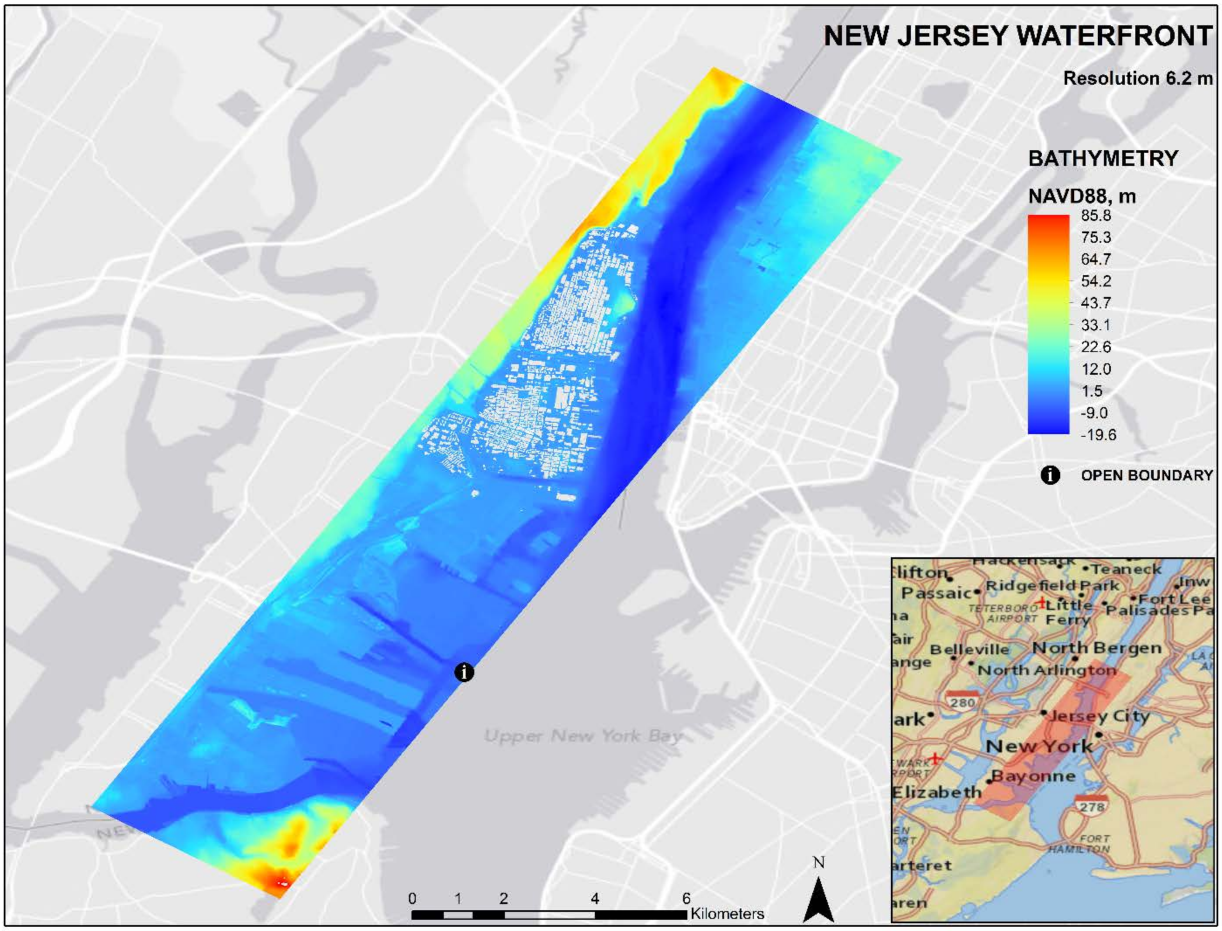


Figure 3. Bathymetry, resolution and model domain. The letter (i) shown on the map is the open boundary where water level information from the NYHOPS model is input.

Wind and pressure fields representing Hurricane Sandy were obtained from Oceanweather Inc. (OWI). Their highly refined mesoscale hindcast methodology uses flight level data taken from hurricane hunter aircraft, ships, moored buoys, offshore platforms, coastal stations, various satellite sensors and wind analysis from the Hurricane Research Division of the National Weather Service. The hindcast methodology can be found in Cardone et al. (1990). The times series of the OWI wind field applied to the NJWIM nest of the model during Sandy is shown in Figure 4.

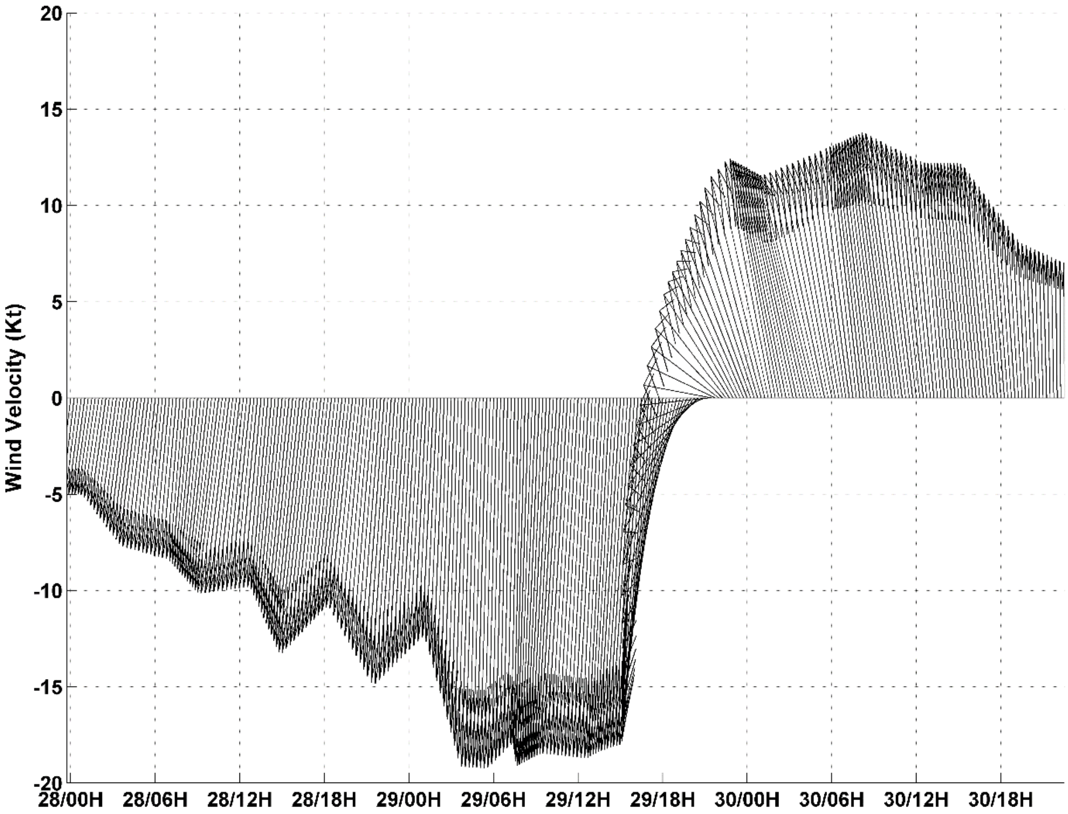


Figure 4. Time series of OWI surface wind applied to the whole NJWIM domain.

The SNAP and NYHOPS nested regional model runs for Sandy utilized OWI over ocean wind field and atmospheric pressure data, offshore wave and water level forcing, dynamically coupled atmospheric heat fluxes from NCEP, and interior stream flow data from USGS. The resulting time series of NYHOPS water level used to force the offshore boundary of the fine resolution waterfront model nest is shown in Figure 5. The NYHOPS total water level results forced by the OWI winds were accurate to within 0.18m in upper New York Harbor and the lower Hudson River, an error similar to the error in the base DTM (Georgas et al. 2014). The model simulation begins at midnight EDT on October 28th and ends at 23:45 EDT on October 30th.

