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Cost estimates for flood resilience and protection strategies in New York City

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In the aftermaths of Hurricanes Irene, in 2011, and Sandy, in 2012, New York City (NYC) has come to recognize the critical need to better prepare for future storm surges and to anticipate future trends, such as climate change and socio-economic developments. The research presented in this report assesses the costs of six different flood management strategies to anticipate long-term challenges the City will face. The proposed strategies vary from increasing resilience by upgrading building codes and introducing small scale protection measures, to creating green infrastructure as buffer zones and large protective engineering works such as storm surge barriers. The initial investment costs of alternative strategies vary between $11.6 and $23.1 bn, maximally. We show that a hybrid solution, combining protection of critical infrastructure and resilience measures that can be upgraded over time, is least expensive. However, with increasing risk in the future, storm surge barriers may become cost effective, as they can provide protection to the largest areas in both New York and New Jersey.

Keywords: storm surge; hurricane; flood management; NYC; NJ; Hurricane Sandy

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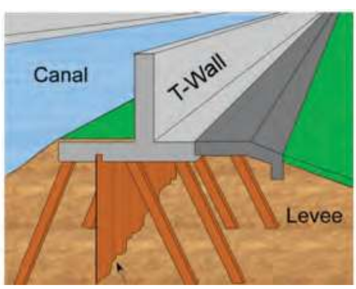

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1. Flood management strategies for New York City

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1.1 Introduction and goal

The devastating impact by Hurricane Sandy showed again that the metropolitan area of New York City (NYC) is one of the most vulnerable cities to coastal flooding around the globe (Nicholls *et al.*, 2008; Aerts *et al.*, 2013; Kunz *et al.*, 2013). Historical flood events have shown that hurricanes and winter storms (nor'easters) can have considerable impacts on the city. NYC has been struck by 15 hurricanes since the year 1815, with a maximum strength of category 3 on the Saffir-Simpson scale (Gornitz *et al.*, 2002). Recently, Hurricane Irene almost caused large-scale flooding in NYC, which served as a wake-up call for the city's flood risk management (Aerts and Botzen, 2012). Flood risks are expected to increase in the future, and a report of the NYC Panel on Climate Change shows that sea level rise is expected to increase the frequency of coastal flooding in NYC and enlarge the potential flood zones (NPCC, 2009). In addition, socio-economic developments, such as population and economic growth, will likely increase the potential consequences of flooding. In the US, in 2003 approximately 153 million people—53% of the nation's population—lived in coastal counties, an increase of 33 million people since 1980 (NOAA, 2005). NYC's population is projected to continue to grow from over 8.2 million in 2006 to 9.1 million by 2030 (NYC-DCP, 2006).

Currently, the City of NY is looking for flood adaptation measures that anticipate future trends such as climate change and socio-economic developments (e.g. NYC-DCP, 2011). The issue of flood management and its role in anticipating future challenges such as climate change and socio-economic developments is very complex. There is no single readily available flood management strategy applicable to NYC. However, cities like NYC have developed the ability to adapt continuously to change and to attract economic activity and investments (Rosenzweig *et al.*, 2010). One could say that cities like NY have already been adapting to changing conditions for many years or even centuries, as well as to the aftermath of Hurricane Sandy and future risks. Climate change is an additional challenge that needs to be addressed in cities' planning, investments and regulations.

However, since the choices made today will influence vulnerability to risks in the future, it is important to evaluate proposed flood management strategies in terms of their costs and benefits, and how these cost and benefits evolve through time. In this context, and given the uncertainty of future developments, there is the need to keep all options open. Because of the uncertainty of future scenarios, one can never predict exactly how the future will develop, and what measures will be needed. Hence, climate-robust and flexible, no-regret or low-regret measures should be examined. In addition, complicated issues like policy making, stakeholder involvement, and financing new measures may hinder the speedy implementation of adaptation measures and may cut ambitious plans to more modest levels.

