HYDROLOGIC FEASIBILITY OF STORM SURGE BARRIERS TO PROTECT THE METROPOLITAN NEW YORK – NEW JERSEY REGION

SUMMARY REPORT

Malcolm J. Bowman
Brian Colle
Roger Flood
Douglas Hill
Robert E. Wilson
Frank Buonaiuto
Peng Cheng
Yi Zheng

November 2004

Final Report to HydroQual, Inc
New York City Department of Environmental Protection
New York Sea Grant
Eppley Foundation

HYDROLOGIC FEASIBILITY OF STORM SURGE BARRIERS TO PROTECT THE METROPOLITAN NEW YORK – NEW JERSEY REGION

Storm surge barriers are protecting many places – London, the Netherlands, Providence, RI, and New Bedford, MA, for example – that have previously suffered loss of life and major property damage from storm flooding. In past floods, the metropolitan region has been spared such devastation, but rising sea level and climate change are likely to cause dangerous flooding in the coming decades. In this study, we examine the hydrologic feasibility of storm surge barriers to protect the metropolitan New York – New Jersey region from flooding during intense storms.

The Threat of Flooding

New York City and the adjacent part of New Jersey surround a complex of waterways influenced by tides and the weather. Much of the region is less than three meters above sea level, an area of about 260 square kilometers at risk from a 100-year flood (Figure 1).

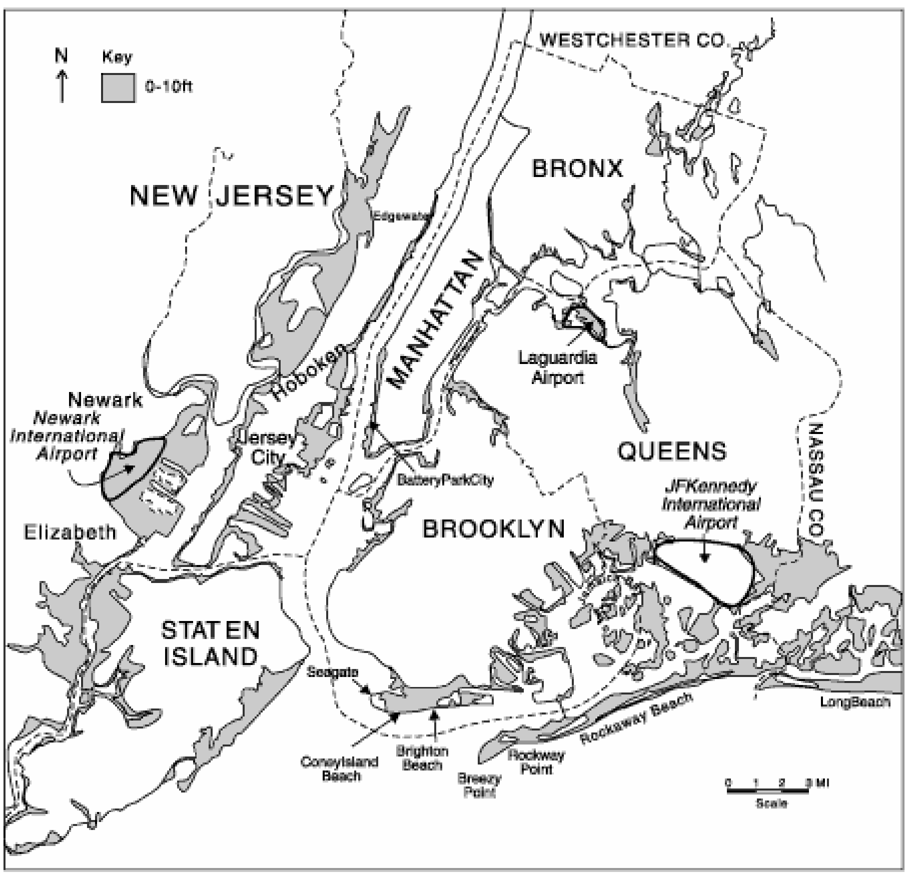


Figure 1. The 100-year flood, shown shaded, covers 260 square kilometers in the metropolitan region, about half of which can be protected with storm surge barriers. Source: V. Gornitz, in C. Rosenzweig and W.D. Solecki, Climate Change and a Global City, Columbia Earth Institute, July 2001.

That is, past experience indicates that there is a one-in-a-hundred chance that the area will be flooded in any year. However, sea level has been rising inexorably at about 0.3 meters per century here, as recorded over a period of 150 years. At that rate, the 100-year flood would become a 30-year flood by the 2090s.

However, global warming is expected to increase the rate at which sea level continues to rise. This rise, combined with the likelihood of more frequent and intense storms, threatens to flood the region much more frequently. While there is great uncertainty in precisely how frequently, modeling results indicate that the 100-year flood will become a 40 to 80-year flood by the 2020s, a 20 to 70-year flood by the 2050s, and possibly even a 4-year flood by the 2080s (Figure 2).

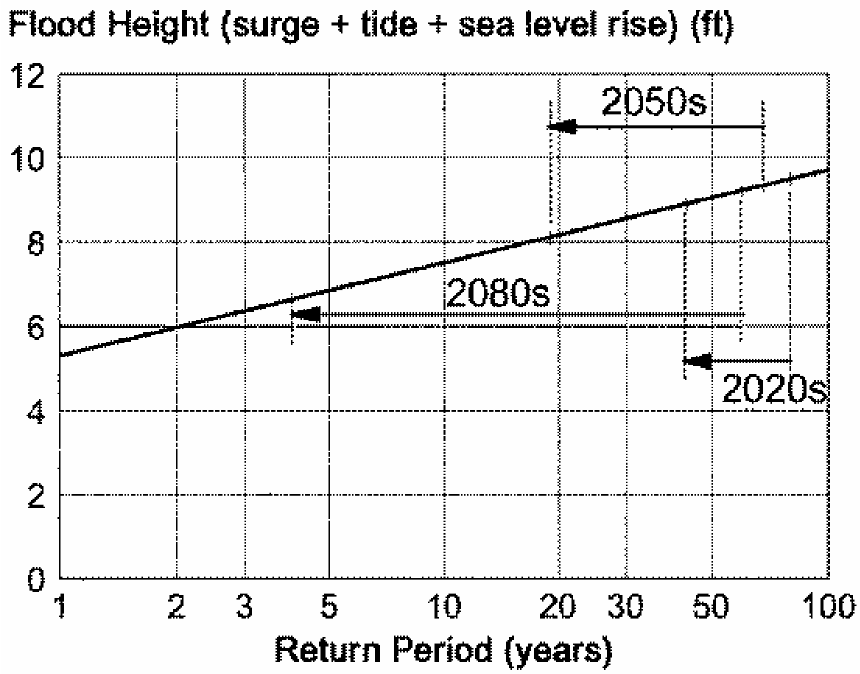


Figure 2. The rise in sea level due to climate warming is expected to increase the frequency of flooding, shown here by the reduction in the return period of a "100-year flood" of 0.3 meters (~10 feet) elevation. Source: V. Gornitz, ibid.

The vulnerability of the region to even a relatively minor flood is illustrated by the nor'easter of 11-12 December 1992. The maximum sea level at the Battery peaked at about 8.5 feet above mean sea level. Although the levels at which floodwater begins to enter or cover vital systems were surpassed by only one or two feet for fairly brief periods, near paralysis of the metropolitan region resulted. The flooding had major impacts on transportation systems, shutting down the New York City subways and the PATH system to New Jersey. If the storm surge had peaked only two feet higher, lives could have been lost both on rail systems and the roadways.

Considering the millions of people who live in this region and the trillions of dollars worth of property at risk, it is timely to examine what can be done to protect the region from flooding. What can be done? Conceivably, local flood defenses such as dikes and

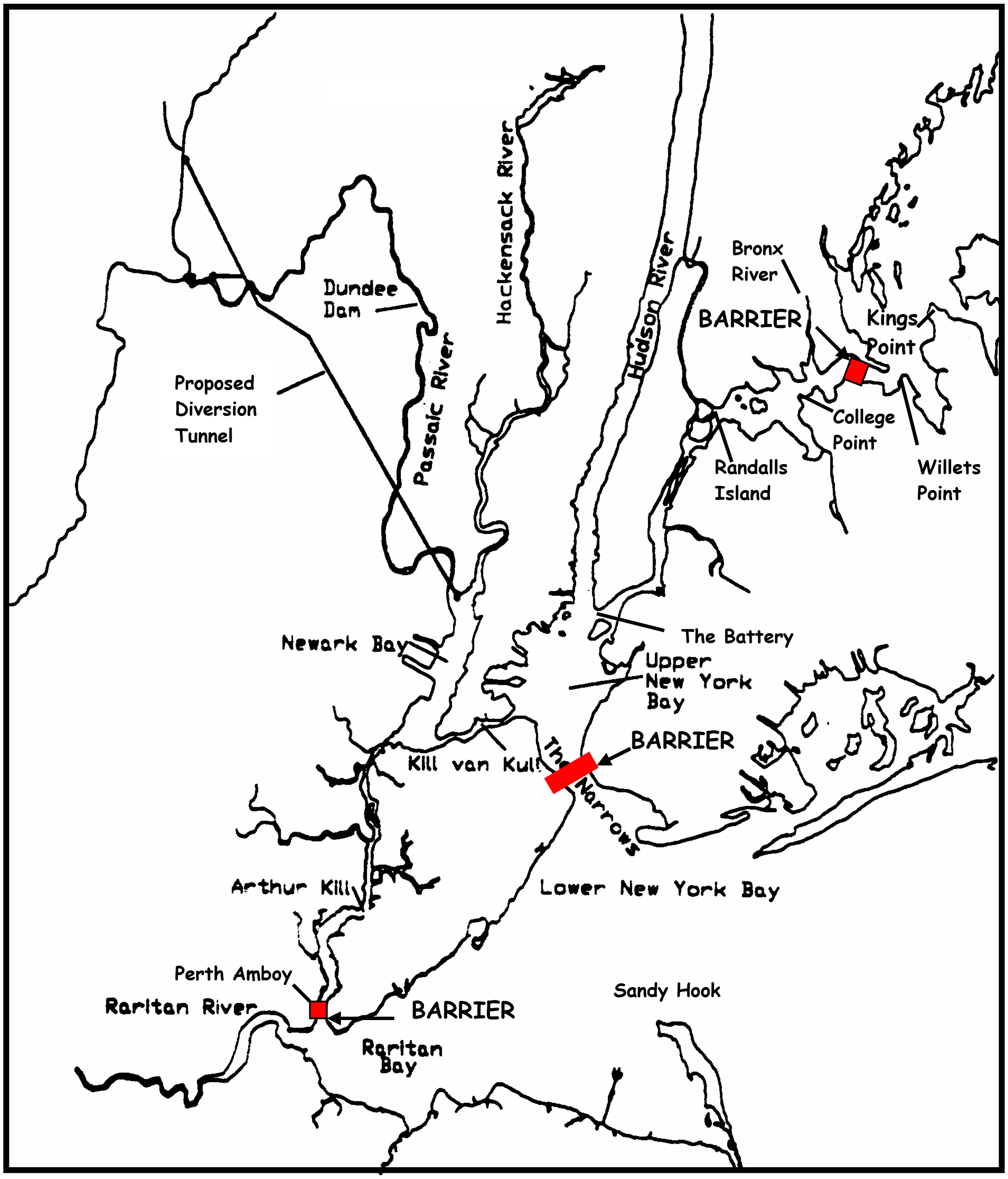


Figure 3. The waterways surrounding New York City can be protected from coastal flooding with three barriers. Figure adapted from Cerco, C.F., B. Bunch, and J. Letter. Impact of flood-diversion tunnel on Newark Bay and adjacent water, Journal of Hydraulic Engineering, April 1999.

seawalls could be built for vulnerable coastal infrastructure. Retreat from the shoreline – abandoning coastal structures – seems unrealistic in New York City, and much waterfront infrastructure, such as wastewater treatment plants, electric generating plants, and waste transfer stations, needs to be there. An alternative is to follow the several examples elsewhere, and construct storm surge barriers.