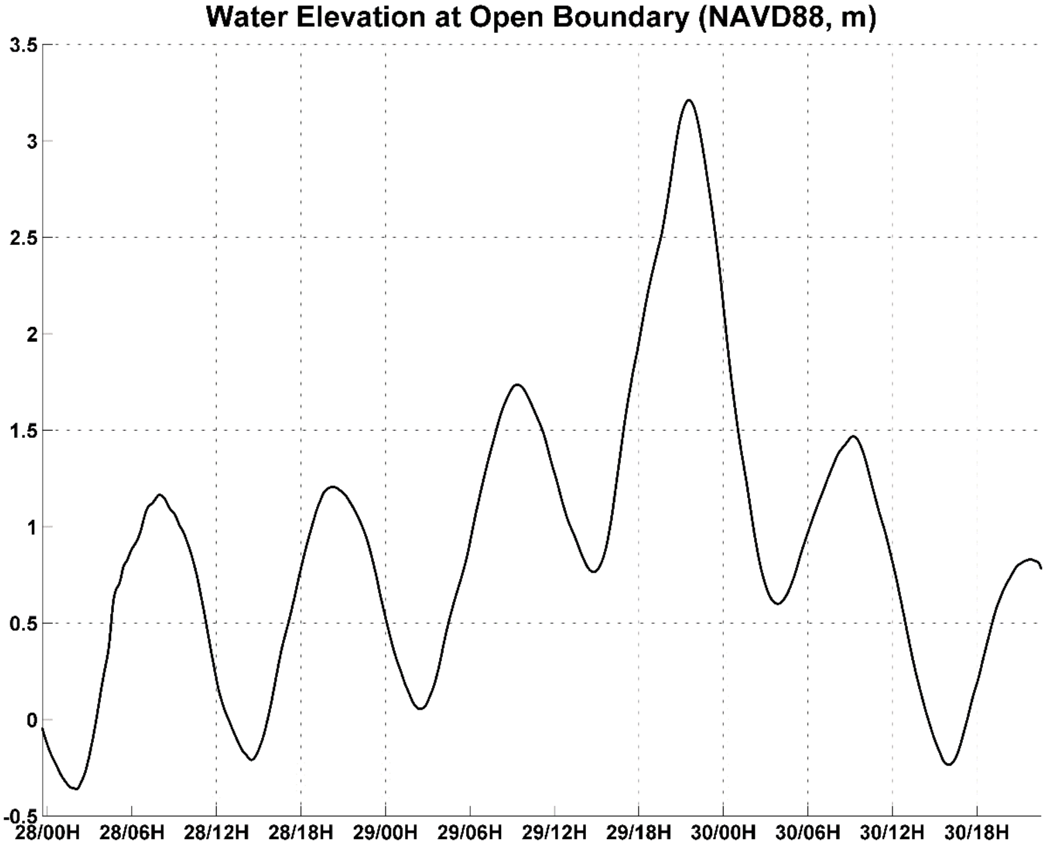


Figure 5. Offshore elevation from the NYHOPS hindcast at the location indicated as (i) in Figure 3.

Model Validation

Multiple types of data sources were used to validate the model. By far the greatest set of "data" came from a crowd sourcing initiative in Hoboken, NJ. Email announcements asking for photographs, videos or just recollections of flooding were sent out to thousands of people. Water level information sought were location of the site observed, height of the water and the time it was observed. Photographs were found to serve the model validation best. Hundreds of photographs were received. Figure 6 was typical of a verifiable crowd-sourced photograph; determining the water level, location and time were easy from this photograph of the NJ Transit Terminal clock tower. Flood heights were determined from the useful photographs by going to the site and measuring the water elevation relative to doors, walls, and vehicles. Unfortunately, most survey responses were of little use. They typically lacked an accurate time registration and often a precise location. People with very useful photographs could not figure out how to off load them from their cell phones. Phone photograph files are apparently private; the people did not want us to help them with the off load. Many witnesses were interviewed; most had great stories of the flooding but little specific information that could be used for model validation.

In total, 56 water marks were used; there were 19 USGS verified high water marks, 26 verbal story water marks and 11 water marks from photographs or videos. Only the USGS water marks measure the highest water level. The comparison of the model results to the water mark observations is shown on Figure 7. The error bars (vertical lines in Figure 7) represent the estimated errors on the height of water whereas the horizontal error bars depict possible errors in the time of the occurrence of the water mark itself. For example, if a witness estimated that a water level occurred at around 8 pm or more specifically at a time between 7:45 and 8:15 pm, the two ends of the horizontal error bar are the maximum and the minimum water levels reached during this estimated time range in the model. The map on the left side of Figure 7 presents the locations of all the water marks.

The correlation coefficient (R^2) between the water mark observations and the model results is 0.93 and the average error is 0.05m. Accounting for the uncertainty in the observations, the standard deviation of the residual error is 0.07 m. The simulated water levels at 78% of the data measurement locations have less than 20% error lower in there prediction of the inundation depth. Inundation depths in excess of 2 m were predicted quite well. In general, the lower water marks have a larger time error while the higher high water marks have a greater elevation error estimate. The greatest differences between observed inundation and modeled one occur at locations 4,19 and 22. These locations are very close to the Hudson River where the water level changes very quickly during Hurricane Sandy. Accurate time estimates from the crowd sourced information were difficult to determine at these locations.

Figure 6 Photograph of the NJ Transit Terminal clock tower on October 30, 2012 6:25am. Credit: Reuters

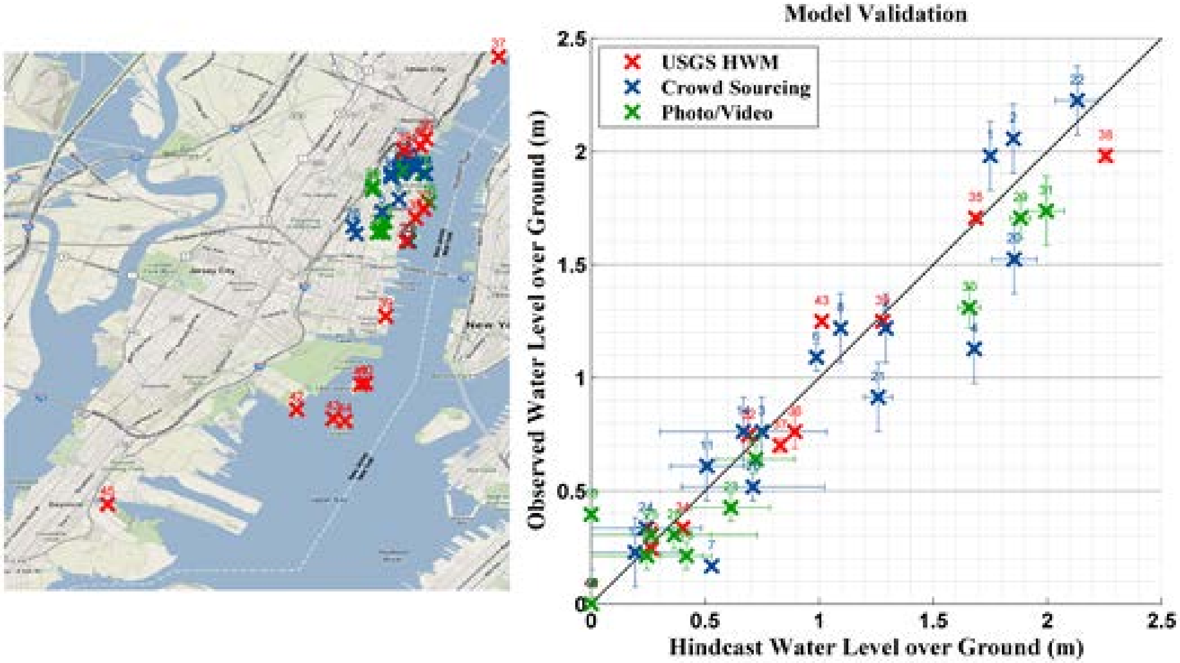


Figure 7. Model inundation validation

The limited crowd-sourced observations in Hoboken also provided 16 flood edgemarks (Figure 8), locations at which the floodwaters stopped. They suggest that the model was able to reproduce the flood extent to within 20 m. This is similar to the results of Wang et al in a study of Sandy inundation in New York City who found a 30m mean absolute difference of the maximum extent of inundation between modeled and the data-derived edgemarks as estimated by the USGS.

The comparison of the model results to the observations shows a remarkable agreement. This is due to the robust wetting and drying physics of sECOM, the high resolution and accurate digital terrain data assembled for this study, the fine resolution used in the model and the high fidelity forcing functions brought to this study. The close agreement found in this paper provides a high confidence in the use of the model for overland inundation prediction.

Figure 8. The maximum extent of flooding in Hoboken during Sandy. The time is October 29, 2012 at 9:30pm The Xs denote where edgemark data has been crowd sourced.