While flood risk is subject to a myriad of definitions, we define risk as a function of hazard, exposure, and vulnerability (Kron, 2002), as used in the Global Assessment Report (GAR) of the United Nations Office for Disaster Risk Reduction (UNISDR, 2011) and the SREX report of the Intergovernmental Panel on Climate Change (IPCC, 2012).

$$\textit{Flood Risk} = f\,(\textit{Hazard},\ \textit{Exposure},\ \textit{and Vulnerability})$$

Hazard refers to the chance and characteristics of the hazardous phenomenon itself (e.g. flood extent, flood depth); *exposure* refers to the location and number of people or economic assets in hazard-prone areas, and *vulnerability* refers to their susceptibility to suffer damage and loss; for example, due to unsafe housing and living conditions. All three elements can be altered by adaptation (i.e. explicit risk management interventions). For example, constructing a river-dike can reduce risk by decreasing the chance of flooding (reduced hazard). Spatial zoning regulations can reduce risk by limiting the number of people or value of assets in flood-prone areas (reduced exposure) (Burby *et al.*, 2000; Poussin *et al.*, 2012). Building codes can reduce risk through vulnerability reduction (Thieken *et al.*, 2006) and insurance covers the residual risk after all of those measures have been implemented (Kunreuther, 2009; Paudel *et al.*, 2012).

Using this general framework, this paper is designed to gather and analyze available cost data on adaptation methods and, by grouping these methods into alternative flood management strategies, to provide some of the basis for decision-making on adaptation to climate in New York City. A *flood management strategy* in this study is defined as *the collection of measures (flood proofing, zoning, barriers, levees, etc.) that is needed to lower flood risk.* This research considers a variety of possible measures, and draws from the experiences of other areas and coastal cities (e.g. Aerts *et al.*, 2009, 2011). These measures consist of various technical engineering options, such as pumps, levees, and surge barriers, to keep the water out of the City. Another domain of solutions lies in lowering the vulnerability (or enhancing resilience) of the NYC waterfront by implementing new building codes and zoning regulations that promote flood proofing of buildings or even reallocate buildings in the flood zones. The residual risk can be covered through flood insurance, and therefore the role of the National Flood Insurance Program (NFIP) is important.

The main goal of this ~~full~~ report is to assess the potential construction and maintenance cost of different flood management strategies. We will describe measures and their costs for two main strategies and their derivates.

(1) **Resilient Open City**. This strategy consists of measures that lower vulnerability by enhancing the building codes (elevation of buildings and flood-proofing). Additionally, tailored local-scale flood protection measures can complement the strategy to protect critical infrastructure that falls outside building code policies. Such flood protection measures should have safety standards that are consistent with providing protection against at least the 1/100 year storm surge.

(2) **Storm surge barriers**. This strategy aims to develop storm surge barriers and can be complemented with additional protection measures.

The strategies described in this special issue do not provide the complete overview of all possible strategies and their measures, nor have we assessed all cost categories that pertain to these strategies. For example, two issues are not included: economic benefits, and the considerable administrative and planning costs associated with climate adaptation. However, the strategies outlined in this research provide a range of possible visions and their associated costs on flood risk management solutions for NYC. These strategies vary in their risk approach, from reducing vulnerability to houses and infrastructure to prioritizing large scale levees for protecting the City. Within this range, a number of combinations of protection and resilience measures are possible, often dependent on geographical situations in the areas to be protected. The surge barrier strategies were developed for a storm surge barrier conference in 2009 (Hill *et al.*, 2013) and updated using expert interviews with the experts that designed the barriers. The other strategies were partly developed in a series of bilateral expert consultations and seminars (Appendix H) with stakeholders in the years 2011 and 2012 (and thus partly before the impact from Hurricane Sandy). Within these meetings, the aim was to find strategies that reduce flood risk as the single criterion. We do address other criteria that play a role in developing flood management strategies, such as environmental effects or socio-economic factors but have not valued them in an economic analysis. In addition, intangible factors may play a role in developing strategies such as whether or not the strategy adds value to the green infrastructure of the City, which may enhance living conditions (Nordenson, *et al.*, 2010). All of these other criteria were not quantified and must be considered in follow-up studies in order to derive a comprehensive idea of the advantages and disadvantages of different flood management strategies.