The Regional Waterways

The configuration of the waterways surrounding New York City lends itself to this possibility. Closing three narrow passages in the face of an imminent storm surge would protect the many square kilometers of property below the 3-meter contour line. These are the Narrows between the Upper and Lower New York Bays, the upper end of the East River where it joins Long Island Sound, and the mouth of Arthur Kill where it meets Raritan Bay (Figure 3).

The hydrological question is: if such barriers were built, how well would they work?

At the center of the New York – New Jersey estuary is Upper New York Bay. It is joined to the east through the East River to Long Island Sound. It is joined to the west through Kill Van Kull to Newark Bay. Newark Bay connects to Raritan Bay and the Atlantic Ocean through Arthur Kill on the western edge of Staten Island. The Hudson River flows into Upper New York Bay from the north. The Passaic and Hackensack Rivers flow into Newark Bay. The Raritan River enters Raritan Bay next to the mouth of Arthur Kill.

Hydrologically, it is a very complex region. Incoming tides move through the Narrows and up the Hudson River as a progressive wave with a tidal amplitude of less than one meter. Slack water during the passage of a progressive wave is normally at mid-tide. With the outflow of the Hudson River superimposed on the tidal motion, however, slack water occurs when the river flow is equal to the in-flowing tidal current.

On the other hand, at the upper end of the East River, tidal motion in Long Island Sound is approximately a standing wave. Slack water occurs when the tide turns at high and low water. The tidal amplitude is more than one meter, and high and low water are reached a few hours later. Currents through the East River – actually not a river but a strait that connects these two disparate tidal regimes – reach 2.5 meters per second in velocity. The flow through the East River is also affected by its connection, at mid-river, through the Harlem River to the Hudson above Manhattan.

The Hydrodynamic Model and Database

To simulate the hydrodynamics of the region, the ADCIRC (Advanced Circulation Model for Coastal Ocean Hydrodynamics) model was selected. ADCIRC is a system of computer models for solving time-dependent, free-surface circulation and transport problems in two dimensions. It was developed to model tidally and wind-driven circulation in coastal waters, and for forecasting hurricane storm surge and flooding. It has been extensively applied to New Orleans, the most severely threatened coastal region in the country.

Unlike other similar models of the waterways of the metropolitan region, ADCIRC can represent coastal flooding, showing the extent to which floodwaters reach inland and then retreat. To make use of this capability, a unique database had to be developed for the metropolitan region that seamlessly integrates bathymetric and topological data (Figure

4). Bathymetric data showing water depths and topological data showing land elevations have been developed for different purposes by different government agencies at different times, and they are referenced to different vertical datums. Moreover, both the bathymetric and topographic datums themselves have changed over time. Tidal datum levels change spatially because of spatial changes in tide range, dredging of waterways, changes in weather conditions, and sea-level rise.

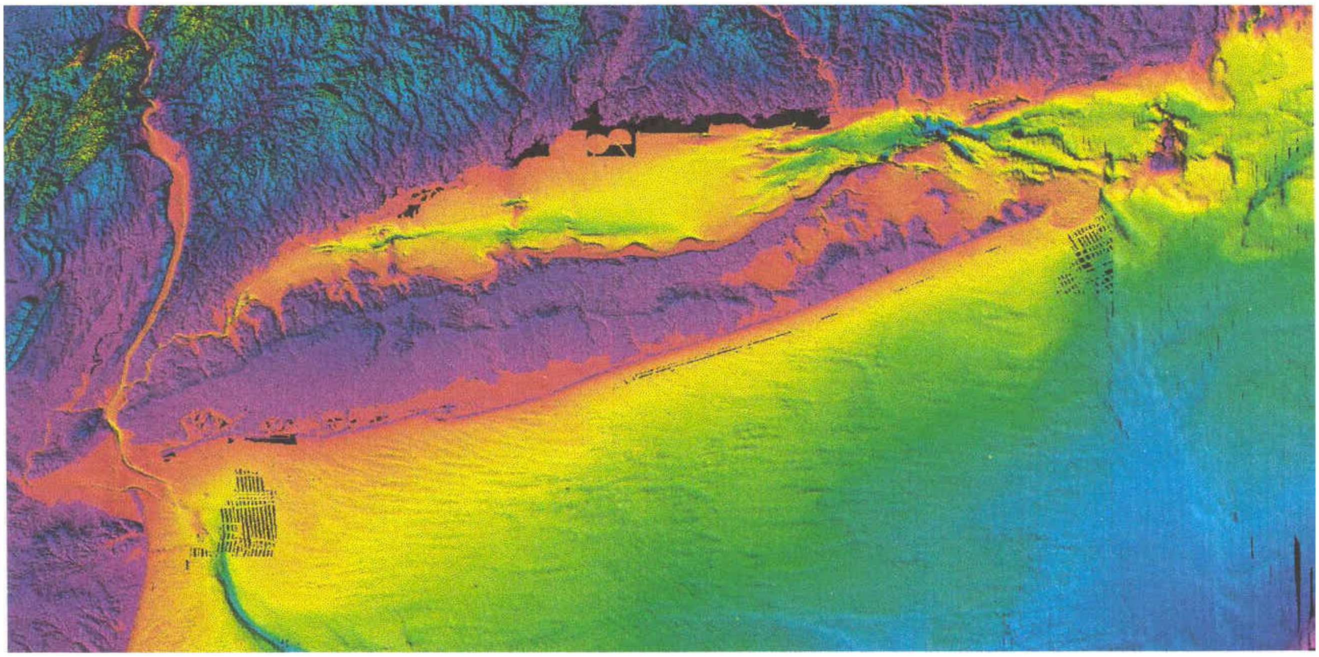


Figure 4. SBSS database is a seamless integration of bathymetric and topographic data.

Both topographic and bathymetric data were converted to the North American Datum of 1983 (NAD 83) using data from many different sources available in early 2002. Improved data continue to become available due to changing terrain and improved technology. We anticipate that the combined bathymetric-topographic database will be updated as our interests expand to larger areas and better data become available.

The Meteorological Model

Storm surges are created by surface winds and a drop in barometric pressure. A representation of the meteorological conditions in hurricanes and severe nor'easters is needed to drive the hydrodynamics in ADCIRC. Fortunately, the Stony Brook Marine Sciences Research Center (MSRC) has for several years of experience in applying and refining the MM5 meteorological model for local weather forecasting.

MM5, the Penn State – National Center for Atmospheric Research model, is a terrain-following sigma-coordinate model designed to simulate and predict mesoscale and regional atmospheric circulation and precipitation. Since September 1999, MSRC, in collaboration with the National Weather Service forecast office in New York City, has been running MM5 in real time twice daily and posting the results on the Web. The local

National Weather Service and other forecasters use the MM5 predictions in their daily operations to help forecast weather in the metropolitan region. These forecasters also provide feedback on the model performance, which has been useful in fine-tuning the model. All real-time MM5 forecasts have been verified using all conventional surface and upper air data. An ensemble MM5 forecast system has recently been developed, which uses various initializations and model physics to help quantify forecast uncertainty.

The domain of the MSRC MM5 model, centered on New York City, covers most of New Jersey and Connecticut and extends out to sea to the edge of the continental shelf (Figure 5). The local MM5 model is driven by atmospheric conditions simulated in the two larger National Weather Service models in which it is embedded, which have domains extending across the country but with more coarse resolution.

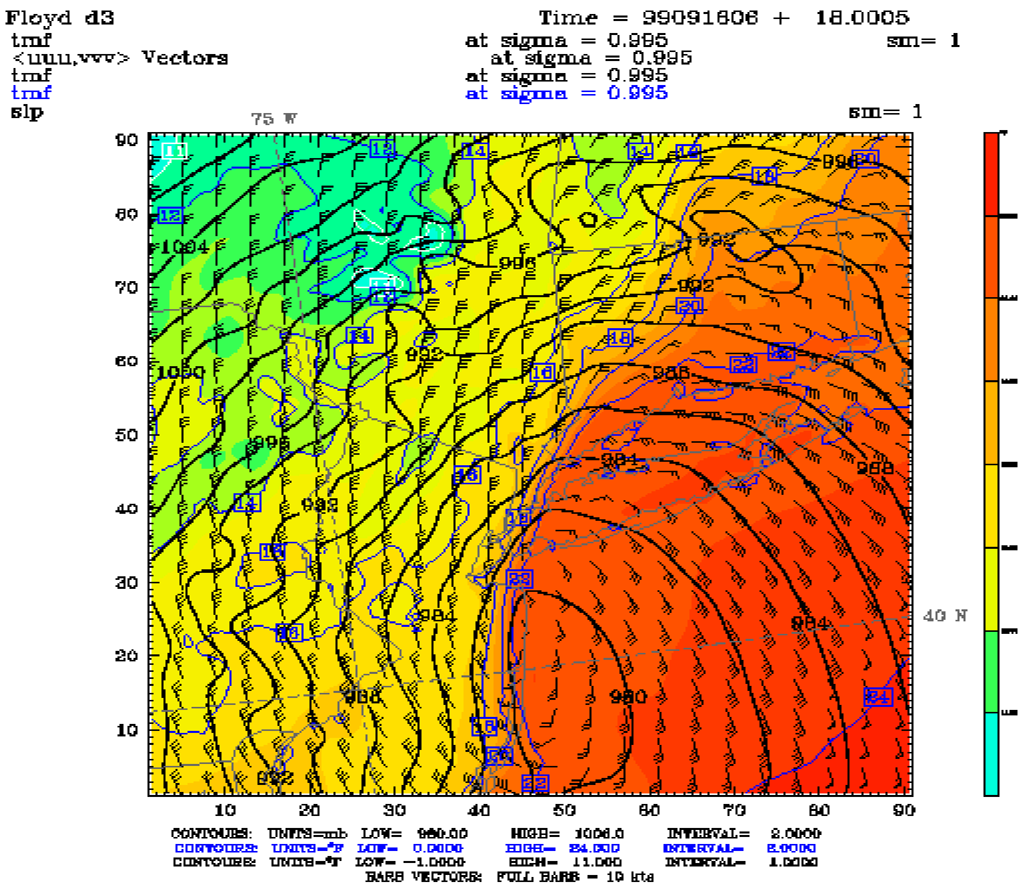


Figure 5. MM5 meteorological model simulation of Hurricane Floydapproaching the metropolitan region shows winds, barometric pressure and temperature.