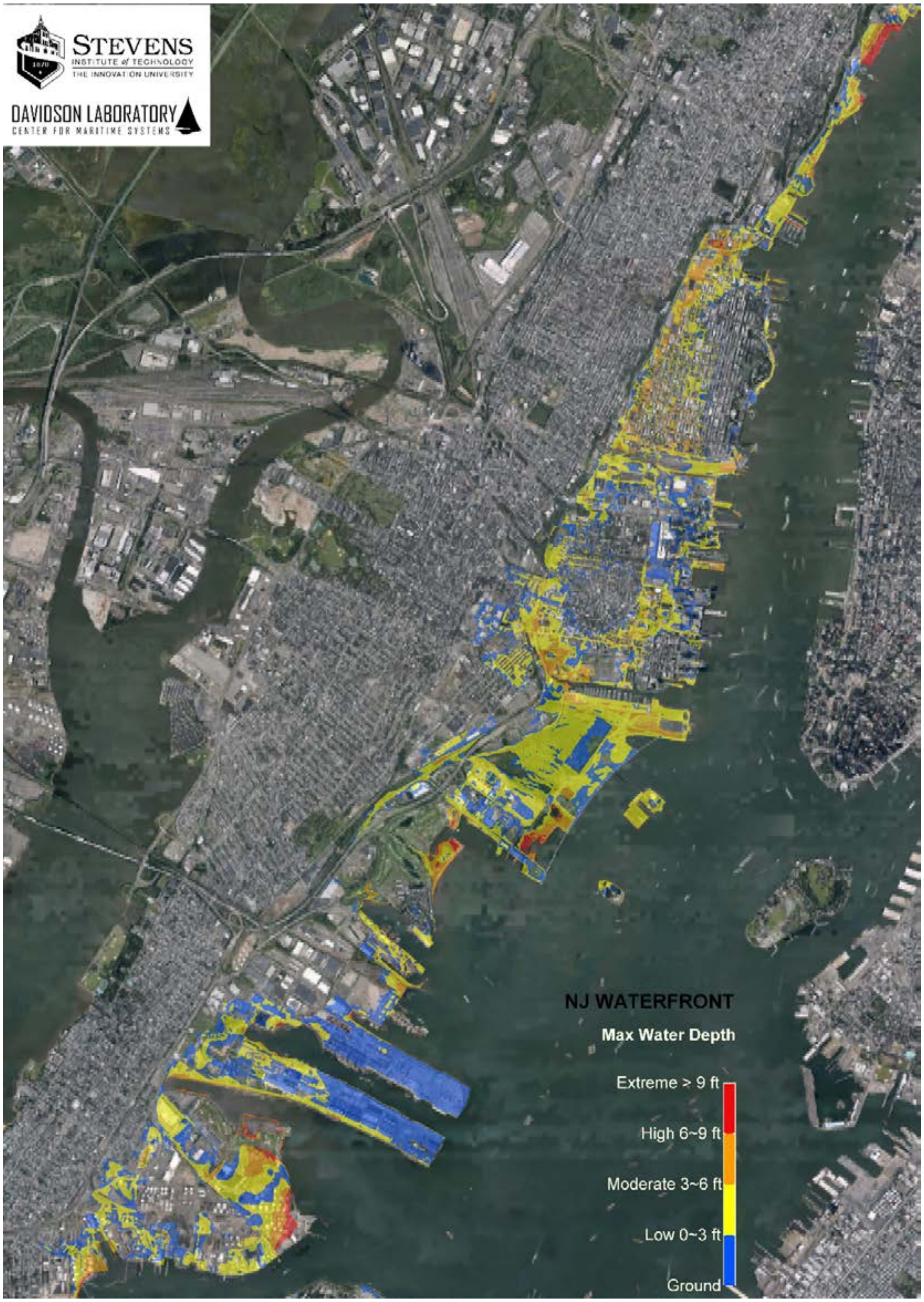


Figure 9 The maximum water level reached in the model domain during Hurricane Sandy.

Flood Pathways

The maximum water levels that were reached in the model domain during Hurricane Sandy are shown on Figure 9. The flooding was widespread and quite deep. An analysis of the flood pathways based on this flooding is useful for resiliency planning.

Hoboken

Figure 10 present the flood pathways into Hoboken as derived from the model simulation. In total, approximately 466 million gallons of floodwater entered into Hoboken. Half of that volume entered Hoboken south of the Hoboken Train Terminal. Along this path, a third of the water volume, or 78 million gallons, did not make it across the Terminal into the streets of Hoboken. A portion of the floodwater remained in the Terminal or flowed south into Jersey City. The remaining 154 million gallons of floodwater flowed either across the Train Terminal or south out of Long Slip Canal into Hoboken. The two major entry points were the open space west of the NJ Transit building (accessing Observer Highway between Willow and Park Avenues) and the northern end of Marin Blvd – 98 million gallons of water entered through the former and 56 million gallons through the latter.

At the north entry point, 191 million gallons of water flowed into Hoboken from Weehawken Cove. Two-thirds of this volume of water entered across the NW bank of the cove and the remainder across the SW bank. These two volumes of water merged in the northwest portion of Hoboken between 15th and 16th streets and propagated south.

Floodwaters from the north and south side of Hoboken met near 7th street; however, a net flux of more than 23 million gallons of water pushed south toward Observer Highway. Small volumes of floodwater entered Hoboken through the Erie-Lackawanna Park at the south end of Hoboken and at the eastern end of 15th street; The floodwaters there were constrained by the higher topography along the east side of Hoboken and contributed little to the flooding in the interior of the city. It is important to note that there are flood pathways between Hoboken and Jersey City. Clearly evident in Figures 10 and 11 there is flow to the south, out of Hoboken and towards Jersey City.

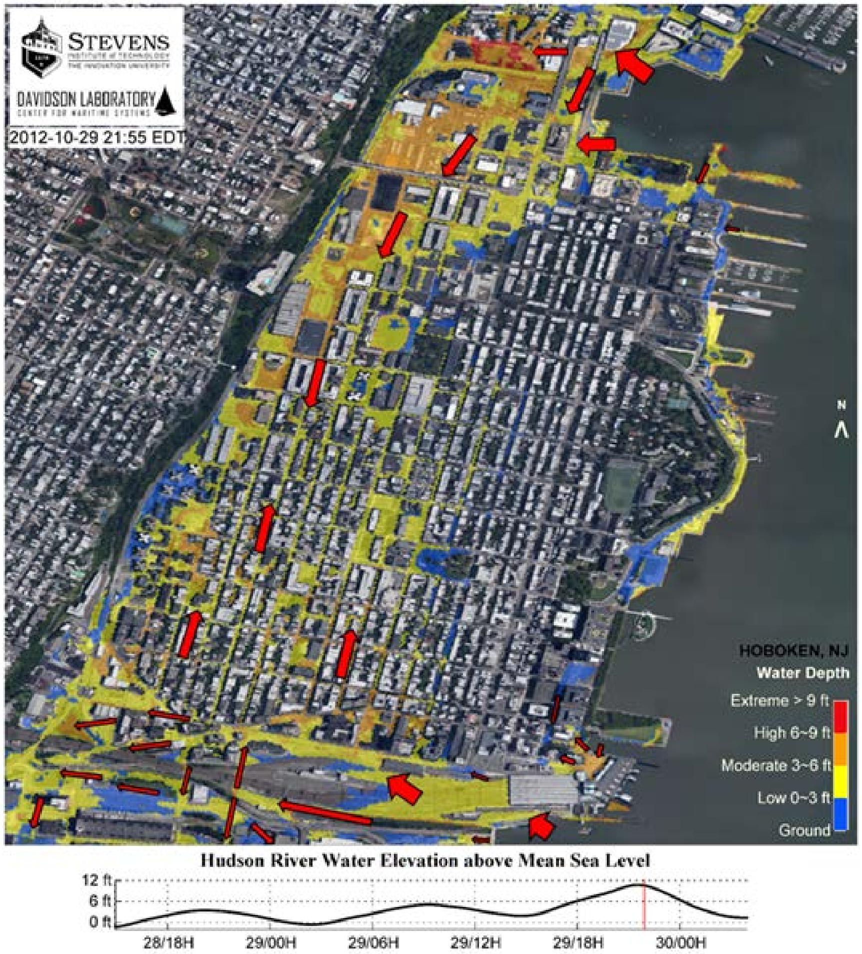


Figure 10. Flood pathways in Hoboken during Hurricane Sandy

Jersey City

The flood pathways into Jersey City are shown in Figure 11. Like Hoboken, floodwaters entered the city at low points located at the north (Long Slip Canal) and south (Morris Canal) boundaries. Unlike Hoboken, floodwater also entered into Jersey City at low points along the Hudson River. Flooding from the Morris Canal started approximately 3 hours before Sandy made landfall along the coast of NJ, when water levels began to exceed 6 ft above NAVD88. Water flowed from the Morris Canal northwest toward the NJ Turnpike and Grand Avenue. Approximately 2.5 hours before landfall, floodwater began to enter Jersey City from the Hudson River at Exchange Place and water began to flow into Liberty State Park form the Morris Canal.

An hour and a half before landfall, water began to enter the northern part of Jersey City from the Long Slip Canal along Marin Boulevard and from the Hudson River at Newport Marina. Floodwaters from Exchange Place flowed west down Columbus Drive and water began to enter the city from Liberty Harbor Marina located on the north side of the Morris Canal. At this time, most of the northern section of Liberty State Park was underwater and water depths were between 1 and 3 ft west of the Morris Canal.

At the peak of the surge, the floodwater entering the city from Liberty Harbor Marina and the west end of Morris Canal merged with the floodwater flowing from Exchange Place and Newport Marina, inundating the eastern side of Jersey City under 1 to 3 ft of water. Northwest of the Morris Canal water depths reached 3 to 6 ft and water began to extend west toward Communipaw and north toward Newark Avenue, flooding the historic downtown. Floodwater that entered from the Long Slip Canal flowed west along 18th street, inundating the northwest portion of Jersey City. After the peak surge, floodwaters continued to flow north from the historic downtown area until they merged with the floodwaters in the northwest portion of the city. Almost all of Liberty State Park was under 3 to 9 feet of water at the peak of the surge.

Figure 11 Flood pathways in downtown Jersey City during Hurricane Sandy

South of Liberty State Park, the dock along the south side of Port Liberte on Caven Point and the docks along the waterfront south to Port Jersey Pier were inundated under 3 to 6 feet of water. Port Jersey Pier was overtopped and covered with up to 3 feet of water.

Bayonne

Flooding along the Hudson River shoreline of Bayonne was predominantly confined to land areas east of Route 440 (Figure 12). Floodwaters entered into the Constable Hook section of Bayonne near the Bayonne Golf Club approximately 3 hours before Sandy made landfall along the coast of NJ, when water levels began to exceed 6 ft above NAVD88. Two hours before the peak surge in the Harbor, the Military Ocean Terminal Pier was overtopped and most of the northeast portion of Constable Hook was under 6 feet of water, south and east of Lefante Way. Water flowed down Lefante Way toward Route 440 and across the southern shoreline of Constable Hook, flooding the refineries south of Old Hook Drive. At the peak of the surge, the western end of the Military Ocean Terminal was under 3 to 6 feet of water, as was the most of the shoreline around Constable Hook.

