Hydrologic Feasibility of Storm Surge Barriers to Protect the Metropolitan New York – New Jersey Region

Malcolm J. Bowman, Roger D. Flood, Douglas Hill, Robert E. Wilson,
Marine Sciences Research Center
Stony Brook University
Stony Brook, NY 11794-5000

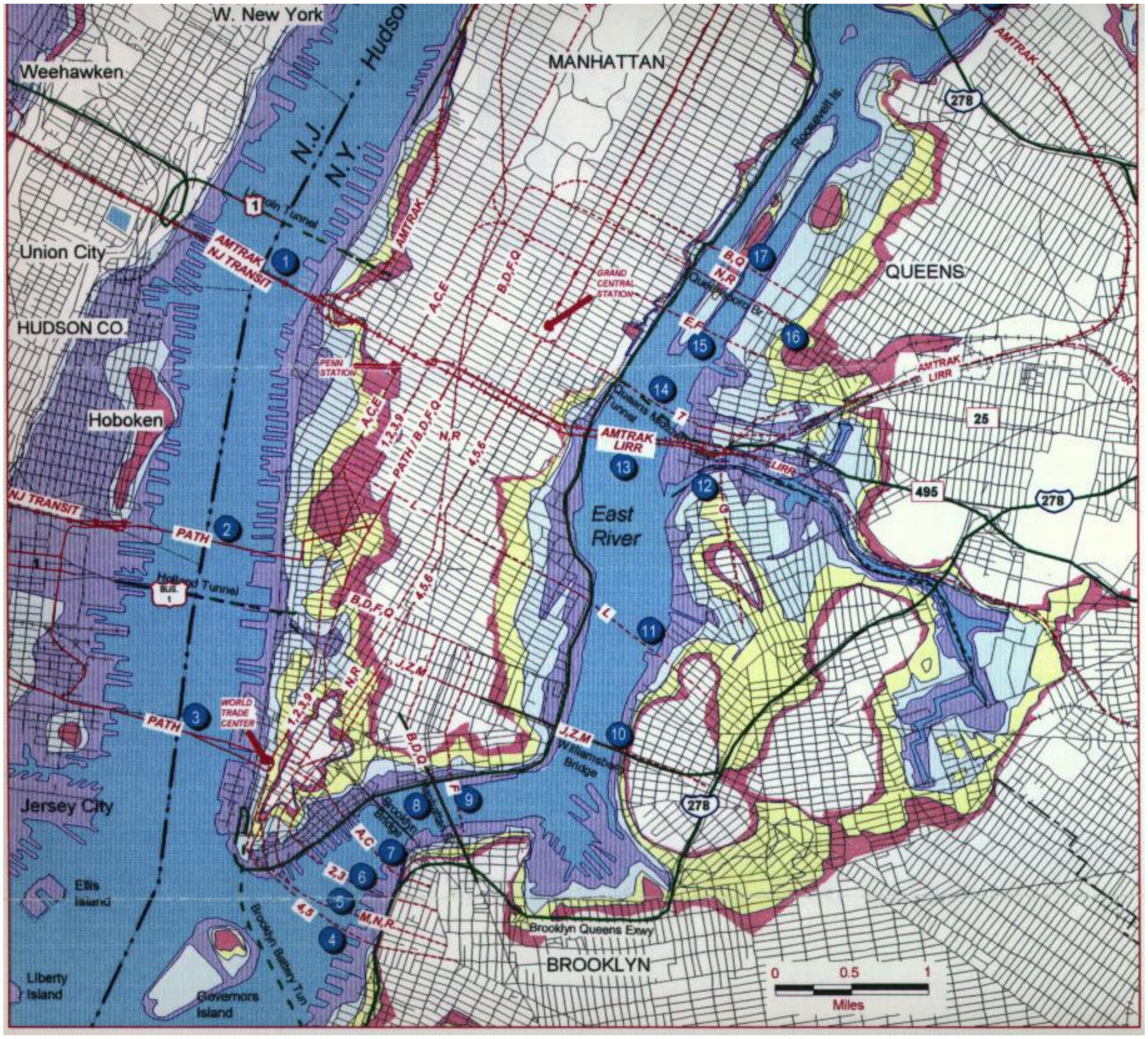
Background

Between floods, people in the New York/New Jersey metropolitan area forget their growing vulnerability to flooding from the Nor'easter storms that arrive in late fall and winter, and from hurricanes that strike infrequently but inevitably. As a reminder, the December 1992 Nor'easter raised the peak water level at The Battery by 8.5 feet above normal. Although water levels reached the point where transportation facilities were being flooded for only a short time and by only one to two feet, near paralysis of the metropolitan area resulted (U.S. Army Corps of Engineers et al., 1995).

Two of the most vulnerable systems, the underground rail networks of the Port Authority Trans-Hudson (PATH) and the New York City Transit Authority subways, were completely shut down. Low points in the rail tunnels were flooded and major damage occurred to the control signals. Passengers had to be rescued from a train stalled in the PATH tunnel. Portions of the system were out of operation for ten days. Surge only one to two feet higher probably would have caused massive flooding of the PATH tunnels.