The database that has been retained for MM5 includes time-tested simulations of two severe storms, Hurricane Floyd (downgraded in this region to a tropical storm) of September 1999 and the December 2002 nor'easter, which caused local storm surges. These were used to validate the Stony Brook Storm Surge model, as described below.

Stony Brook Storm Surge System

The winds and barometric pressure computed by the MSRC MM5 model are used to drive the ADCIRC hydrodynamic model in the Stony Brook Storm Surge System (SBSS). This linkage consists of a series of computer scripts to interpolate MM5 winds and pressures at one-hour intervals to the SBSS grid. With our present computer, it takes three hours of clock time to run one model tidal cycle.

The ADCIRC calculations are made for each of thousands of nodes in a grid of triangular elements (Figure 6). For the water grid without inland flooding, there are 12,000 nodes. With the model domain to include inland flooding, there are approximately 85,000 nodes.

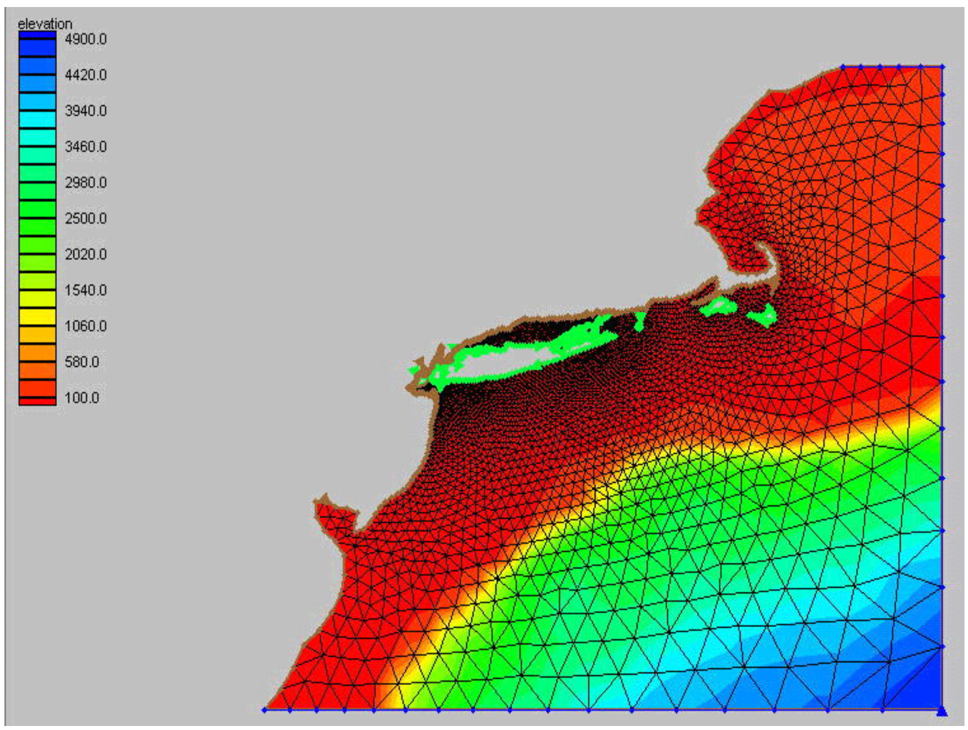


Figure 6. Domain of the ADCIRC model showing the varying size of the triangular grids according to the detail needed to simulate the hydrodynamics.

The size of the triangular elements varies with the refinement needed for the local simulation. Far at sea, the elements are about 70 kilometers on a side. In narrow passages within New York City, there are at least five elements across each channel. Closer grid spacing is used where more detail in the current behavior is needed. The grid was established using the Surface-water Modeling System (SMS) with special care to define the coastlines. In New York harbor, virtually the entire coastline is bulkheaded, and the elevations of the tops of the bulkheads are not precisely known. For our purposes, they were all assumed to be one meter above mean sea level.

The SBSS domain was chosen to match that of MM5. This extends from 37^{o} to 44^{o} north latitude, and from 68^{o} to 76^{o} west longitude. The grid over water extends up the Hudson

River to Hastings-on-Hudson and otherwise stops at the mouths of the rivers. On land, the grid extends to the 8-meter contour line, limited to the east by the extensions of a transect across Long Island Sound from Rye in Westchester County to Matinecock Point in Nassau County.

Validation of SBSS

The SBSS model was validated by comparing its simulation of water levels in a hurricane and a nor'easter with actual observations, with no "tuning" of the model necessary to improve the match. The storm surges from hurricanes and nor'easters are typically quite different. In hurricanes, the surge comes on very rapidly, peaking in a few hours. This is followed by a trough that is much lower than normal, and possibly a second high peak before the normal tidal fluctuation resumes. Nor'easters, on the other hand, typically come on slowly, but elevated water levels may be experienced through several tidal cycles over a few days.

The storms chose for validating the SBSS model were Hurricane Floyd of September 1999, which had been downgraded to a tropical storm by the time it reached New York, and the Christmas 2002 nor'easter. These were chosen because we have the MM5 meteorological simulations to drive the storms. The timelines of water levels were compared over three and a half days at three locations: the Battery, Sandy Hook, which is south of the Narrows, and Willets Point or nearby Kings Point, which is near the juncture of the upper East River and Long Island Sound.

In all cases the simulation of the tidal fluctuation preceding the arrival of the storm surge closely tracks observed values, both in phase and amplitude, with the diurnal variation between successive high tides evident. In the 2002 nor'easter, the only difference between simulated and observed values is a slightly higher (about 0.2 meters) peak at the Battery and Sandy Hook (Figure 7).

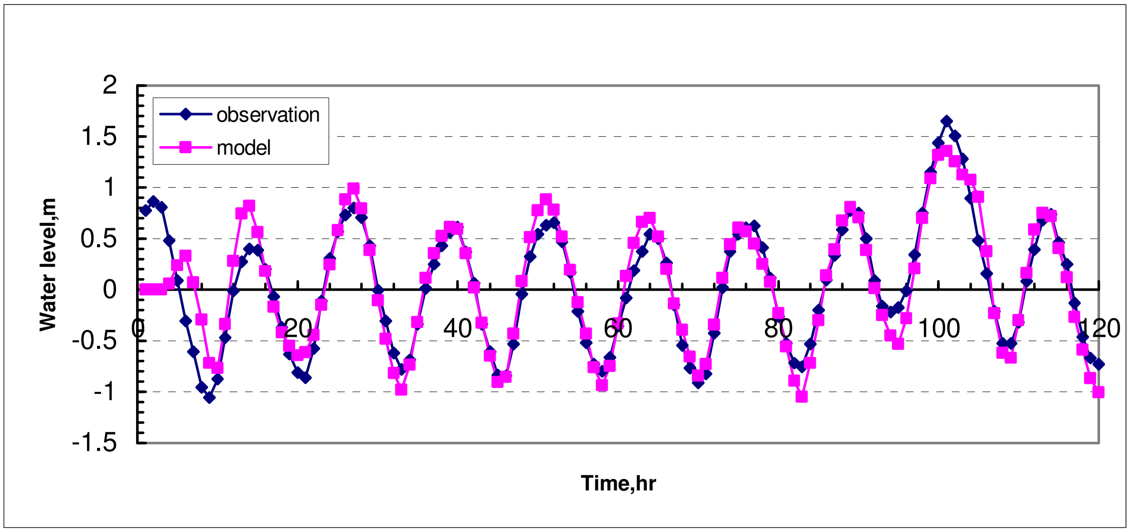


Figure 7. Ths SBSS simulated values of water level at the Battery during the December 2002 nor'easter closely match those actually observed.

The Floyd simulation similarly tracks the normal tidal variation closely, with only a slight displacement in time (observations lagging about one hour) evident at Willets Point. The highest peak water levels during the storm surge also match closely. Following that, however, the observed value drops below the simulated value through about one tidal cycle before resuming the track at the Battery and Sandy Hook (Figure 8). At Willets Point, there is a similar difference between the observed and simulated water levels at the next high tide. Despite this unexplained discrepancy, the otherwise excellent match between simulated and observed values through the peak water level is taken as validation of the SBSS model.

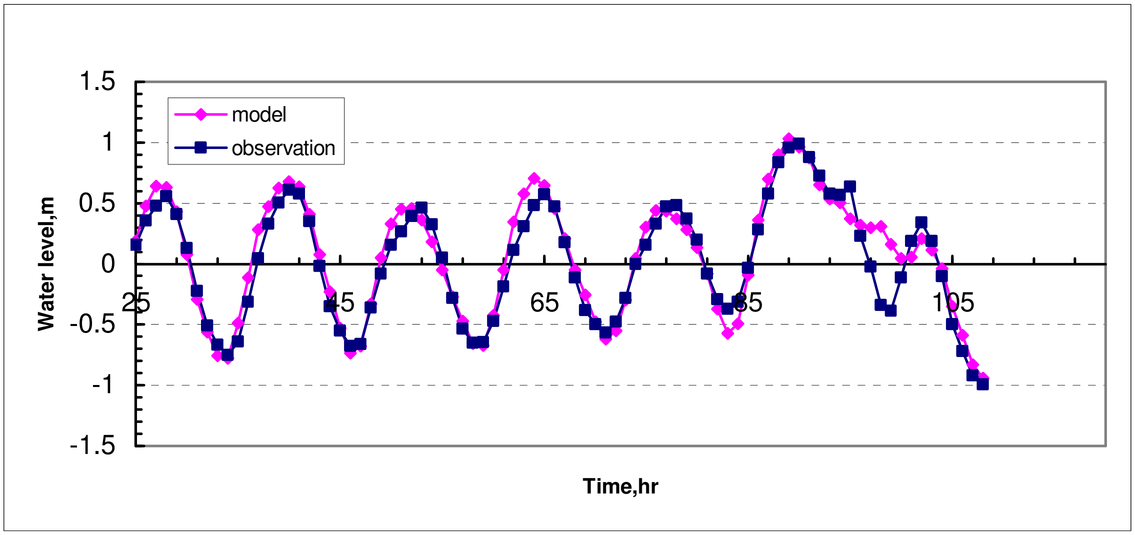


Figure 8. The SBSS simulated values of water level at the Battery closely match those actually observed in Tropical Storm Floyd through the storm surge peak.

Scenario Results

The performance of the storm surge barriers was then examined for a number of different operational scenarios. To assure that coastal flooding was observed, a synthetic storm, Super Floyd, was created by increasing the wind speeds of Floyd by a factor of 1.6, thus doubling the wind force. This led a peak water level at the Battery of 1.2 meters, higher than the one-meter peak of Tropical Storm Floyd, and higher than the one-meter height assumed for bulkheads in New York City.

Three Barriers Closed

To simulate normal barrier operation, the three barriers were closed at slack water before the surge from Super Floyd, and then reopened when the water levels equalized inside and outside the barriers. The barriers worked as expected, with water at or below normal sea level at each of the three barrier locations and the Battery (Figure 9).