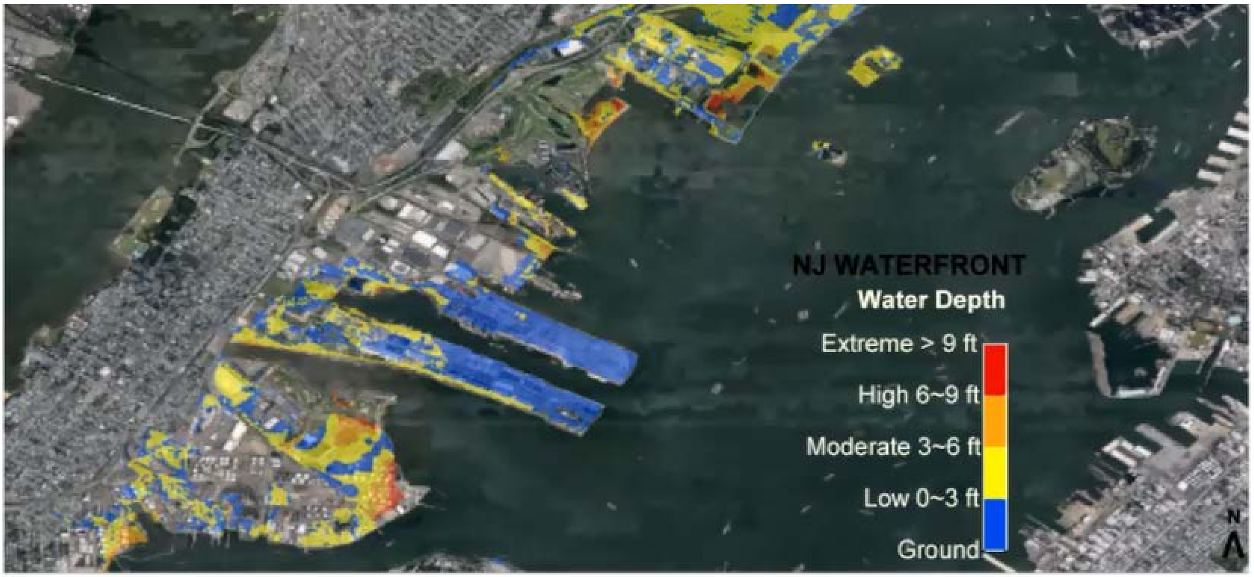


Figure 12. The maximum water level reached in Bayonne during Hurricane Sandy.

Flood Interventions

Assessment of the flood pathways revealed that a majority of the inundation experienced along the Hudson River waterfront of Hudson County can be attributed to three main entry points – the Morris and Long Slip Canals, and Weehawken Cove. Flooding along the southern portion of Liberty State Park and the piers and shorelines to the south is attributed to the low elevation of the shoreline and structures. The model results indicate that significant regional flood prevention benefits can be obtained by siting flood protection interventions at a few specific locations. Here we examine the effectiveness of placing flood prevention works at: (1) the north end of Hoboken along Weehawken Cove; (2) the south end of Hoboken across the NJ Transit Terminal and Long Slip Canal; (3) the north and south wall at Hoboken combined; (4) the Hoboken north and south walls combined with flood gates at Marin Boulevard and Grove Street; (5) Filling in the Long Slip Canal; (6) floodwall along Washington Street in Jersey City; and (7) floodwalls around the Morris Canal.

Each of the interventions were simulated in the model by inserting a thin dam of infinite height along the model grid elements along the footprint of the structure. The filling of the Long Slip Canal was represented in the model by increasing the elevation of the grid cells in the Canal to 12 feet above Mean Sea Level (Figure 13). The location of the thin dams for the Hoboken north and south walls, and the flood gates at Marin Boulevard and Grove Street is presented in Figure 14. The floodwall along Washington Street in Jersey City is shown in Figure 15 and the floodwall around Morris Canal is shown in Figure 16. Grid convergence experiments showed that the 3.1 m resolution provided practically equivalent results compared to the highest resolution attempted 6.2 m. For the flood interventions a grid size of 6.2m was used as it reduced the computational time by a factor of 8. Difference plots showing inundation changes with and without each intervention are provided in Appendix A.

Figure 13. Filling of Long Slip Canal represented by increasing the elevation of the model cells in the canal (indicated in red) to +12 feet Mean Sea Level.

Figure 14. Location of Flood Interventions in Hoboken represented as Thin Dams.

Figure 15. Location of Floodwall along Washington Street in Jersey City represented as a Thin Dam.

Figure 16. Location of Floodwall around the Morris Canal and along the northeast edge of Liberty State Park represented as a Thin Dam.

Hoboken North Floodwall

Figure 17 presents the model results with and without the wall along Weehawken Cove at the north end of Hoboken. Placing the floodwall from the edge of the rise on the west side of Hoboken east along the light rail line and along the southern bank of Weehawken Cove to the Hudson River at 13th Street prevents almost all of the 191 million gallons of floodwater that flowed into Hoboken from Weehawken Cove. The lower panel of Figure 17 shows that the northern wall prevents flooding of the northern portion of Hoboken as far south as 10th street. This area was under 3 to 6 ft of water during Sandy (see Appendix A). Flood levels are reduced as far south as 4th street, indicating the significant volume of water that entered Hoboken from the north. Interestingly, flood elevations to the north of the wall in Weehawken are also reduced, indicating that a portion of floodwater entered Weehawken from Hoboken.

Hoboken South Floodwall

Figure 18 presents the model results with and without the wall along the shoreline south of the NJ Transit Terminal at the south end of Hoboken. Placing the floodwall from the southern end of the Transit Terminal south across Long Slip Canal and into Jersey City prevents water from crossing the train tracks and flowing west out of the Canal into Hoboken. Flooding is prevented as far north as 2nd street and significantly reduced as far north as 8th street (see Appendix A). Floodwater from the north still reaches as far south as 1st street; however the flood levels in the southwest side of the city are significantly reduced. Floodwater still enters Hoboken through the Erie-Lackawanna Park at the south end of Hoboken and along the eastern shoreline along the Hudson River. The inundation difference plot in Appendix A also shows that flood depth in northwest Jersey City are also significantly reduced by the south floodwall.

Hoboken North and South Floodwalls

Figure 19 presents the model results with and without the north and south Hoboken floodwalls combined. The combined floodwalls prevent almost any water from entering the City of Hoboken. Floodwater still enters Hoboken through the Erie-Lackawanna Park at the south end of Hoboken and along the eastern shoreline along the Hudson River but only inundate the riverfront roads and piers. Flooding is also eliminated in the northwest portion of Jersey City (Appendix A).

Hoboken North and South Walls and Floodgates at Marin Blvd and Grove St

A model simulation that included north and south floodwalls as well as floodgates at Marin Boulevard and Grove Street at the location of the railroad bridges was conducted. The result is presented in Figure 20. This intervention prevents any storm surge floodwater from entering Hoboken during Sandy. Flooding is also eliminated in the northwest portion of Jersey City, indicating that water from Long Slip Canal was responsible for the flooding in this area as well (Figures 21 and 22).