Almost simultaneously, the New York City subways lost electrical power for the entire system. One train had to be backed out of a tunnel that was filling with water. Hundreds of passengers had to be rescued from stranded trains. Other railroads were also severely affected, including Metro-North service into Grand Central Station, Long Island Rail Road service on several lines, and New Jersey Transit in several locations. La Guardia Airport was closed due to flooded runways. Roadway flooding was also widespread. Battery Park Tunnel held six feet of water, and the FDR Drive had major flooding that required rescues by emergency personnel. Major parkways were flooded in Nassau County, Westchester County, and New Jersey.

Not only transportation, but valuable real estate is at risk from flooding, particularly in lower Manhattan, Jersey City, and Hoboken. Bellevue Hospital and the New York University Medical Center on the east side of lower Manhattan could be flooded in a Category 1 hurricane (winds of 74 to 95 mph and a storm surge elevation of 10 feet at The Battery). The West Street entrance of the World Trade Center would be under twelve feet of water from the storm surge of a Category



Color Code		Winds (mph)	Maximum Surge at The Battery (feet)
Purple	Flood area of a Category 1 hurricane	74-95	10.5
Light blue	Additional flood area of a Category 2 hurricane	96-110	16.6
Yellow	Additional flood area of a Category 3 hurricane	111-130	23.9
Red	Additional flood area of a Category 4 hurricane	131-155	28.7

Figure 1. Worst case hurricane flood areas in lower Manhattan and environs. Source: U.S. Army Corps of Engineers et al., 1995.

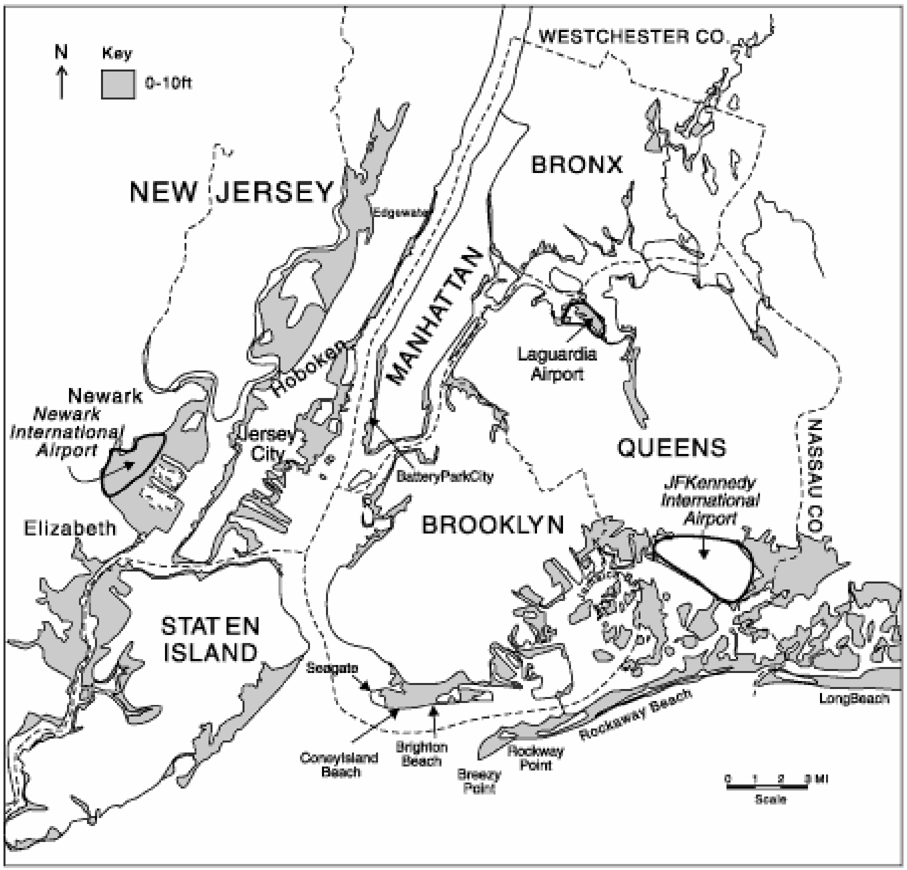


Figure 2. The 100-year flood now. Source: Gornitz, 2001.

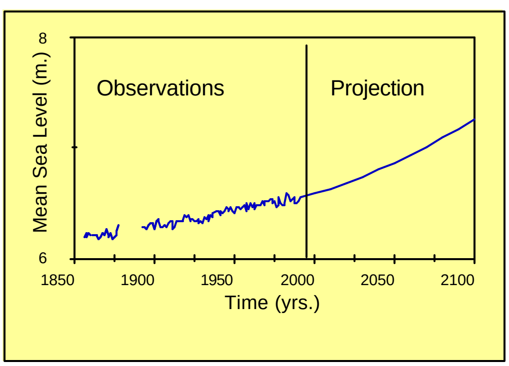


Figure 3. Rise in sea level at The Battery.

3 hurricane (winds of 111 to 130 mph with a storm surge elevation of 24 feet at The Battery). Most of the financial district would be flooded, and City Hall would sit on an island separate from the rest of Manhattan (Figure 1). The ambitious new commercial development now taking place in Jersey City opposite lower Manhattan would be flooded in a Category 1 hurricane. Secaucus would be an island in the completely flooded Hackensack Meadowlands.