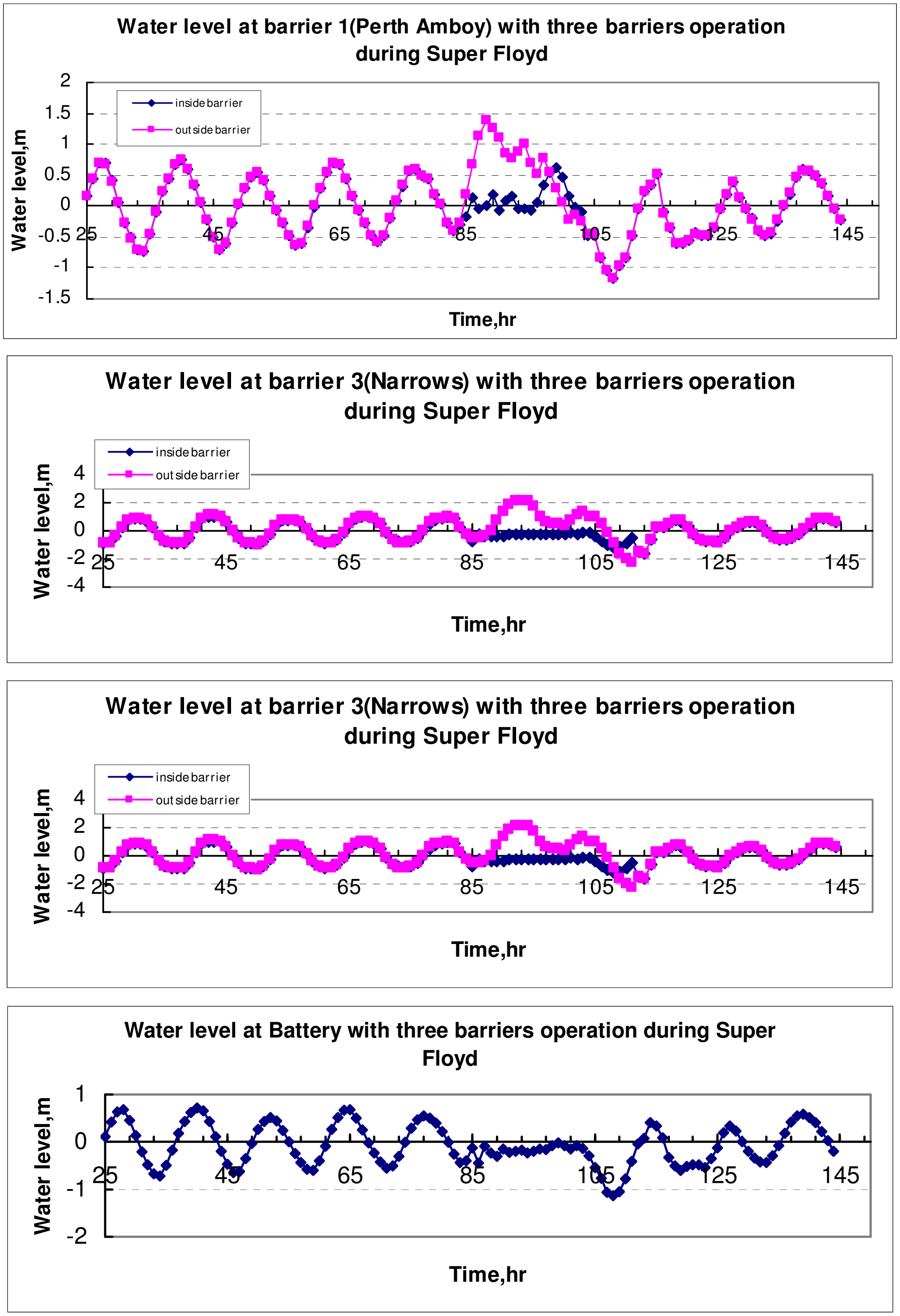


Figure 9. Closing the three barriers during Super Floyd lowers the water level inside the barriers to approximately mean sea level.

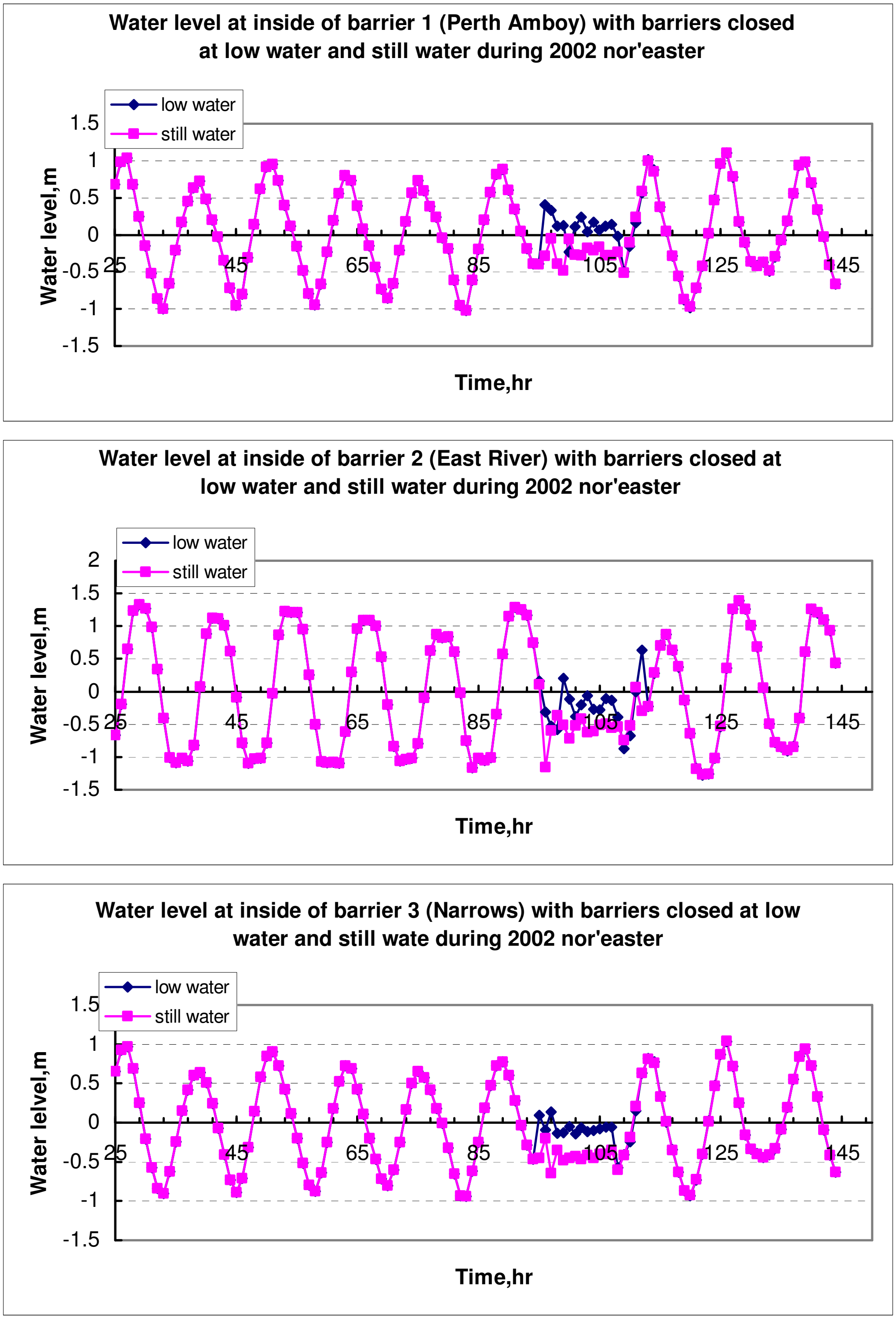


Figure 10. In the 2002 nor'easter, closing the barriers at slack water leads to lower water levels behind the barriers than if they were closed at low water.

When the barriers are closed at low water for Super Floyd, the water levels inside the three barriers remain negligibly lower inside the three barriers. Closing the barriers at low water in the 2002 nor'easter leads to a slightly higher water level inside the barrier than if they were closed at slack water. Still, it is below sea level at the Narrows and East River barriers, and only slightly above sea level at the Perth Amboy barrier (Figure 10).

Three Barriers Partially Closed

To investigate the effect of partial restrictions to the storm surge, the model was run with the three barriers extending into the waterway one-quarter, one-half and three-quarters across the span. Barriers one-quarter closed could be seen to represent the restriction due to fixed piers in the river on which the moveable barriers are mounted. (By comparison, the piers at the Thames River barrier occupy 18 percent of the river width.) The peak water level was measured a few kilometers inside the barriers. No refinement in the gridding was made to better represent the restricted flow through the partially closed barriers.

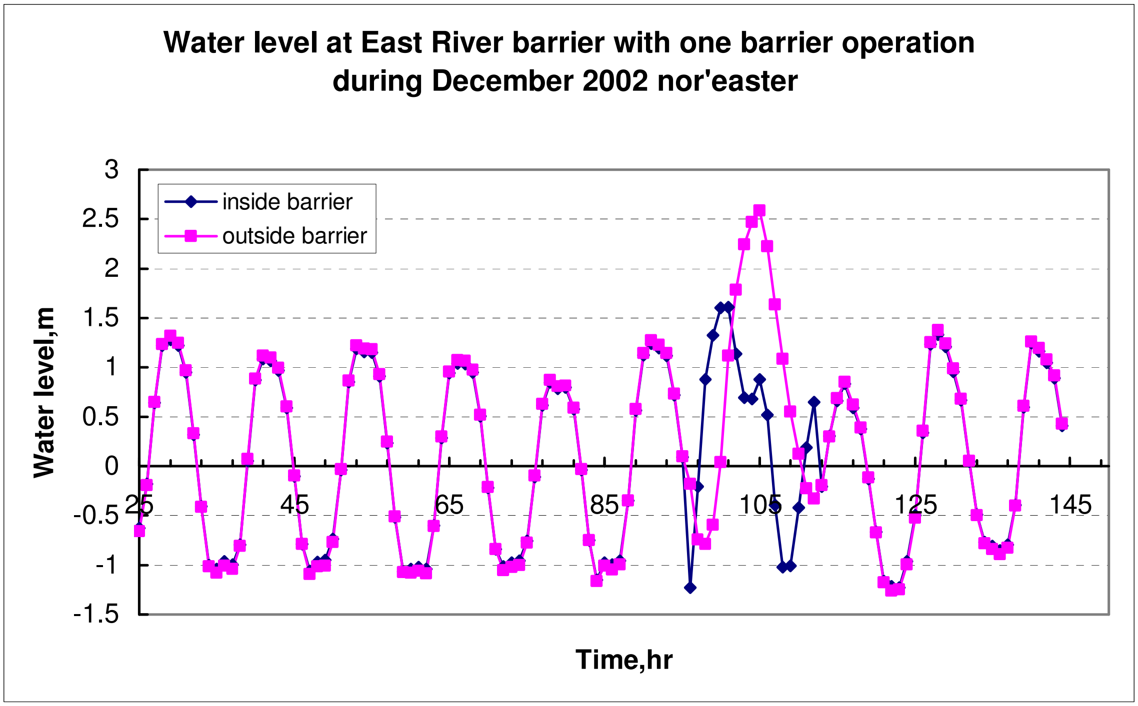
The results were inconsistent. With the barriers one-quarter closed, the peak water levels were higher by 0.6 to 0.8 meters than with no barriers, except at the East River barrier where it was about the same. With the barriers one-half closed, the peak water levels were only slightly higher, by 0.1 to 0.3 meters, than with no barriers, except at the East River barrier where it was 0.8 meters lower. With the barriers three-quarters closed, the peak water levels were moderately higher, by 0.3 to 0.5 meters, than with no barriers, except at the East River barrier where it was 0.5 meters lower.