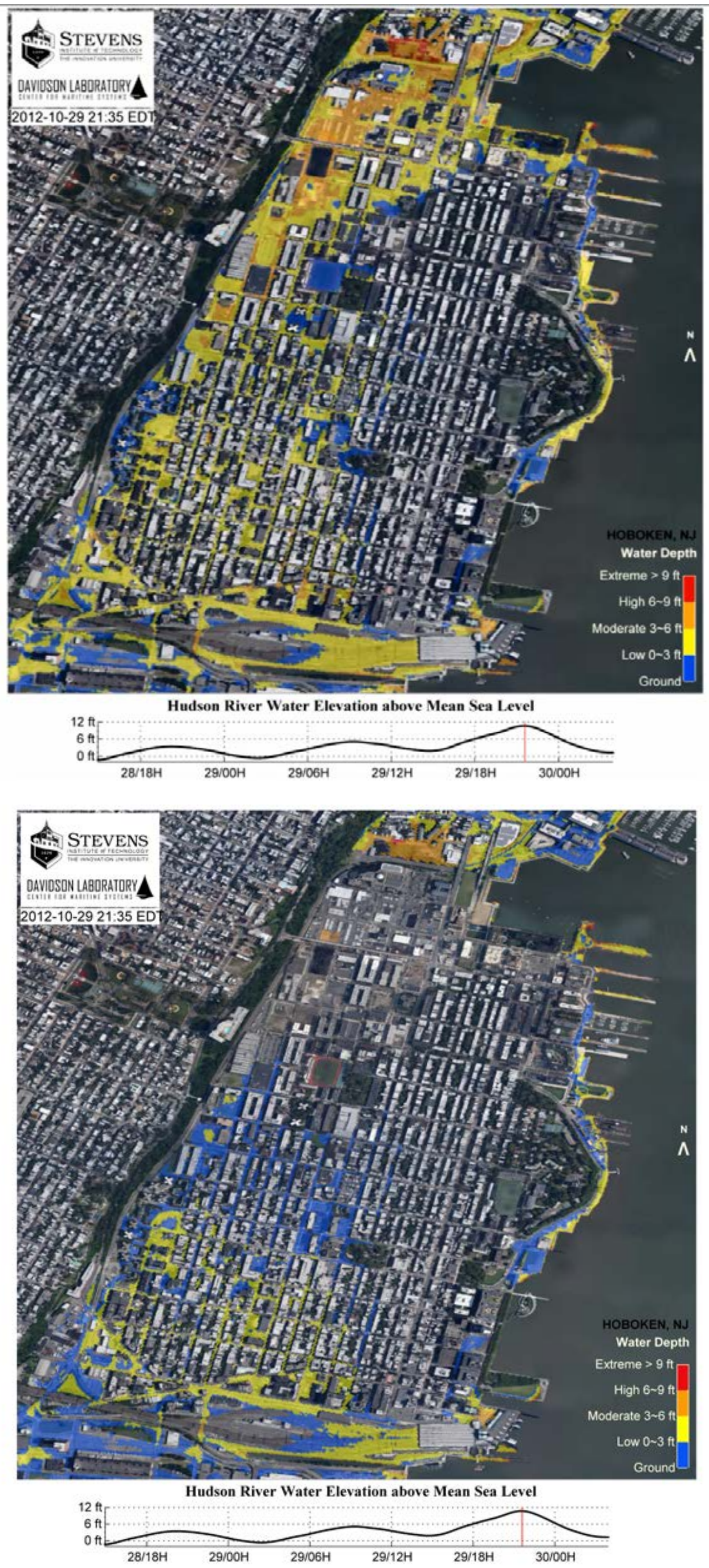


Figure 17. Comparison of Inundation levels during Sandy in Hoboken without (top) and with (bottom) a floodwall along Weehawken Cove.

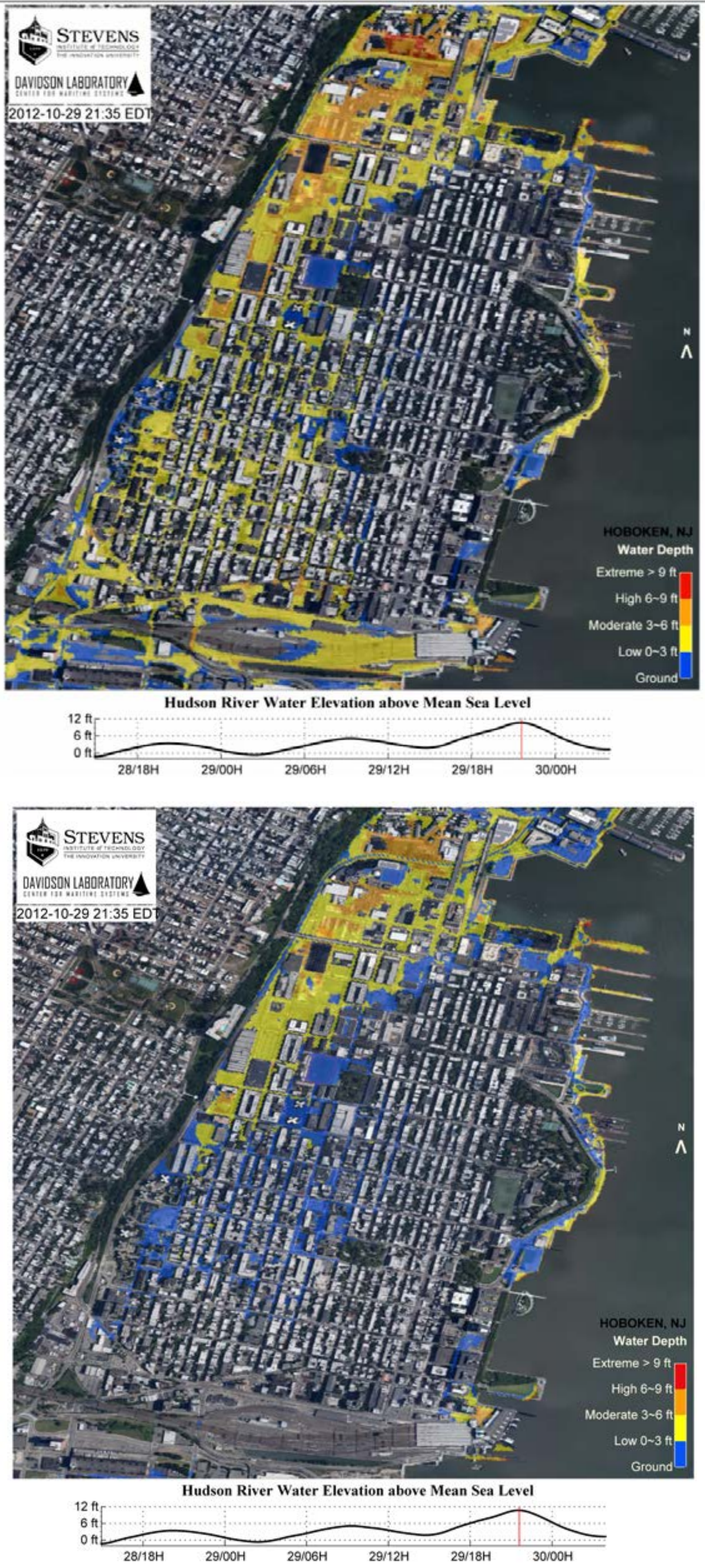


Figure 18. Comparison of Inundation levels during Sandy in Hoboken without (top) and with (bottom) a floodwall along the NJ Transit Terminal.

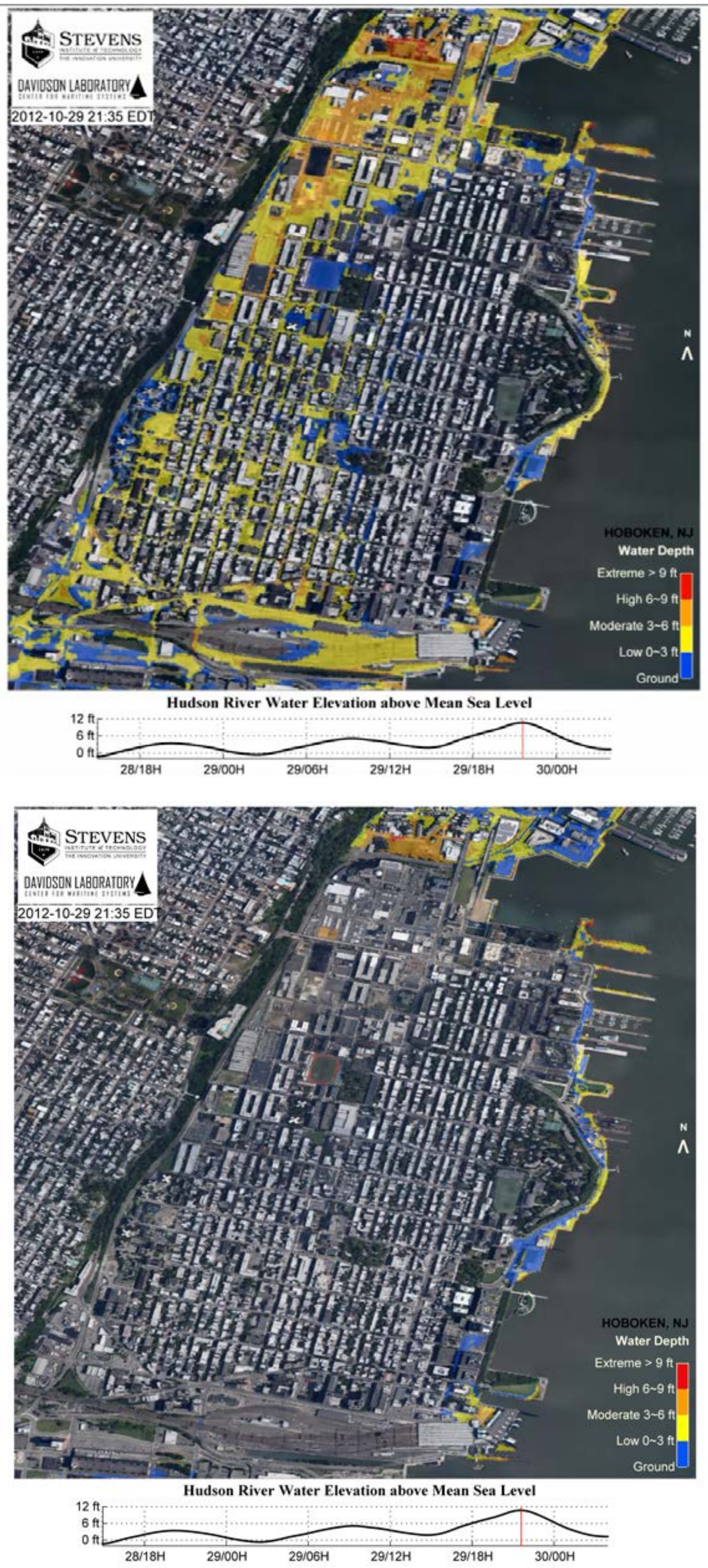


Figure 19. Comparison of Inundation levels during Sandy in Hoboken without (top) and with (bottom) north and south floodwalls.

Figure 20. Comparison of Inundation levels during Sandy in Hoboken without (top) and with (bottom) north and south floodwalls and floodgates.