What is now the 100-year flood of 9.7 feet (above NGVD[1]) inundates a large portion of the metropolitan region: not just lower Manhattan and nearby New Jersey, but sections of Brooklyn and Queens, including La Guardia Field, Hackensack Meadowlands, and Newark Airport. This is the terrain below the 10-foot contour line shown darkened in Figure 2.[2]

[1] National Geodetic Vertical Datum of 1928
[2] The minimum elevation of Newark Airport is elsewhere reported at 10.3 feet, a discrepancy of 0.3 feet.

Moreover, sea level has risen inexorably over the past century and a half (Figure 3), at a rate that is expected to accelerate with global warming. As sea level rises, the vulnerability of the New York metropolitan region to storm flooding will intensify. The return period of flooding decreases disproportionately with sea level rise, independent of any change in storm patterns. This is illustrated in Figure 4, which shows the extremes of estimates of the recurrence of a 100-year flood at The Battery. At the current trend, sea level will have risen by another 1.1 feet by the 2090s, reducing the return period to that of a 30-year flood. For the highest estimate of a 3.8 foot rise in sea level by the 2090s, the return period is reduced to every other year.

In the metropolitan region, sea level increased by 9 to 15 inches during the 20th century. Projections based on climate change simulations suggest that it will rise another 4 to 12 inches in the next 20 years, 7 to 24 inches by the 2050s, and 10 to 42 inches by the 2080s (Gornitz, 2001).

As a result of sea level rise, storm floods will be higher, cover a wider area, and occur more often. What is now a 100-year flood would, on average, have a probability of occurring once in 43 to 80 years by the 2020s, once in 19 to 68 years by the 2050s, and once in 4 to 60 years by the 2080s (Figure 5).

In a worst-case scenario envisioned in the Metro New York Hurricane Transportation Study, hurricane winds striking New York's skyscrapers would result in debris falling into the streets from broken windows and dislodged masonry. Pedestrians would seek shelter in the subways from severe winds, rain and the falling debris. Hurricane surge waters would quickly fill the subway tunnels, even if the elevation at the surface were above potential flood levels, drowning those underground. No estimate is made of the likely number of casualties (U.S. Army Corps of Engineers et al., 1995).

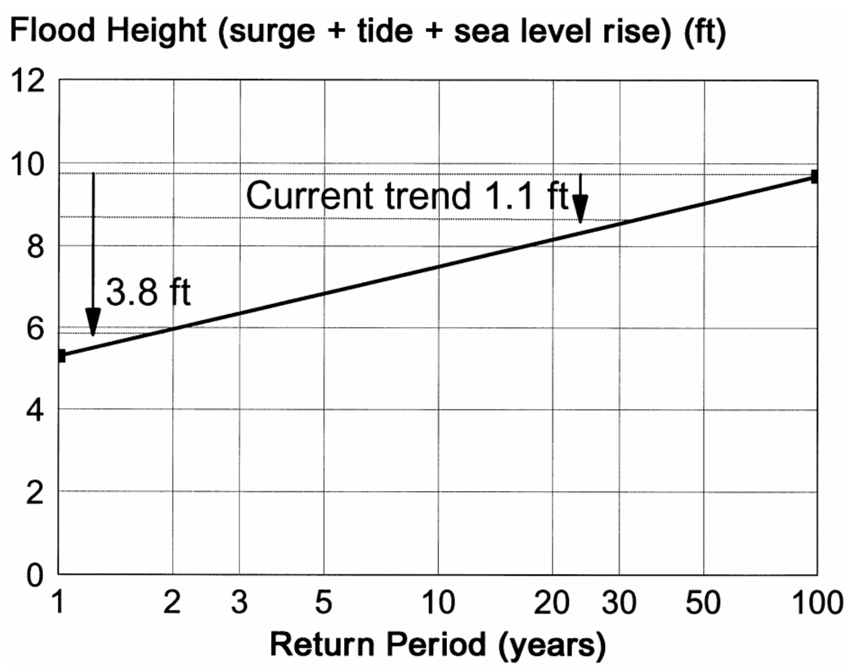


Figure 4. The reduced return period due to rising sea level of the present "100-year flood" in the metropolitan region by the 2090s, showing the extremes from 30 years at the current rate of sea level rise to as little as every second year. Source: V. Gornitz, 2001.