To investigate more conclusively the effect of partially closed barriers, a finer representation of the flows through them is needed. This can be achieved by refining the gridding around the barrier piers that takes into account their size, shape and location.

Single Barrier in the East River

With nor'easters the more common cause of flooding in the metropolitan region than hurricanes, the use of a single barrier in the East River deserves examination. Northeast winds drive surface currents directly down Long Island Sound to the bottleneck at the upper end of the East River. However, due to the Ekman effect, northeast winds south of Long Island tend to drive surface currents to the right, and thus into New York harbor.

With a single barrier located in the East River at College Point/Ferry Point Park, the water level just inside the barrier rises no higher than the normal high water level (Figure 11). The peak water level at the Battery, located at the other end of the East River, is essentially unaffected by closing the East River barrier, presumably due to the surge driven through the Narrows. The water level on the east side of barrier rises 0.27 meters from what it would be without the barrier. However, this rise diminishes, roughly exponentially, to the east of the barrier, dropping by about one-third at Willets Point (Figure 12).



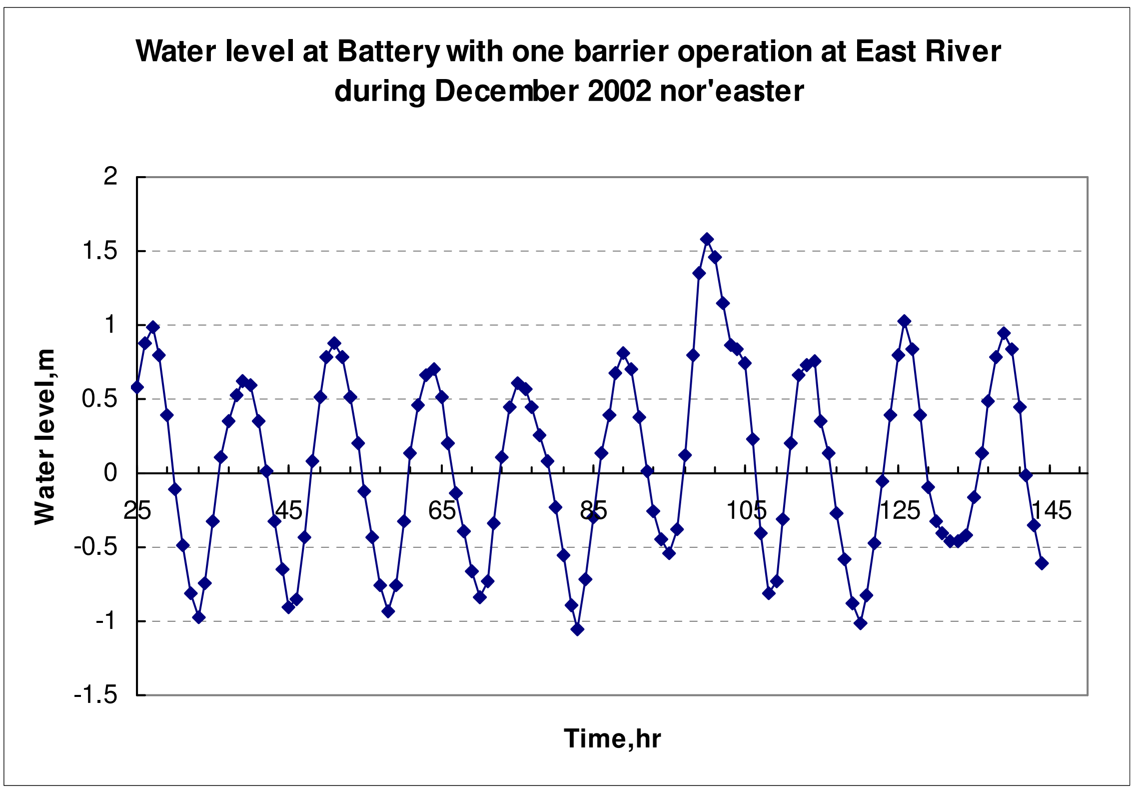
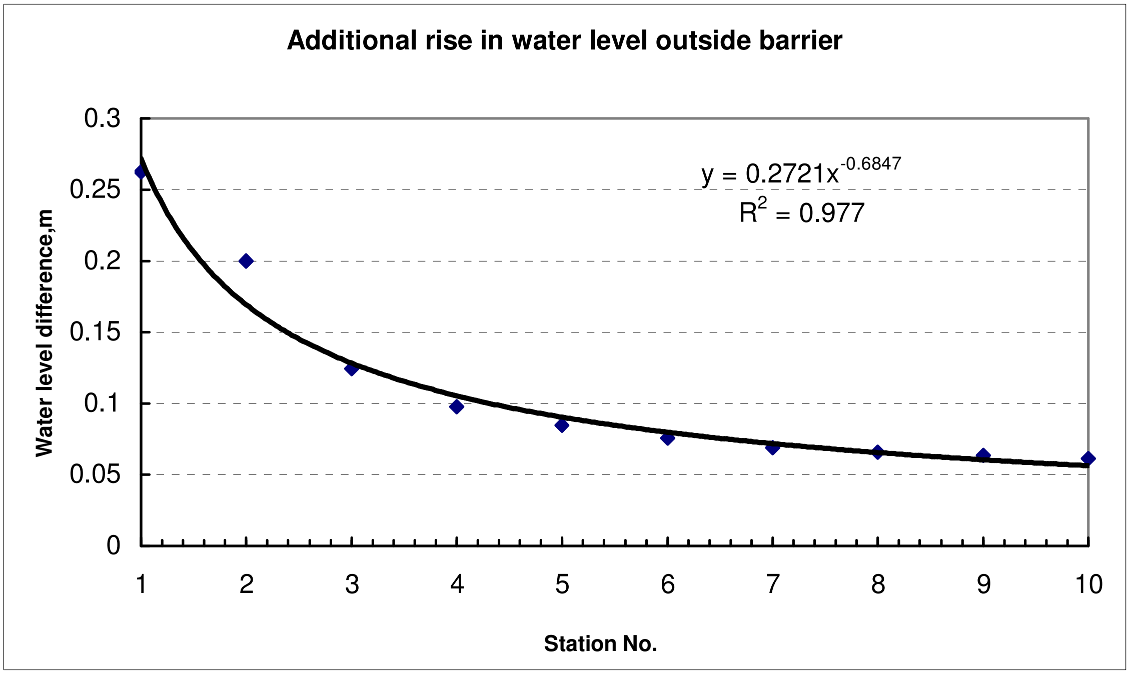


Figure 11. With a single barrier, located in the East River, the storm surge from Long Island Sound is stopped, but the water elevation west of the barrier nevertheless reaches flood level.



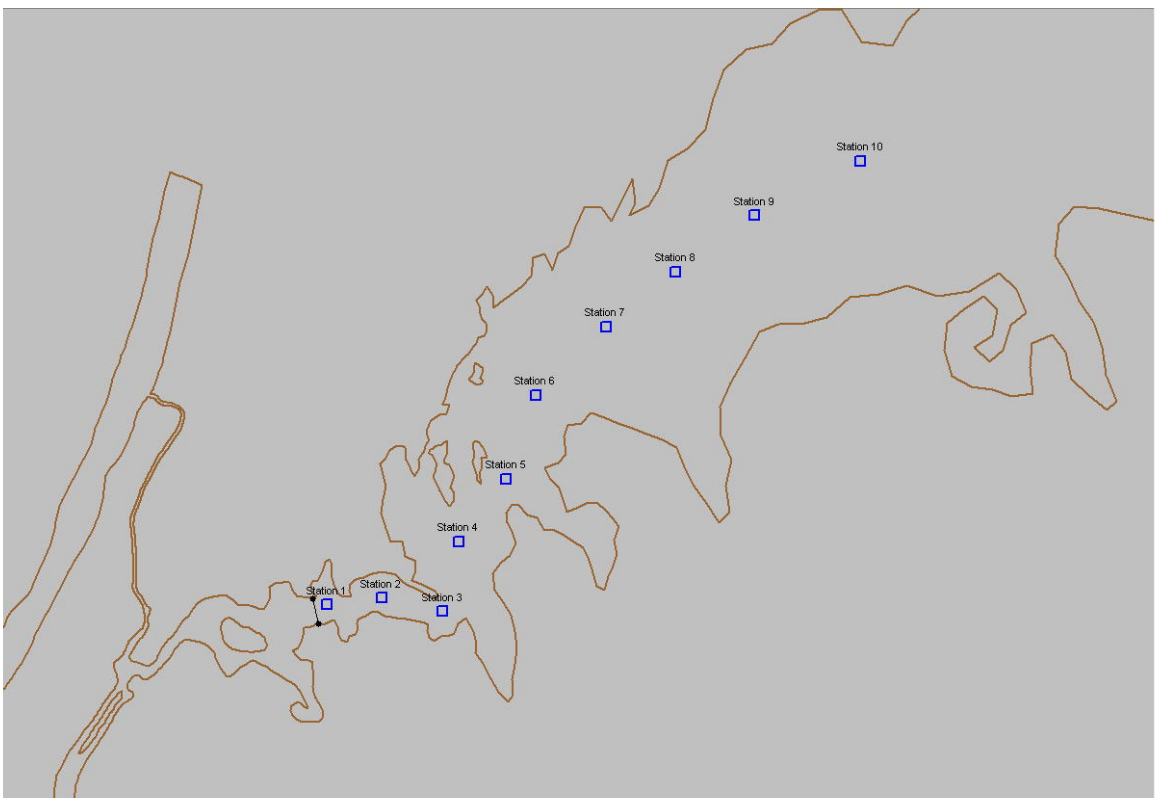


Figure 12. Pushed against the closed East River barrier in the 2002 nor'easter, the water level rises an additional 0.27 meters. However, this additional rise diminishes exponentially with distance from the barrier, dropping by about one-third at Willets Point.