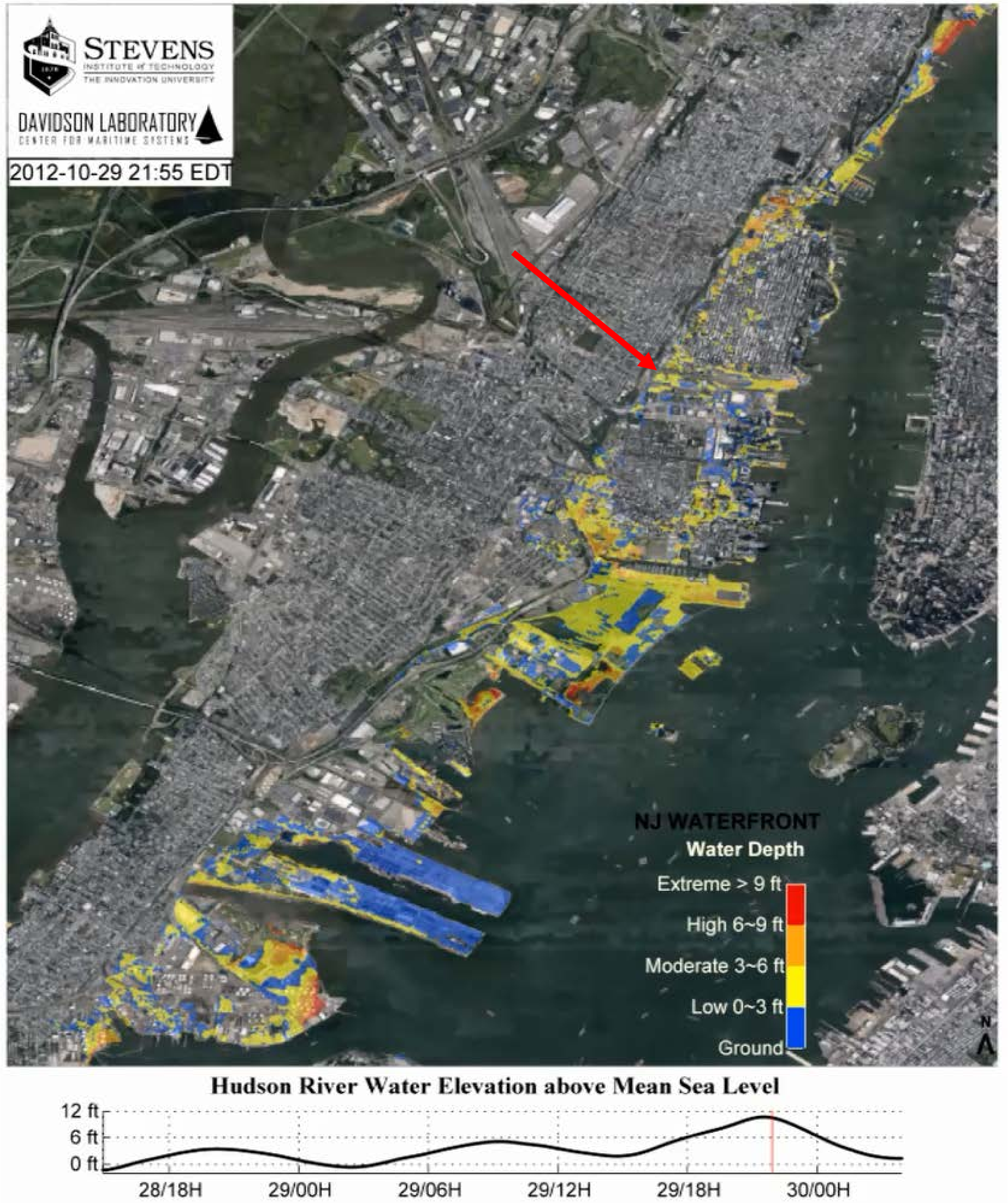


Figure 21. Inundation levels during Sandy in Hudson County without flood mitigation structures.

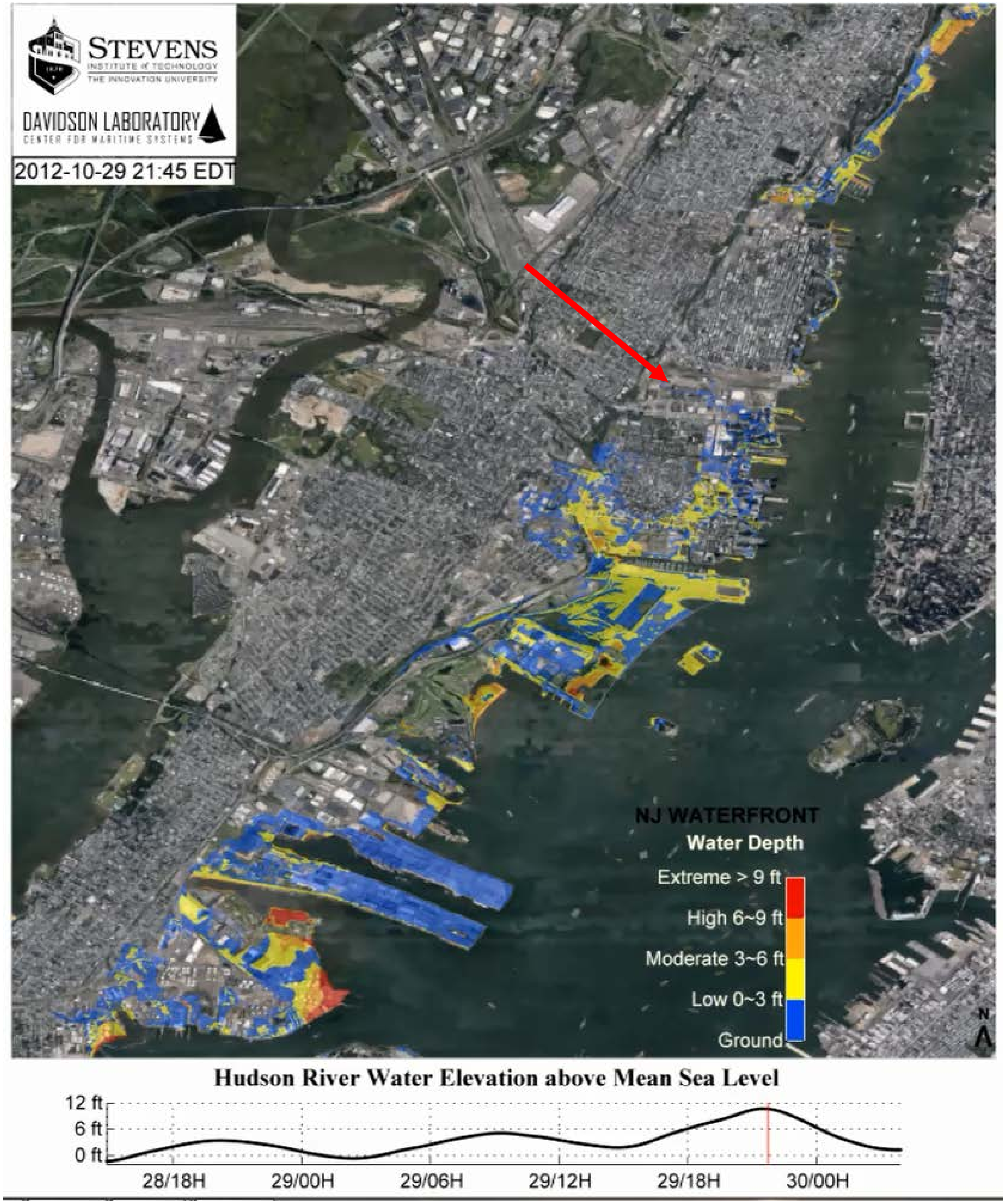


Figure 22. Inundation levels during Sandy in Hudson County with north and south floodwalls and floodgates in Hoboken.

Filling of the Long Slip Canal

As discussed previously, Long Slip Canal was found to be a major entry point for floodwaters into Hoboken and the northwest portion of Jersey City. Filling the canal to an elevation greater than the Sandy surge elevation was investigated as a means to prevent inundation of southern Hoboken and northern Jersey City. Within the model, the Canal is 100 ft wide, bulkhead to bulkhead. The elevation of the grid elements covering the Canal were set to +14.5ft NAVD88, 3.2 ft above the peak water level of +11.3 ft NAVD88 measured by the NOAA tide gauge during Sandy at The Battery in New York City.

Following are a series of model snap shots at four times during Sandy's pass through the area. They present the change in flood pathways and inundation depth with the Canal filled. Figure 23 presents the onset of street flooding that occurred at 19:15 EDT on October 29, 2012, two hours before the peak storm surge in Hudson County. The bottom panel of Figure 23 shows that during Sandy, floodwater flowed onto Marin Boulevard at the west end of the Canal and propagated north into Hoboken and south into Jersey City. Floodwater is also propagating across the train yard onto Observer Highway in Hoboken. The top panel of Figure 23 only shows flooding of the southeastern portion of the train yard indicating a significant attenuation of the storm surge due to the filling of the Canal at that time.

The top panel of Figure 24 shows that the floodwater will still enter onto Marin Boulevard through the rail yard. Floodwater begins flowing onto the road at 19:35 (top panel) showing that a portion of the surge during Sandy flowed across the rail yard onto Marine Boulevard. At this time, floodwaters are also flowing across the rail yard onto Observer Highway. The filling of the Long Slip Canal to elevation +14.5 ft NAVD88 delays the entry of floodwaters into Hoboken and Jersey City by about 20 minutes.