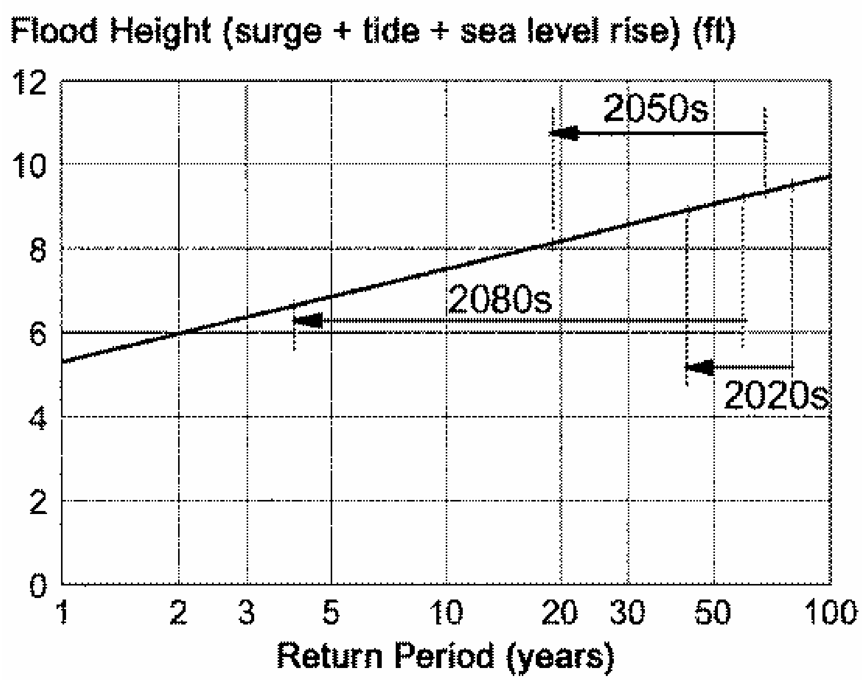


Figure 5. The reduced return period due to rising sea level of the present "100-year flood" in the metropolitan region, showing the estimated range for the 2020s, 2050s, and 2080s. Source: V. Gornitz, 2001.

The effects of flooding vary according to the speed with which flood waters rise as well as their height and duration, and the degree, rate, and pattern of the associated sediment movement. The infrastructure at risk includes, for example, subway entrances that are close to sea level, tunnels and their air and vent shafts, subway track and signal systems, bridge access roads, small bridges, airports, port freight-handling facilities, water pollution control plants and their tide gate regulators, combined sewer outfalls, landfills, solid-waste transfer stations, pipelines, power plants, and buildings in areas with high property values and dense population (Zimmerman, 1996).

Short-term fixes are now being undertaken, such as putting high doors at the entrances to the PATH subway in Hoboken which was inundated in the 1992 Nor'easter. However, to protect the myriad individual structures with dikes or, where feasible, by raising them, would become increasingly difficult and would end, presumably, with dikes along the entire shoreline.

The waterways surrounding New York City are particularly prone to flooding because of the topography and bathymetry of the region. The orientation of Long Island Sound makes it a natural funnel for strong northeast winds which drive surface waters into the western Sound and the upper East River. Northeast winds pile up water against the south shore of Long Island and into The Narrows by the Ekman effect: due to the rotation of the earth, surface waters are driven to the right of the wind direction.

If the eye of a hurricane were to strike New Jersey, the counterclockwise winds would come from the southeast driving surface water into the angle at the entrance to New York Harbor formed by the New Jersey and Long Island coasts. The upward sloping continental shelf makes the wedge three-dimensional.

The onset and duration of storm surges differ between hurricanes and Nor'easters. As illustrated in Figure 6, the surge from a hurricane lasts only a few hours, but rises very rapidly. The extent of flooding therefore depends upon the state of the astronomical tide at the time. For Nor'easters, on the other hand, the surge typically rises more slowly but lasts a few days, running the risk of flooding with every high tide, as illustrated in Figure 7 (Pore and Barrientos, 1976).

In contrast to the innumerable local flood measures that would be required to protect vulnerable infrastructure, it seems possible to protect the entire central metropolitan region with two or three storm surge barriers. These would be placed at The Narrows, at the eastern mouth of the East River, and possibly at the mouth of Arthur Kill (Figure 8). In a hurricane, the barriers would be closed for a few hours to stop the surge. During threatening Nor'easters, the barriers would be closed during high tides over a few days.

Such steps have already been taken to protect southern Holland and London, England. Since its completion in 1982, the Thames Barrier below London has been raised more than 20 times, largely as a precaution, to protect London from flooding, in addition to monthly testing (Letting Company [Greenwich] Ltd, 2000). (The Thames Barrier has also become a tourist attraction.) Surge barriers are also planned to protect Venice, Italy, by blocking three inlets to the Venice

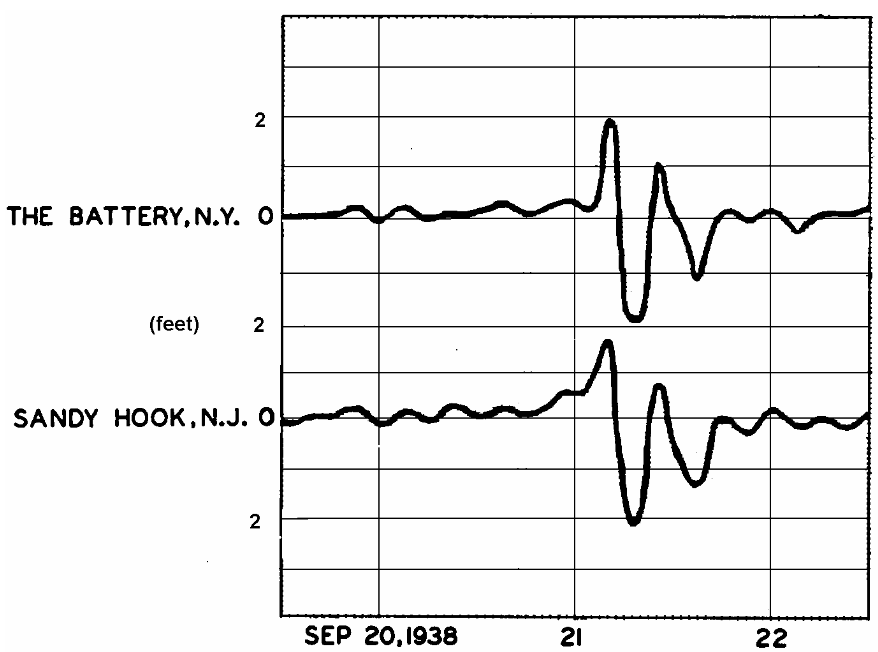


Figure 6. Storm surge of the 21-22 September 1938 hurricane. Typically, a hurricane storm surge rises rapidly but lasts only a few hours. Dates are shown at noon. Source: Pore and Barrientos, 1976.