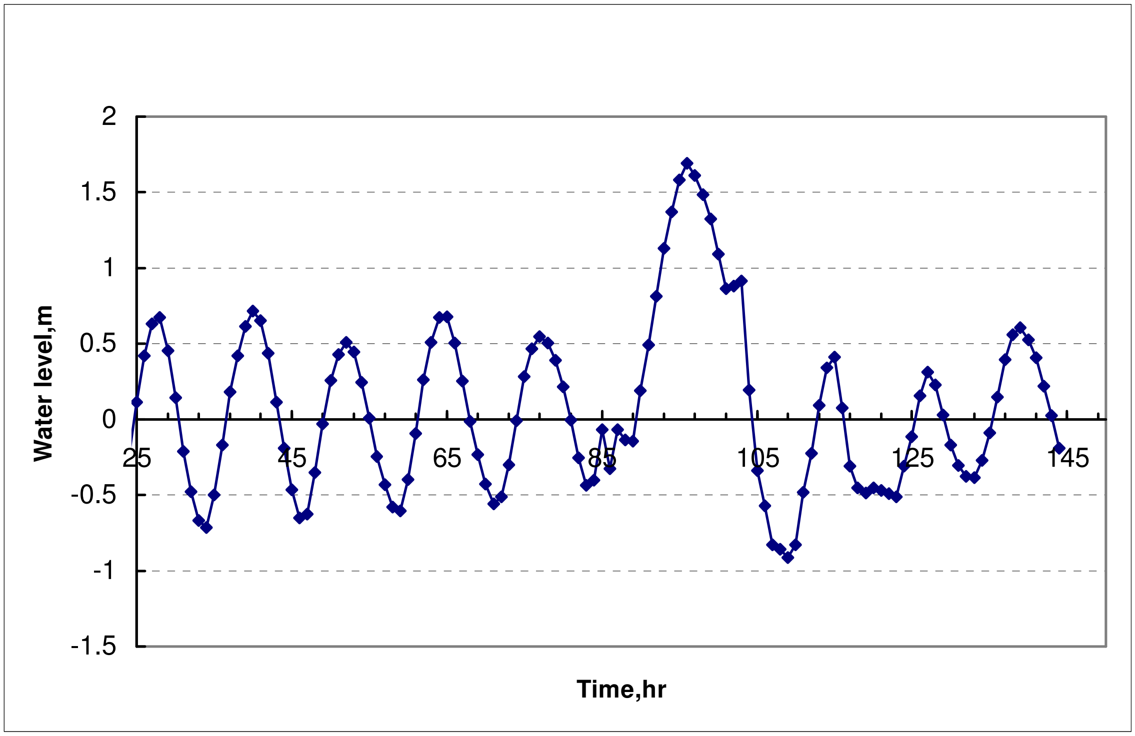


Figure 13. With two barriers closed and the East River open during Super Floyd, the peak water level is higher than if all three barriers were open.

Two Barriers Only at the Narrows and Perth Amboy

Suppose that the East River barrier was inoperative, and only the two barriers at the Narrows and Perth Amboy were closed during Super Floyd. Would that reduce flooding in the central city? Apparently, the opposite is true. With only the two barriers closed, the peak water level at the Battery reaches 1.6 meters, compared to 1.2 meters with all barriers open, apparently due to the influence of the higher water level peak that occurs at the upper end of the East River (Figure 13).

Water Levels Outside the Ocean Barriers

We have seen that closing the East River barrier raises the peak water levels on the outside the barrier an additional 0.28 meters. Does this additional rise also occur outside the closed barriers at the Narrows and Perth Amboy, which face the open ocean. Qualitatively, yes. The water level is higher at the barrier face and diminishes with distance from it, but the maximum rise is only about 4 to 8 centimeters.

Coastal Flooding

The purpose of the barriers is to protect the inner city and nearby New Jersey from coastal flooding due to storm surges. Scenario runs were made for Super Floyd to generate maps of areas subject to coastal flooding inside and outside the barriers. It was assumed in all cases that the protection offered by the barriers was extended inland with dikes high enough to prevent the high water bypassing the barriers.

To identify the flooding inside the barriers, the waterfront was tightly gridded inside the barriers. With Super Floyd, it can be seen that without barriers coastal flooding occurs around the edges of lower Manhattan, in nearby Brooklyn, at Hoboken and Jersey City (where high-rise commercial buildings have recently been built) (Figure 14).

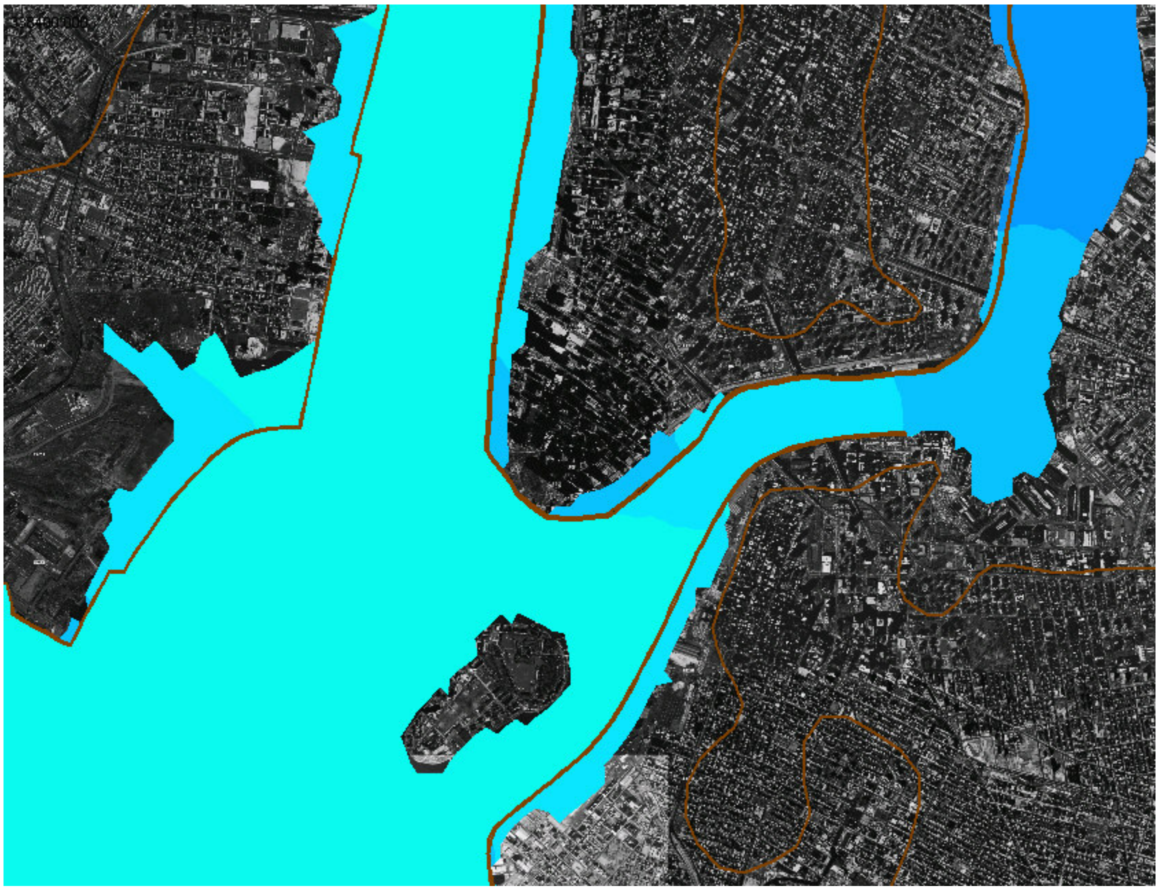


Figure 14. Superposition of Super Floyd flooding predictions and aerial photographs of lower Manhattan and environs.

Outside the barriers, La Guardia Airport would be flooded if the East River barrier were located to the west at Randalls Island (Figure 15). Flooding in other regions in the south Bronx might become evident if the coastal area were more tightly gridded in the model. Placing the barrier in western Long Island Sound, bridging City Island and Kings Point, would prevent flooding in the Bronx and unduly low water in Little Neck Bay following the storm surge.

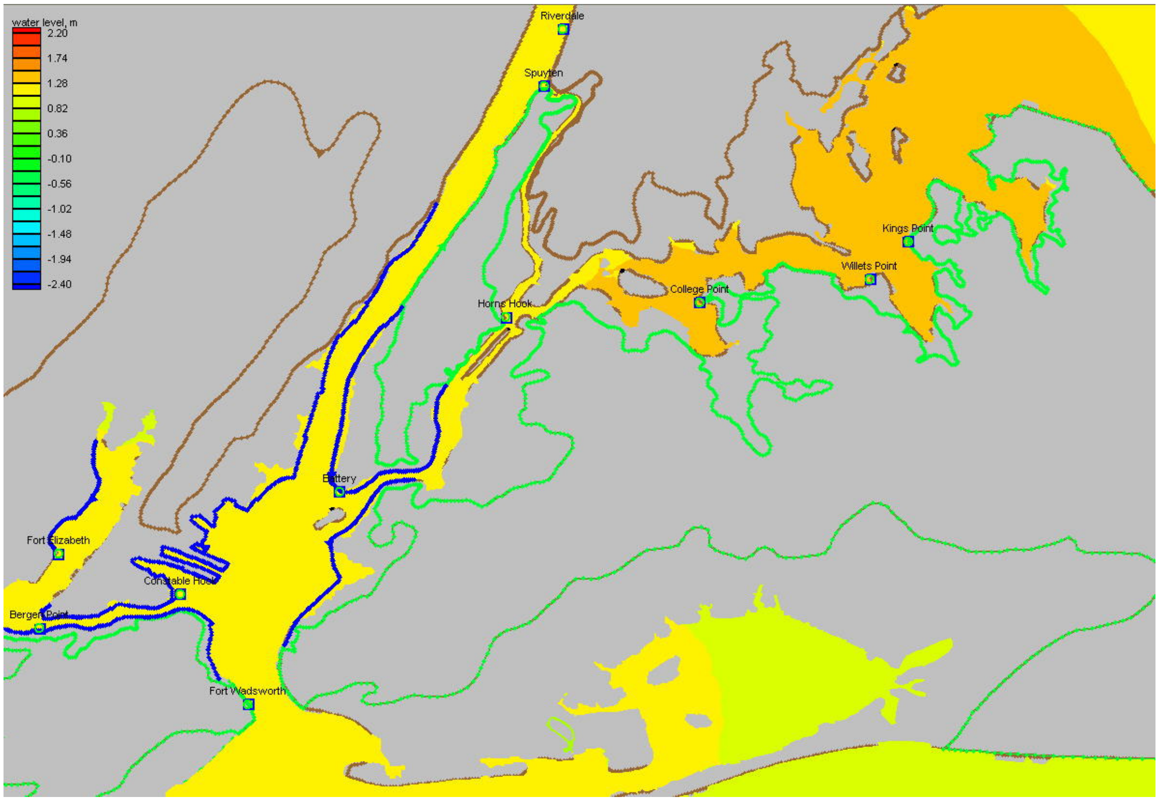


Figure 15. Without barriers in place, Super Floyd would cause coastal flooding in many areas within the central metropolitan region.

Rainfall Runoff Flooding

The question arises: Would rainfall runoff, especially through the rivers that empty into the waterways of the metropolitan region, accumulate to cause the flooding that the closed storm surge barriers were intended to prevent?