Figure 25 presents the extent and depth of flooding at 20:35 EDT on October 29, 2012. At this time, floodwaters extended as far north as 5th street in Hoboken and as far south as 15th street in Jersey City during Sandy (bottom panel of Figure 25). Flood depths in the NJT rail yard are about 5 feet and are approaching 9 feet on Marin Boulevard at the west end of Long Slip Canal. The model simulations with the Canal filled (top panel of Figure 25) indicate that floodwaters are spreading north through the southwest portion of Hoboken but only reaching as far as the intersection of 4th and Clinton streets. Inundation depths are less than 3 feet everywhere except along the eastern portion of the rail yard and on Marin Boulevard at the west end of the Canal. In both panels, floodwaters can be seen entering Hoboken from Weehawken Cove (top left) and into Jersey City from Morris Canal (lower left).

Figure 26 presents the extent and depth of the floodwater at the peak of Sandy's storm surge at 21:35 EDT. Although the spatial extent of the flooding is almost the same with

Figure 23. Comparison of Inundation levels during Sandy on Oct. 29, 2012 at 19:15 EDT, with (top) and without (bottom) the Long Slip Canal filled to an Elevation of +14.5 ft NAVD88.

Figure 24. Comparison of Inundation levels during Sandy on Oct. 29, 2012 at 19:35 EDT, with (top) and without (bottom) the Long Slip Canal filled to an Elevation of +14.5 ft NAVD88.

Figure 25. Comparison of Inundation levels during Sandy on Oct. 29, 2012 at 20:35 EDT, with (top) and without (bottom) the Long Slip Canal filled to an Elevation of +14.5 ft NAVD88.

Figure 26. Comparison of Inundation levels during Sandy on Oct. 29, 2012 at 21:35 EDT, with (top) and without (bottom) the Long Slip Canal filled to an Elevation of +14.5 ft NAVD88.

Figure 27. Comparison of Inundation levels during Sandy on Oct. 29, 2012 at 23:15 EDT, with (top) and without (bottom) the Long Slip Canal filled to an Elevation of +14.5 ft NAVD88.

and without the filled in Canal, the depth of the floodwater is reduced when the Canal is filled in. Inundation depths are now typically 3 feet or less throughout most of Hoboken and northern Jersey City with the Canal filled. This is a reduction of about 1.5 feet (between 0 and 3 feet) in the flood depth that occurred over the same area during Sandy, as indicated by the change in color shading from yellow to blue in Figure 26. Figures 23, 24, and 25 can be thought of as independent events, each forced by a Hudson River flood elevation. This suggests that flood reductions can be realized for events of lesser magnitude than Sandy if the Canal were to be filled in.

Flood depths in the western portion of Hoboken and Jersey City reached their peak an hour and 45 minutes after Sandy's peak storm surge in New York Harbor. Figure 27 shows the extent and depth of the floodwater at its peak. Water depths in Hoboken and the northwestern portion of Jersey City are reduced in comparison to the flood depths that occurred during Sandy when the canal is filled in.

Figure 28 presents the difference in maximum flood extent and depth with and without the Long Slip Canal filled in A significant reduction in flood depth of about 9 inches (between 7 and 11 inches) is realized immediately to the west of the Long Slip Canal between the NJ Transit Rail Line and the NJ Trunpike Holland Tunnel entrance ramp (yellow shaded area of Figure 28). Flood depths are reduced the greatest, somewhere between 11 to 14 inches, along the southwest corner of the canal. Over most of the area within the western half of Hoboken that flooded during Sandy, flood depths are reduced about 5 inches or so (light green shaded area of Figure 28). The area of Jersey City south and west of the Holland Tunnel would experience a reduction in flood depth of 3.5 inches (light blue shaded areas) with the canal filled. A slight increase of 2 inches in flood depth is predicted immediately adjacent to the southeastern portion of the canal (blue shaded area in Figure 28) due to the blocking effect of the increase in topographic elevation of the filled canal.

The red dotted areas on Figure 28 indicate the areas of Jersey City and Hoboken that would not flood by filling in the Long Slip Canal. Although not significant in terms of total flood area, the extent of flooding is slightly reduced by filling the Canal. Of most importance is that a reduction of almost a half a foot (between 3 to 7 inches) in Hoboken will result. This is a significant change in the maximum flood depth that can be achieved by simply filling in the Long Slip Canal. A half foot reduction in maximum floodwater elevation could be the difference between a dry first floor and flooded first floor of a structure.

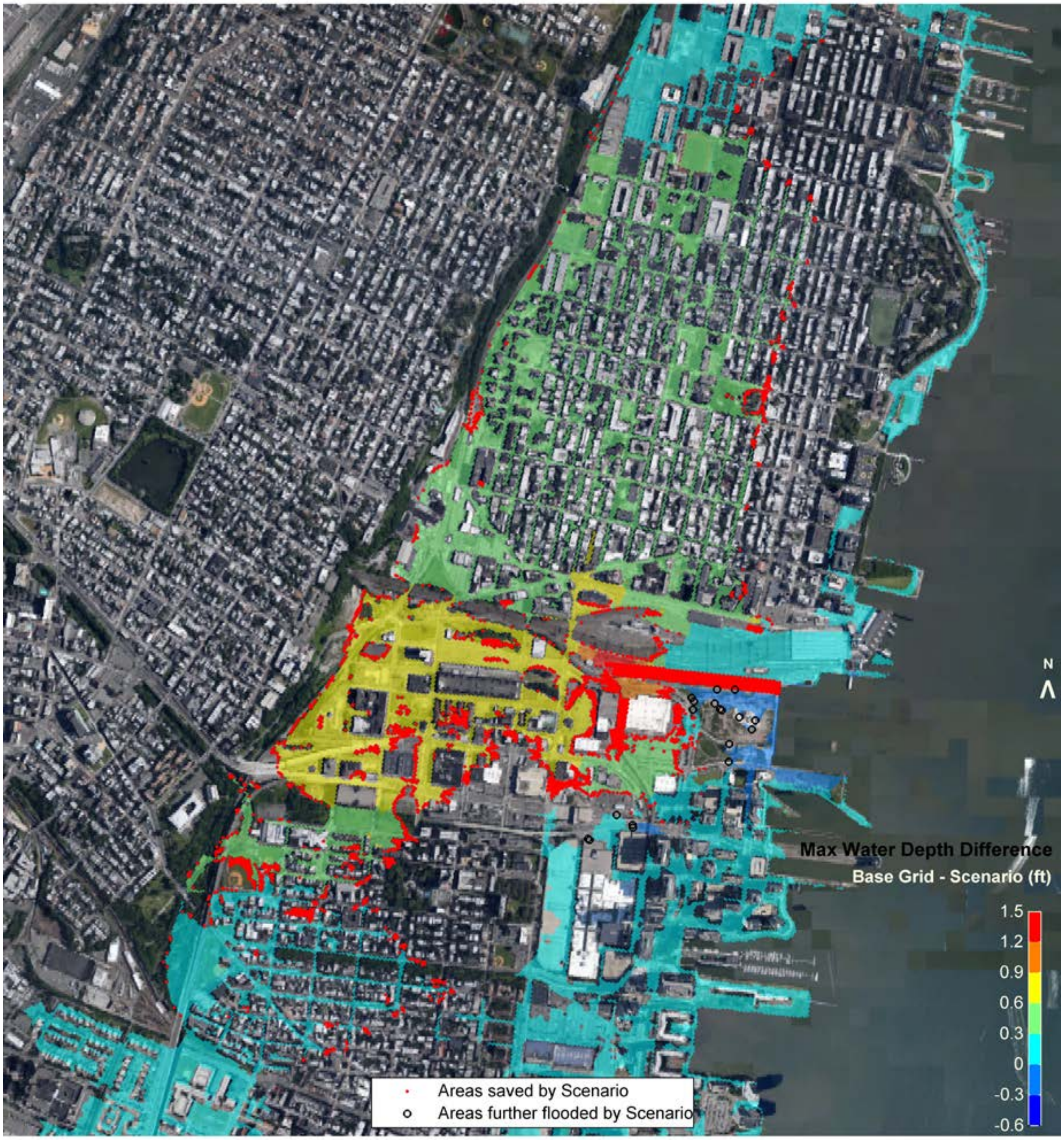


Figure 28. Maximum inundation difference plot with and without the Long Slip Canal filled in to an elevation of +14.5 ft NAVD88. Positive values indicate a reduction in inundation depth.

Filling the Canal does not eliminate floodwater from flowing over the train yard or onto Marin Boulevard and propagating into Hoboken and Jersey City. Figure 28 shows that the extent of flooding is reduced very little by the filling of the Long Slip Canal; however the maximum flood depths are reduced across southwest Hoboken and northwest Jersey City by an average of about 7 inches. Maximum reductions in flood depths of about 1.3 to 1.6 feet occur immediately adjacent to the Long Slip Canal. A slight increase of about 4 inches in the flood depth occurs along the southeast portion of the Canal.