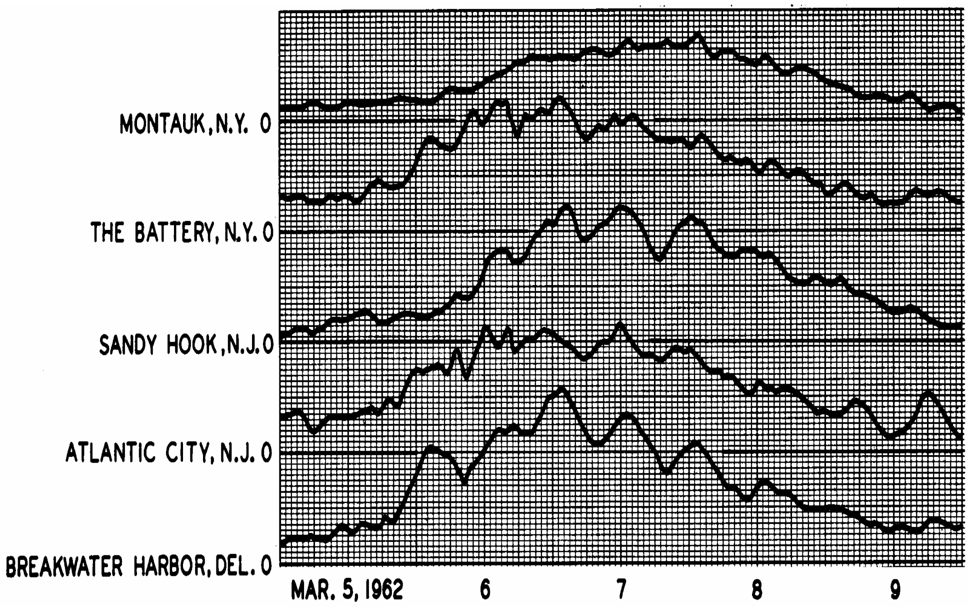


Figure 7. Storm surge of the 5-8 March 1962 Nor'easter. Typically, the storm surge of the Nor'easter rises slowly but lasts a few days. Dates are shown at noon. Source: Pore and Barrientos, 1976.

lagoon (Harleman et al., 2000). Nearer home, there are five hurricane and coastal storm surge barriers on the southern coast of New England: at New Bedford-Fairhaven, Massachusetts; Fox Point, Rhode Island; New London, Pawtucket, and Stamford, Connecticut (Wiegel, 1993).

A storm surge barrier at the mouth of the Arthur Kill would have a span about the same as that of the Thames Barrier. The span of a barrier at The Narrows and the upper East River in the vicinity of the Whitestone Bridge would be up to three times longer, equivalent to the total length of the barriers at the three inlets to the Venice lagoon. All are far smaller than the 3,000 meter span of the Eastern Scheldt Barrier in the Netherlands.

The construction cost of such barriers across the East River was estimated to be on the order of one to two billion dollars, depending upon their location and design, by two major engineering firms (Abrahams and Matlin, 1994; Szeligowsky, Ekezian and Hixenbaugh, 1994).

The wonder is that the feasibility of this concept to protect the New York/New Jersey metropolitan area has not yet been established. While there can be little doubt that such structures can be built, the questions are: How well would they work? Would such barriers worsen flooding on the weather side to an unacceptable degree? Would the rivers swollen with rainfall lead to flooding within the barriers anyway? Would there be sufficient protection and greater cost-effectiveness with partial blockage at some of the barrier locations?