Our use of the SBSS model did not normally include flooding from rainfall runoff. However, the model shows that in Super Floyd, the water level behind the closed barriers would not otherwise rise above mean sea level. The normal tidal amplitude at the Battery is about one meter. Unless the accumulated rainfall exceeded one meter, therefore, there would be no flooding due to rainfall behind the barriers.

Hurricane Floyd, although it was downgraded to a tropical storm by the time it reached New York, was nevertheless the worst rainfall event in this region over the past half century. It set records for rainfall all up and down the Atlantic Coast, including the Raritan River basin in New Jersey, Windsor Locks in western Connecticut, and Albany, New York. Whether Tropical Storm Floyd would have caused an accumulation of rainfall behind the barriers of more than one meter is then the question.

The record of variation in the water level at the Battery during Floyd shows a spike of about 30 centimeters followed shortly after the peak runoff in the Raritan River (Figure 16). The Raritan River enters Raritan Bay, which is outside the Narrows. However, the peak runoff even appears evident at Sandy Hook, the outer boundary of Raritan Bay, as well as at the Battery. Thus, it appears that record rainfall in nearby New Jersey caused a peak in the water level of New York Harbor, but it would not have been sufficient to cause a freshwater flood behind the barriers.

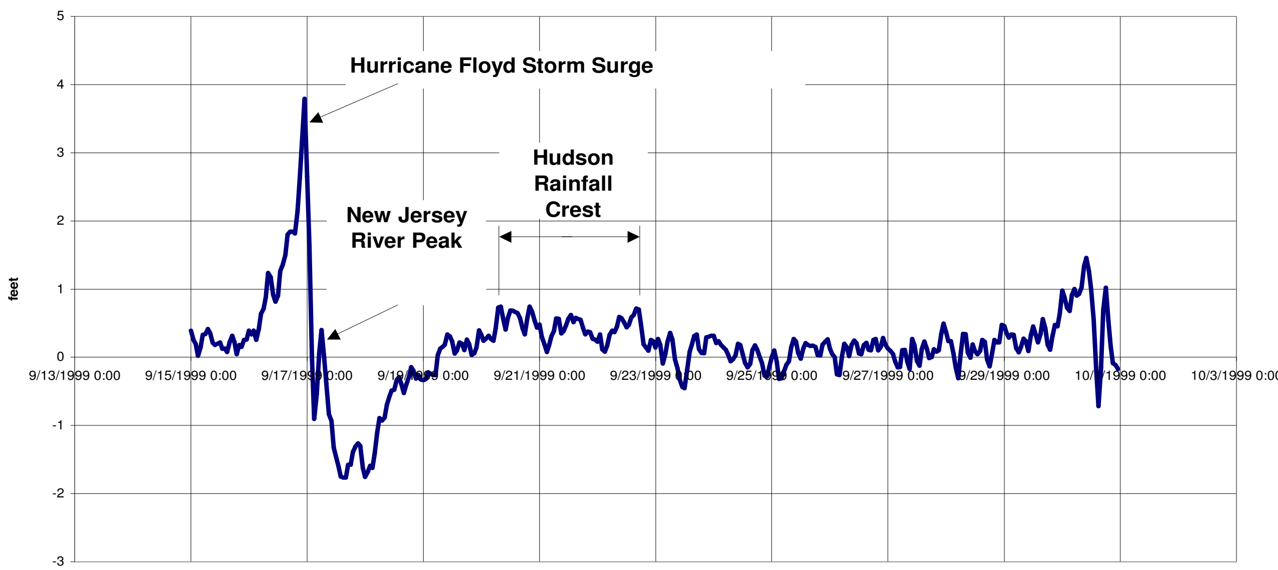


Figure 16. Deviations from normal tide levels at the Battery due to Tropical Storm Floyd.

The Passaic and Hackensack Rivers empty into Newark Bay, which is directly connected to Upper New York Bay, that is, behind the barriers. These did not experience the same intense rainfall as the Raritan River. However, the Passaic River, which loops through northern New Jersey, also drains much of northwest New Jersey through the Pompton River. Local flooding near the conjunction of these rivers has led to a proposed 32-kilometer long flood diversion tunnel that would channel upstate flood water directly into Newark Bay. This would raise the peak flow into the bay by 60 percent and cause it to occur 15 hours sooner. Combined with the Raritan River flow, this could have caused a higher peak in New York Harbor, but likely not one meter high.

The Hudson River watershed, in which rainfall records were also set during Floyd, is far greater in size than the New Jersey watersheds. However, it is almost entirely far upstate, and the rainfall runoff did not begin to reach New York City for 2½ days after the storm surge. The crest in the river runoff, about 14 centimeters high, lasted about 2½ days. Could this accumulation have caused flooding behind the barriers?

To answer this question, SBSS was run with the estimated Hudson River and Floyd runoff. During the 20 hours that the barriers would have been closed during Floyd, the accumulated runoff from the rain-swollen Hudson River would have raised the water level behind the barriers on the order of 0.25 meters (Figure 17).

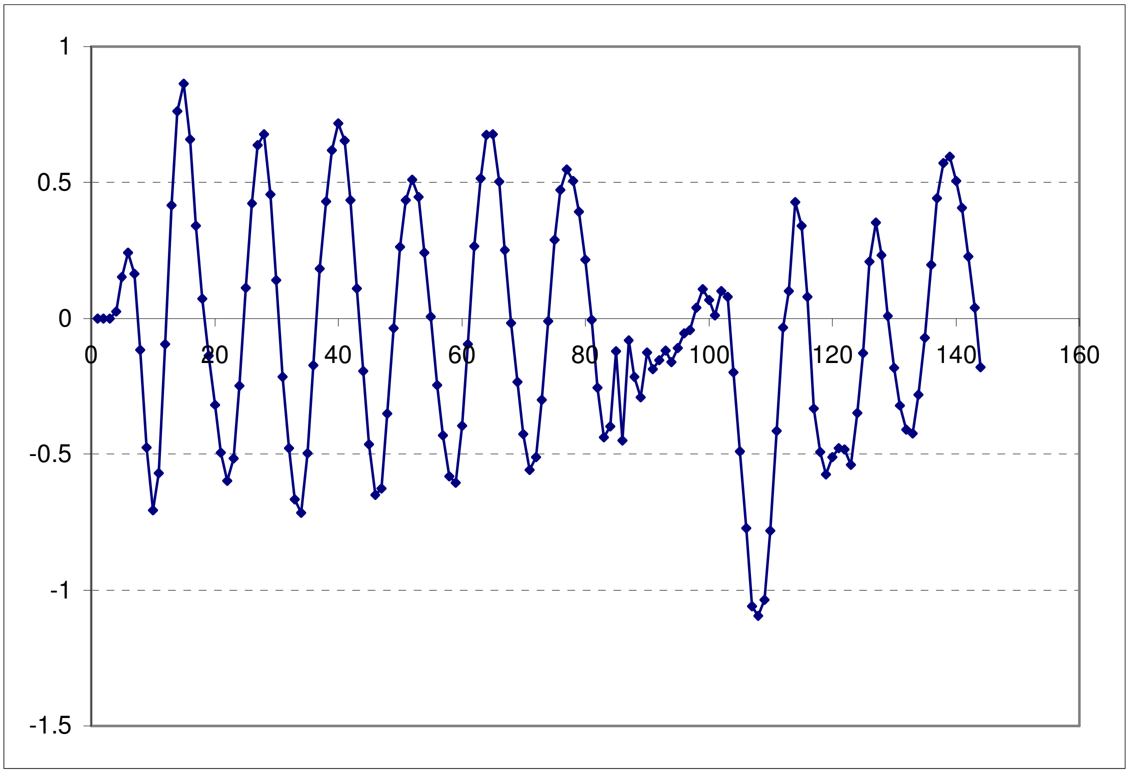


Figure 17. The SBSS simulation indicates that the water level behind the barriers would have risen about 0.25 meters due to the inflow from rain-swollen rivers during the 20 hours the barriers were closed in Tropical Storm Floyd.

The surface area of the waterways surrounding New York City, reaching up the Hudson River about 33 kilometers, is 133 square kilometers. The slope of the river is exceedingly slight, dropping only about 20 centimeters in the lower 48 kilometers. This provides an enormous reservoir in which to accumulate rainwater. As estimate that took only the storage area in the Hudson River into account indicates that the rise in water level behind the barriers would have been about 0.3 meters if they were closed for 20 hours. Moreover, even if the closing time were doubled to 40 hours, the rise would have been less than 0.4 meters (Figure 18).

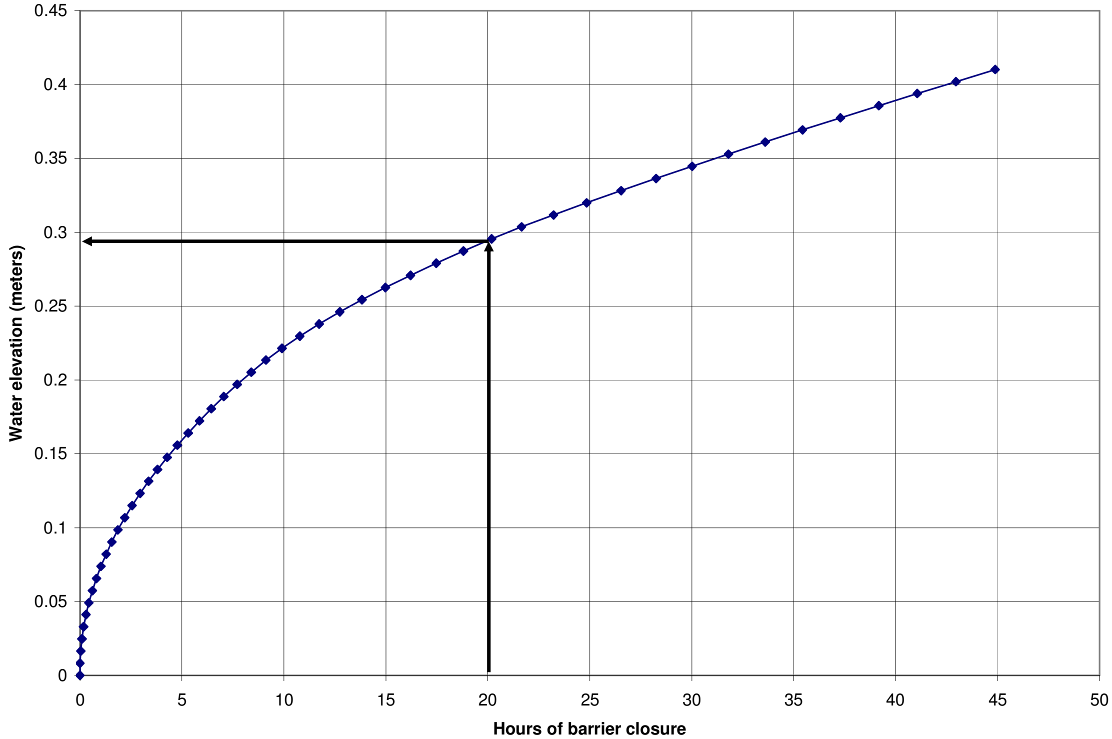


Figure 18. Considering only the storage volume above the upward sloping Hudson River, the rainfall runoff crest would raise the water level behind the barriers less than 0.3 meters during the 20 hours that they would have been closed for Tropical Storm Floyd, and less than 0.4 meters in 40 hours.