Filling the canal alone will not significantly reduce the flooding that occurred during Sandy; however, filling the canal does delay the entrance of floodwater into southern Hoboken and northern Jersey City. This delay reduces the maximum flood depths reached during Sandy. Filling the Canal in combination with the construction of flood walls along the northern and southern portions of Hoboken would eliminate all of the flooding that occurred in Hoboken and the northwest portion of Jersey City and eliminate the need for floodgates at Marin Boulevard and Grove Street. An extension of the floodwall south of the NJT train station along the Hudson River into Jersey City will eliminate the slight increase in flooding immediately south of the Canal.

Floodwall along Washington Street in Jersey City

The flood pathways analysis indicated that floodwater entered Jersey City from low points along the Hudson River. To eliminate flooding from the river, the effectiveness of a floodwall located along Washington Street from the south edge of the Long Slip Canal to York Street was evaluated with the modeling system (Figure 29). The top panel of Figure 29 shows that the flooding generated by Sandy's storm surge stopped to the north and west of the Paulus Hook section of Jersey City. Placing a floodwall along Washington Street eliminates the flooding that occurred within the Newport Mall area of Jersey City and reduced inundation depths locally north of the Mall to 18th Street (see Appendix A). The fact that floodwater is present on both the east and west sides of the floodwall indicates the significant amount of water that entered the City from the Morris Canal through Liberty Harbor Marina. A floodwall paralleling the riverfront would have done little to mitigate the overall flooding experienced in Jersey City during Sandy.

Figure 29. Comparison of Inundation levels during Sandy in Jersey City without (top) and with (bottom) a floodwall along Washington Street.

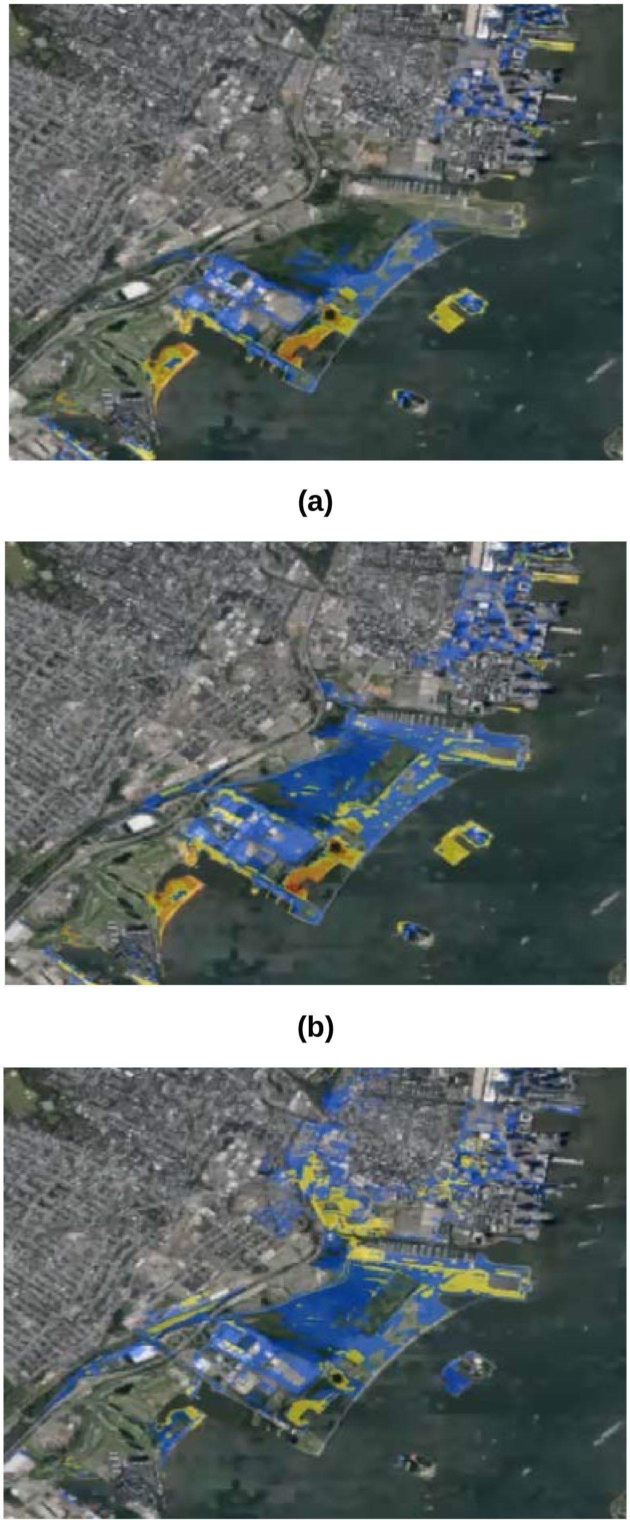
Floodwall around the Morris Canal

A significant volume of floodwater entered Jersey City from the Morris Canal located between Jersey City and Liberty State Park. The effectiveness of a floodwall around the canal was evaluated in the modeling system. The results are presented in Figure 30. Comparing the top and bottom panel in Figure 30 the area of inundation is approximately the same with and without the floodwall in place. The maximum flood depth, however; is reduced by 1 to 2 feet in the southwest portion of Jersey City (see Appendix A) and flooding is eliminated in the area north of Grand Street and west of the NJ Turnpike. The floodwall additional reduces inundation depths in the center portion of Jersey City by 0.5 to 1 foot by preventing floodwater from entering the city from Liberty Harbor Marina. Significant flooding still occurs from water entering the city from the Hudson River shoreline.

A comparison of the time of maximum flooding (see timeline at bottom of panels in Figure 30) shows that the presence of the floodwall around the canal delays the propagation of the floodwater into Jersey City from the south. Floodwater begins to flow into Liberty State Park from the south and east approximately a half hour before the peak surge in the Upper Bay of NY Harbor (Figure 31a). At the peak of the surge, floodwater can be seen propagating along the floodwall located at the western end of Morris Canal and into Jersey City along Jersey Avenue and across the Hudson County light rail tracks (Figure 31b). The surge persists until maximum flood depths are reached an hour and a half after the peak surge in the Upper Bay (Figure 31c).

The result of the Morris Canal floodwall model simulation indicates that a significantly greater volume of floodwater will enter Jersey City from the south across Liberty State Park than from the Canal itself. This result indicates that, for effective storm surge flood prevention, the floodwall will have to extend west of the NJ Turnpike overpass to the location of the light rail tracks.

Figure 30. Comparison of Inundation levels during Sandy in Jersey City without (top) and with (bottom) a floodwall around the Morris Canal.



(a)

(b)

(c)

Figure 31. Time series of the spatial extent of flooding at (a) 20:55, (b) 21:35, and (c) 00:05 EDT on October 29-30, 2012.

Conclusions

A new, high-resolution, hydrodynamic model for the Hudson River waterfront on the New Jersey side facing Manhattan; including four municipalities – Weehawken, Hoboken, Jersey City and Bayonne, has been developed and validated. The New Jersey Waterfront Inundation Model (NJWIM) has a constant 6.2m resolution and is nested within the three dimensional NYHOPS model at its offshore open boundary, influenced by estuarial tide and storm surge. Wetting and drying of land features in the model's external time step is as low as 0.1 sec in its 2D barotropic mode. This mode provides for the dynamic prediction of depth integrated flood elevations and velocities across land features during inundation events. The NJWIM was calibrated using the NYHOPS hindcast of Hurricane Sandy. The hindcast utilized Sandy over ocean wind field and atmospheric pressure data, offshore wave and tidal boundary forcing, atmospheric heat fluxes, and interior streamflow data.

Water marks at 56 locations and 16 edemas from a combination of USGS data archives and crowd-sourced photographs, videos and stories were obtained. A comparison shows that the model is capable of hindcasting overland water elevation accurately. The correlation coefficient (R^2) between the water mark observations and the model results is 0.93. The standard deviation of the residual error is 0.07 m. The simulated inundation levels at 78% of the data measurement locations have less than 20% error. Inundations in access of 2 m were predicted quite well. Because the model was able to capture the spatial and temporal variation of water levels in the region observed during Hurricane Sandy, it was used to identify the flood pathways and suggest where flood preventing interventions could be build.

Assessment of the flood pathways revealed that a majority of the inundation experienced along the Hudson River waterfront of Hudson County can be attributed to three main entry points – the Morris and Long Slip Canals, and Weehawken Cove. Constructing flood mitigation structures at these critical entrance points should eliminate the majority of storm surge related flooding experienced in Hudson County during Hurricane Sandy. Model simulations with flood interventions located at the north and south side of Hoboken, at Long Slip Canal, at Morris Canal, and along the Jersey City Hudson River were examined individually and in combination. Results indicate that almost all storm surge flooding can be eliminated in Hoboken and northwest Jersey City through the construction of north and south floodwalls, and the filling in of the Long Slip Canal. The result of the Morris Canal floodwall model simulation indicates that a significantly greater volume of floodwater will enter Jersey City from the south across Liberty State Park than from the Canal itself. An extension of the floodwall along the canal west to the Hudson County Light Rail line is required to prevent the flooding of the southwest portion of Jersey City during storm surges similar or greater than the one generated by Hurricane Sandy.

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Appendix A

Inundation Difference Plots

Hoboken North Floodwall

Hoboken South Floodwall

Hoboken North and South Floodwalls

Hoboken North and South Floodwalls & Floodgates at Marin Blvd. and Grove St.

Jersey City Floodwall along Washington Street

Morris Canal Floodwall