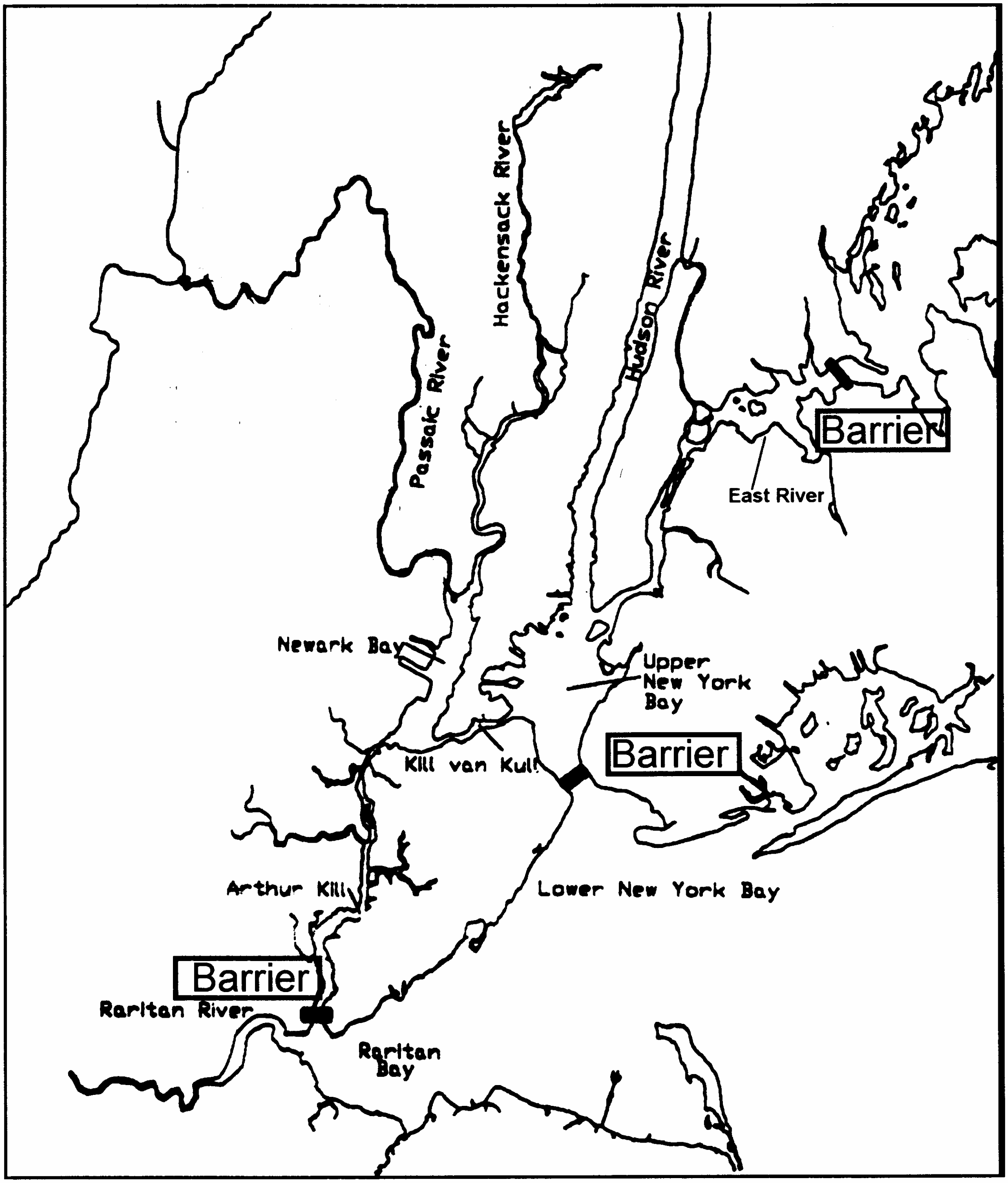


Figure 8. Location of storm surge barriers.

Table 1. Comparison of storm surge barrier spans

Storm Surge Barrier	Span (meters)
Eastern Scheldt, the Netherlands	3,000
Thames River, England	520
Venice Lido Inlet	800
Venice Malamocco Inlet	400
Venice Chioggia Inlet	400
East River (vicinity of Whitestone Bridge)	1,300
Arthur Kill mouth	520
The Narrows	1,600

Sources: Harlemann et al, 2000; Letting Company (Greenwich) Ltd. 2000; Slagter 1982

There are hydrodynamic models that can answer these questions. These have been applied to analyze flooding in San Francisco, San Diego, Tampa Bay, and the North Carolina coast, although not, to our knowledge, to evaluate storm surge barriers. The proposed research would advance this body of knowledge (1) by an application to a more complex estuary with three tidal openings, and (2) by demonstrating its applicability to evaluating surge barriers.

Moreover, we would expect the model to considerably improve our understanding of present flooding. The proposed project will complement other projects on coastal flooding in the metropolitan region, and allow the opportunity to review various approaches.

Hypothesis

Storm surge barriers placed at The Narrows, the eastern mouth of the East River, and possibly the mouth of the Arthur Kill can prevent flooding of low-lying areas in New York City and nearby New Jersey due to storm surges from Nor'easters and hurricanes.

.

Objectives

The objective of this research is to determine whether this hypothesis can be accepted: whether storm surge barriers can protect New York City and its environs from the worsened flooding that is expected from Nor'easters and hurricanes.

To this end, we propose:

1. To establish a valid scientific information basis for deciding whether to consider further the construction of such a set of storm surge barriers
2. To improve the quality of flooding models available for the metropolitan region that can address mitigation measures
3. To establish the hydrologic performance requirements to be met by engineering designs (e.g., the preferred location of surge barriers, and the degree of blockage necessary).

We emphasize that this is an evaluation of hydrologic feasibility, not an engineering or cost analysis

Research Plan/Methods

General Approach

Hydrodynamic models exist by which the effectiveness of storm surge barriers at the choke points surrounding the metropolitan region, either singly or in combination, can be estimated. Consideration will also be given to the flow of water down the Hudson, Passaic, and Hackensack Rivers. Fortunately, hurricanes, which occur in summer and fall, and Nor'easters, which occur in the late fall and winter, do not coincide with the maximum river flows which occur in the spring.

Our general approach is to adapt a contemporary storm surge model to the bathymetry and topology of the metropolitan region, and determine the flooding that would result – inside and outside the barriers – under typical storm conditions, without barriers and with barriers, singly or in combination.