There is no fixed relationship between the timing of a storm surge and rainfall runoff crest. However, the Hudson crest is likely to lag the New Jersey river rainfall crest by two or three days, so they are not additive. We conclude from the record of Tropical Storm Floyd that rainfall runoff is unlikely to cause flooding behind the barriers, even if they were closed for a few days.

Existing Storm Surge Barriers

The several storm surge barriers in operation in New England and Europe demonstrate a variety of structural designs that have performed well for a few decades. The three barriers in New England, completed in the 1960s, are smaller in size than would be needed in the metropolitan region, and they were built before many of the present review processes were established. The Thames barrier in England, opened in 1984, is now operated to prevent flooding more than a dozen times a year, twice the earlier rate. In the Netherlands, the massive Delta Project has included three moveable barriers, the first completed in 1958 and the most recent in 1997. In Italy, work has begun to close the three inlets to the Venetian lagoon after decades of controversy.

Except in the case of Venice, where chronic flooding threatens the very foundations of the city, these barriers were built in response to flood disasters. The September 1938 hurricane left 600 dead in Providence, RI, and was followed by Hurricane Carol in 1954 when 60 died. In a 1953 storm in the North Sea, 300 drowned due to the Thames River flooding. In the Netherlands, where the dikes collapsed, 1,835 people drowned, 100,000 had to be evacuated, and 200,000 hectares of land flooded. It remains to be seen whether it will take a similar disaster for storm surge barriers for the New York – New Jersey metropolitan region to be seriously considered.

In all these cases, a national decision was required to build the barriers, and national funding was provided. In all cases, the local population remained exposed as decades passed from the time of the disastrous flood to the completion of barriers. In the face of projected worsening of flooding in the metropolitan region due to global climate change, the exposure time can be reduced by preliminary planning now.

The hurricane barriers in New England were designed, built and continue to be overseen by the New England District, U.S. Army Corps of Engineers, although they are operated by local authorities. The Fox Point Barrier at Providence, is a 7.6 meter (25 foot) high concrete structure which spans the 88-meter (290 feet) wide Providence River, contains three tainter gates in openings 12.2 meters (40 feet) wide (Figure 19). The tainter gates rotate on a horizontal axis to provide an overhead clearance of 7.6 meters (25 feet). The gates can be closed in 25 minutes, and opened in 75 minutes. The narrow river upstream of the barrier has no reservoir capacity, and, alone among the existing barriers, the structure includes pumps to remove the water that accumulates behind the closed barriers. Dikes extend from both ends of the barrier to higher ground.

Figure 19. Hurricane barrier at Fox Point, Providence, Rhode Island, showing pump house on the left and three open tainter gates on the right.

Figure 20. Hurricane barrier at New Bedford, Massachusetts, looking east toward Fairhaven, showing the open sector gates in the distance and a conduit gate in the foreground.

The New Bedford barrier is a 6.1-meter (20-foot) high, 1,370-meter (4,500) foot long structure consisting of a packed clay core faced with large boulders (Figure 20). The structure extends along the New Bedford shore as a massive dike, part of three sets of dikes in the area. There is a 46-meter (150-foot) opening in the barrier that can be closed with two facing sector gates. The gates rotate on a vertical axis, rolling on steel wheels that ride on the concrete sill 12 meters (39 feet) below mean sea level. Compressed air jets blow away any sediment in front of the wheels. Like the Providence tainter gates, the New Bedford sector gates have a circular face, so that hydrostatic pressure on them is aimed through the axis and therefore does not resist their rotation through the water. Closure procedures begin one-half hour early to allow a 20-minute warning to mariners and 12 minutes for the gates to close.

The hurricane barrier on the East Branch above Stamford Harbor is a 28.6-meter (94-foot) wide flap gate, a hollow steel structure that normally rests on the bottom sill 4.3 meters (14 feet) deep (Figure 21). The gate is hinged at the bottom and is raised by arms attached to the gate and an operating mechanism at the top of the abutment, an operation taking 20 minutes. Although it would seem that the barrier operation might be obstructed by the accumulation of sediment, it has only been necessary to remove a small amount of material 153-229 cubic meters (200-300 cubic yards) once. There was a problem with the gate skewing while it was being raised, but this have been remedied by upgrading the gate-lifting mechanism with computer-monitored sensors. During the December 1992 nor'easter, the gate was closed during six successive high tides.

Figure 21. Hurricane barrier at Stamford, Connecticut, a flap gate which lies submerged until it is raised with mechanical arms.

Figure 22. Thames River tidal barrier with the tainter gates in the undershot position, allowing the river current to scour out any accumulated sediment.

The Thames River barrier spans the 520-meter wide river with four large openings for shipping and six smaller openings (Figure 22). The four main gates, 61 meters wide, are basically tainter gates that can be rotated from a full overhead position for maintenance, to a vertical position to serve as a barrier, to a bottom position flush with concrete sill 9.2 meters deep, which leaves the channel above completely open. The gates are also placed in an undershot position to allow water to rush beneath them to remove sediments. To minimize the reflected wave that might cause downstream flooding, the gates are also temporarily kept in the undershot position before they are fully closed.

Figure 23. The Eastern Scheldt Storm Surge Barrier in the Netherlands, the longest such barrier in the world.

The Delta Project on the south coast of the Netherlands, the world's largest complex of water control structures, includes three moveable storm surge barriers. The works is a complicated system of dams, locks, sluices, channels, bridges, slides, and gates working together. The first moveable barrier, installed on the Hollandse Ijssel River in 1958, consists of a vertical plate that can be raised 12 meters above water level. An adjacent navigation gate is used for vessels to pass through when the gate is closed. The largest structure, almost 3 kilometers wide, is the Eastern Scheldt Storm Surge Barrier, which was opened in 1986 (Figure 23). The barrier consists of 66 giant concrete piers, spaced 45 meters apart with steel gates 41.3 meters wide between them. A sill beam varies from 4.5 to 10.5 meters below mean sea level. Concrete box girders, extending from one to 5.8 meters above mean sea level, form a road deck atop the piers. Thus, there is no clearance for vessels to pass through the barrier.

The final element in the Delta Project is the Stormvloedkering on the New Waterway, opened in 1997 (Figure 24). This consists of two sector gates, each with a radius of 246 meters (807 feet), facing each other on opposite shores. Each gate is 22 meters (72 feet) high, and is 15 meters (149 feet) wide at the base. To close the barrier, the roller gates of the parking docks are opened, and the two sector gates are swung to meet in the middle of the river. The ballast tanks in the gates are then flooded to sink to a sill 17 meters (56 feet) below sea level.

Figure 24. Stormvloedkering, sector gates which are rotated across the New Waterway in Holland, then sunk to provide the storm surge barrier.

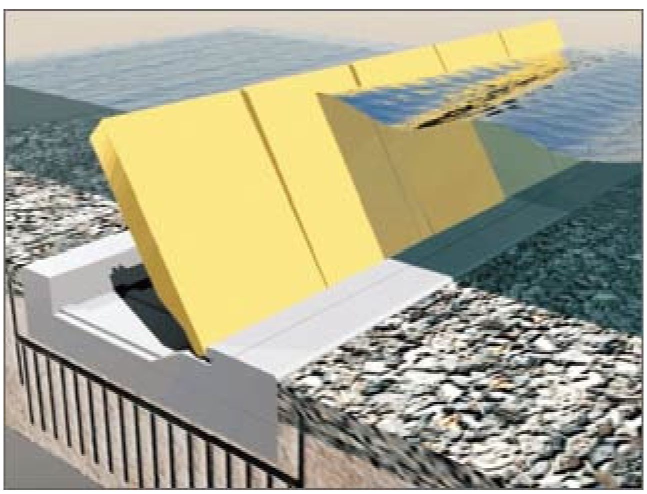


Figure 25. Flap gate to be used in Project Moses at Venice, Italy

Project Moses, to close the three inlets to the Venice lagoon, will consist of a series of 79 submerged flap gates (Figure 25). To close the gates, air will be pumped into them to float them to the surface. The adjacent edges will be sealed so that there is a continuous surface blocking the storm surge. The individual gates measure 30 meters high, 20 meters wide, and 4 to 5 meters thick. The total length of the three barriers will be 1,600 meters (1,750 yards). The barriers are expected to be completed in 8 to 10 years.

Conclusions

Based on its simulations of the change in water levels during Tropical Storm Floyd and the Christmas 2002 nor'easter, we believe that the results of the SBSS combined meteorological-hydrodynamic model can be accepted with confidence. Our principal conclusion is that three barriers – located at the Narrows, Perth Amboy, and the upper end of the East River – would successfully prevent flooding from storm surges in hurricanes and severe nor'easters. To assure flood protection, all three barriers would need to be closed. It is unlikely that there would be flooding from rainfall runoff behind the barriers.

The area protected includes valuable real estate around the edges of lower Manhattan, low-lying areas in Brooklyn and Queens, western Staten Island, Jersey City and Hoboken and a large coastal area in nearby New Jersey.

The highest rise in normal tides occurs in western Long Island Sound and the upper East River, and the storm surge may double this rise. The presence of the barrier there raises the level of the surge an additional 0.27 meters, less than one foot, at its face. However, this additional rise diminishes sharply with distance from the barrier, and would not greatly exacerbate local flooding.

The most suitable location for a barrier is clear at the Narrows, where the opposite shores are closest, and Perth Amboy, where there is high ground on both sides of the mouth of the Arthur Kill. Choosing a location for the barrier in the upper East River, however, will require detailed analysis that takes into account not only flooding patterns but engineering feasibility, environmental consequences, cost and social justice issues. The candidate sites include Randalls Island/Lawrence Point, College Point/Ferry Point Park, the Whitestone Bridge area, and City Island/Hewlett Point.

The moveable barriers may require fixed piers at intervals spanning the waterways. The effect of these structures in partially restricting normal flow through the rivers needs to be examined, taking into account their size, shape and location. This can be accomplished with SBSS by refining the model grids in the immediate vicinity of the piers.

The project developed two tools that can continue to be useful in analyzing coastal flooding:

- The seamless bathymetric-topographic database, which continues to be updated as new data become available
- The SBSS combined meteorological-hydrodynamic mode, which is now being fine-tuned to provide near real-time forecasting of coastal flooding for coastal early warning.

The existing storm surge barriers in New England and Europe have proved successful in preventing possible flooding without adverse effects such as, for example, worsened sedimentation. The decision to build these barriers came after disastrous flooding that did enormous damage and cost many lives. Even so, there were delays of decades after the tragic floods before the barriers were completed. With the increasing likelihood of major flooding in the metropolitan region due to climate change, such a delay should be minimized here. There is at present no broad public awareness of the growing danger of coastal flooding, and thus no political concern. We conclude that it is incumbent upon the professional community – scientists and engineers inside and outside government – to take the initiative to move forward with the further evaluation of the feasibility of storm surge barriers in the metropolitan region.

More can be done now.