Steps to be Followed

The principal steps will be:

1. Review hydrodynamic models. The models to be evaluated include:

- ADCIRC (Advanced Circulation Model for Coastal Ocean Hydrodynamics), developed by J. Westerink and R. Luettich. ADCIRC is a system of computer models for solving time-dependent, free-surface circulation and transport problems in two and three dimensions. It has been used for modeling tidally and wind-driven circulation in coastal waters, and forecasting hurricane storm surge and flooding.
- SLOSH (Sea, Lake and Overland Surges from Hurricanes) is a computerized model run by the National Hurricane Center to estimate storm surge heights resulting from historical, hypothetical, or predicted hurricanes by taking into account pressure, size, forward speed, track, and winds. It was used by the Corps of Engineers to estimate flooding in the New York – New Jersey metropolitan region due to hurricanes of various strengths.
- TRIM2D, by R.T. Cheng and V. Casulli, a semi-implicit, finite-difference model for two-dimensional shallow water that allows for wetting and unwetting of shallow areas, which has been applied to the bays of San Diego and San Francisco.
- Tampa Bay ECOM-3D 24-hour forecast model, with river inflows, and open boundary water levels provided by a combination of tidal and non-tidal components. Surge data are being entered.
- North Carolina State University model developed by L. Xie and L. Pietrafesa, a three-dimensional model that predicts coastal flooding in North Carolina caused by a hurricane's storm surge and rainfall.

At present, these models can provide an understanding of the problem. To our knowledge, they are not being used for mitigation, which is the next step. We will develop a model with greater skill and finer resolution in which we can have more confidence.

Criteria for evaluating the models include:

- Facility for absorbing high-resolution bathymetric and topographic anomalies
- Gridding flexibility to repeat small-scale bathymetric and coastal morphology features
- How adequately they represent the dynamics of wetting and drying at the water margins
- Predictive skills of the model for present conditions.

2. Acquire the model and set it up at the Marine Sciences Research Center.

<u>Data Sources</u>

3. Review the operational experience at existing storm surge barriers to guide model development and scenario analysis.

4. Acquire bathymetric and coastal topographic data from federal, state and city sources. These sources include National Oceanic and Atmospheric Administration, Army Corps of Engineers, New York State Department of Environmental Conservation, New York City, U.S. Geologic Survey, and New York State Geographic Information System Center at Cornell University.

5. Merge the topographic and bathymetric data sets for our purposes.

These purposes include the representation of friction and wave propagation in very shallow water. Will flooded subways reduce the elevation of flooding? Should the model be able to incorporate this? MSRC has prepared merged data sets in this fashion in a study of Raritan Bay and a part of the Hudson River for the New York State Department of Environmental Conservation (Flood, 1999; Bell et al., 2000).

6. Load merged data into the selected model. Make a grid quality check and any necessary refinements or corrections to make a pilot model run.

The grids for the data set can be adjusted as necessary to represent cross-section areas in the convergence channels at The Narrows and straits. If bottom roughness is important, we may use alternative gridding strategies to reduce high-resolution data to that usable in the model.

7. Determine historical patterns of river flows due to storms during the hurricane and severe Nor'easter seasons to establish a range of parametric inputs to the model.

The river flow in the Hudson River opposite The Battery is only one-tenth to one one-hundredth of the tidal flow, depending upon the season. More than half the Hudson River flow occurs in April and May, not months in which hurricanes or severe Nor'easters occur. Flooding usually occurs in upstate New York and the Passaic River valley in New Jersey. A planned 20-mile long, 42-foot diameter flood diversion tunnel to channel flood waters in Sussex County, New Jersey, directly to Newark Bay would raise peak flow into the bay by 60 percent and cause it to occur 15 hours sooner (Cerco, Bunch and Letter, 1999). Projections of climate change in the metropolitan region include the possibility of more precipitation extremes and changes in the pattern of snow melt in the upstate watersheds (Rosenzweig and Solecki, 2001; McCabe and Ayers, 1989).

We will characterize the river discharges under extreme precipitation for parametric input to the flooding model.

8. Make a series of runs to calibrate the model with astronomical tides, using NOAA tracking data available for the metropolitan region on the Worldwide Web. Validate the model by comparing its results with two historical events: the 1992 Nor'easter and a hurricane.

9. Prepare first-year report. Result of the first year's work will be a developed tool: a documented model and a report of the year's work.

10. The <u>experimental design</u> is scenario analysis. During the second year, a series of scenarios will be examined with the model. Variation in the scenarios will include:

- Type and severity of storms
- Location of barriers (uncertainty is principally on the East River)
- Number and combinations of barriers closed
- Sequence of opening and closing the barriers
- State of the tide
- Partial restriction of surges
- Possible future physical changes: e.g., New Jersey flood diversion tunnel; changes in the depth of the bay bottom for deep-draft vessels.

<u>Expected Results</u>

The principal results of this work will be answers to the questions:

- Would storm surge barriers work in this region?
- To what degree would they succeed?

The products of the analysis will be:

- Series of maps showing flooding inside and outside the barriers
- Strategies for barrier operations
- Identification of trade-offs in flooding inside and outside barriers
- Hydrologic performance requirements to be met by engineering designs (i.e., location of the barriers, whether or not complete blockage of the choke points is required, or what degree of partial blockage?)

More broadly, we will develop a modeling approach capable of predicting present flood levels and those resulting from modifications of the estuary which will be useful here and elsewhere.

Expected Significance to User Groups

Flood protection barriers were built in the Netherlands after more than 1,800 people were drowned in 1953. The Thames River barrier was built after more than 300 people drowned. It may take a similar disaster for storm surge barriers to be seriously considered to protect the New York – New Jersey metropolitan region. Before that occurs, however, the proposed study can lay a firm scientific foundation for the justification (or not) of such barriers.

These results will establish, first of all, whether storm surge barriers to protect the metropolitan region in extreme storms deserve further consideration. Such barriers would be a major public capital investment, and serious consideration of them should be based on reliable scientific information. Flooding maps showing the impacts with and without the barriers under various conditions would provide the basis for the trade-offs and benefits that would need to be evaluated to make such a major public decision.

Our results will be most directly useful to federal, state, and municipal agencies responsible for flood control and emergency planning. Mounting losses in human casualties and property damage in the 1990s have led such organizations to shift priorities from disaster relief to mitigation. For example, the Federal Emergency Management Agency (FEMA) has established a Mitigation Directorate, on a par with its Response and Recovery Directorate (National Research Council, 1999). When the next flood does occur, our results can help such agencies provide an answer to the public's question: *What are you doing about it?*

Ultimately, a decision to invest in storm surge barriers for the metropolitan region would be made in the political arena. The political debate should be informed by scientific understanding. Ideally, it should take place before flooding becomes a frequent – or fatal – problem. The effect of storm surge barriers cannot be answered with present information or desktop analysis. Existing models developed for forecasting are too coarse and inadequate as they stand. (In this region, for example, they do not represent forcing from Long Island Sound.) However, they can be adapted for evaluating mitigation measures – the next step – with finer structure and better data, and we plan to adapt one of them.

At the conclusion of this study, questions will still exist as to the engineering feasibility, costs, and environmental impacts. However, our results will provide the basis for moving on to these questions: What is it that must be engineered? What will be the effects on the physical oceanography that that determine other environmental impacts? We start with the basic question: How will coastal flooding be affected by storm surge barriers? If they wouldn't work, environmental concerns are moot.

Literature Cited

Abrahams, M.J., and A. Matlin (of Parsons Brinkerhoff Quade & Douglas). 1994. East River tidal barrage. In: D. Hill (ed.) The East River tidal barrage: a symposium on a multipurp ose addition to New York City's infrastructure, Vol. 742, Annals of the New York Academy of Sciences.

Bell, R.E, R.D. Flood, S.M. Carbotte, W.B.F. Ryan, C. McHugh, M. Cormier, R. Versteeg, D. Chayes, H. Bokuniewicz, V. Ferrini, and J. Thissen. 2000. Hudson River Estuary Program Benthic Mapping Project, New York State Department of Environmental Conservation, final report, April 28, 2000.

Cerco, C.F., B. Bunch, and J. Letter. 1999. Impact of flood-diversion tunnel on Newark Bay and adjacent water, Journal of Hydraulic Engineering, April 1999, pp. 328-338.

Flood, R.D. 1999. Multibeam mapping in Long Island coastal waters (abs), Geology of Long Island and Metropolitan New York, April 24, 1999.

Gornitz, V. 2001. Sea-level rise and coasts. In: Rosenzweig and Solecki, 2001.

Harleman, D.R.F., R.L. Bras, A. Rinaldo, and P. Malanaotte. 2000. Blocking the tide. Civil Engineering, Vol. 79, No. 10, October 2000. pp. 52-57.

Letting Company (Greenwich) Ltd. 2000. The Thames Barrier. http://www.greenwich-letting.co.uk/barrier.html.

McCabe, G.J. Jr., and M.A. Ayers. 1989. Hydrologic effects of climate change in the Delaware River Basin, Water Resources Bulletin, Vol. 25, No. 6, December 1989.

National Research Council, Board of Natural Disasters. 1999. Mitigation emerges as major strategy for reducing losses caused by natural disasters, Science, Vol. 284, No. 5422, 18 June 1999. pp. 1943-1947.

Pore, N.A., and C.S. Barrientos. 1976. Storm surge. Marine Ecosystem Analysis Program, MESA New York Bight Atlas Monograph 6, New York Sea Grant Institute, February.

Rosenzweig, C., and W.D. Solecki (eds.) 2001. Climate change and a global city: the potential consequences of climate variability and change: Metro East Coast. A report of the Columbia Earth Institute for the U.S. Global Change Research Program. April.

Szeligowski, J.J., H. Ekezian, and L.H. Hixenbaugh (of TAMS Consultants). General concepts for and design issues related to an East River tidal barrage. In: D. Hill, ibid. pp. 115-128

Slagter, J.C. 1982. The joint evaluation of design and construction of large-scale concrete coastal structures. In: Eastern Scheldt Storm Surge Barrier: Proceedings of the Delta Barrier Symposium, Rotterdam, 13-15 October 1982.

U.S. Army Corps of Engineers, FEMA, National Weather Service, NY/NJ/CT State Emergency Management. 1995. Metro New York hurricane transportation study, interim technical report, November.

Wiegel, R.L. 1993. Hurricane and storm surge barriers in New England. Shore and Beach, April 1993, pp. 30-49.

Zimmerman, R. 1996. Global warming, infrastructure, and land use in the metropolitan New York area. In: D. Hill (ed.) The Baked Apple? Metropolitan New York in the Greenhouse. Vol. 790, Annals of the New York Academy of Sciences. Johns Hopkins University Press. pp. 57-83.

Acknowledgements

This research is sponsored by the New York Sea Grant Program and the New York City Department of Environmental Protection.