All storm surge barrier strategies require cooperation between government institutions in the states of New York (NY) and New Jersey (NJ), since they link to land of both states. Moreover, all three barrier strategies protect people and economic assets in parts of both the states of NY and NJ, and hence benefits of investing in storm surge barriers pertain to areas in both NYC and NJ.

All summary cost tables are in US$ 2012 values. Indexing was applied using the Construction Cost Index from ENR (Engineering News-Record, http://enr.construction.com/economics). The CCI annual escalation rate was set to 2.4%, on May 2nd 2013.

1.2 Description of different Flood Management Strategies

Strategy 1, **Resilient Open City** aims at creating a resilient waterfront by keeping channels and estuaries open as long as possible. This is achieved by enhancing building codes and zoning regulations and some additional measures that reduce the vulnerability of buildings and infrastructure in the flood zones, such as local levees. The floodproofing and elevation measures will be implemented in flood zones that are currently classified by FEMA as the 1/100, as well as the 1/500 flood zones in order to anticipate climate change (current building code policies only pertain to the current 1/100 flood zones). Large-scale storm surge barriers are not considered. The rationale behind this strategy is that it connects well to current policies and governance structures. Moreover, by investing in buildings and infrastructure, the flood adaptation measures add value to the city. For example, through innovations such as green (or soft) infrastructure (Nordenson *et al.*, 2010), the NYC waterfront will be developed into a resilient coastal area against storm surges, which is also increasingly attractive to citizens (NYC-DCP, 2011). By only increasing resilience of buildings and infrastructure, parts of the city can still be flooded, but it is assumed that flood damage will be lower compared to the damage from a Hurricane like Sandy, because of stricter building codes. Moreover, since infrastructure will be protected, the economic losses from a storm surge will be limited with relatively minor business interruptions. The Resilient Open City strategy has been divided into three alternatives, Strategies 1a, 1b, and 1c.

Strategy 1a: Resilient Open City: upgrading building codes

Strategy 1a Resilient Open City (Figure 1.1) aims at estimating only the cost of various building code measures in the 1/100 and 1/500 flood zones, to lower the vulnerability of buildings. Measures include:

a. 1/100 and 1/500 flood zone: elevation of the base floor of houses (+2, +4 ft, or +6 ft) above base flood elevation (BFE);
b. 1/100 and 1/500 flood zone: dry- and wet floodproofing (lowering vulnerability) for different heights (+2, +4 ft, or +6 ft);
c. The measures are applied to existing and new buildings.

Strategy 1b: Resilient Open City+: protecting infrastructure

As in Strategy 1a, the *Resilient Open City+* strategy aims at implementing floodproofing and elevation measures in zones that are currently classified as the 1/100 and the 1/500 flood zones. These measures are applied to existing and new buildings. However, the '+'refers to additional measures needed to protect critical infrastructure. Since a lot of vulnerable infrastructure remains unprotected in Strategy 1a, Strategy 1b Resilient Open City+ (Figure 1.2), aims at enhancing resilience of critical infrastructure, such as power-plants, subways, water treatment plants, airports, etc. This is performed using local scale adaptation measures that protect these facilities. We use the proposed adaptation measures and their costs provided by the infrastructure companies and authorities, such as elevating or sealing tunnel entrances, small scale levees or the hardening of power lines. Large-scale storm surge barriers are not considered. Measures include:

a. 1/100 and 1/500 flood zones: elevation of the base floor of houses (+2 ft, +4 ft, or +6 ft) above base flood elevation (BFE);
b. 1/100 and 1/500 flood zones: dry and wet floodproofing (lowering vulnerability);
c. The measures are applied to existing and new buildings;
d. Local-scale flood adaptation measures that enhance the resilience of critical infrastructure, such as power plants, water treatment plants, transport infrastructure and medical facilities.

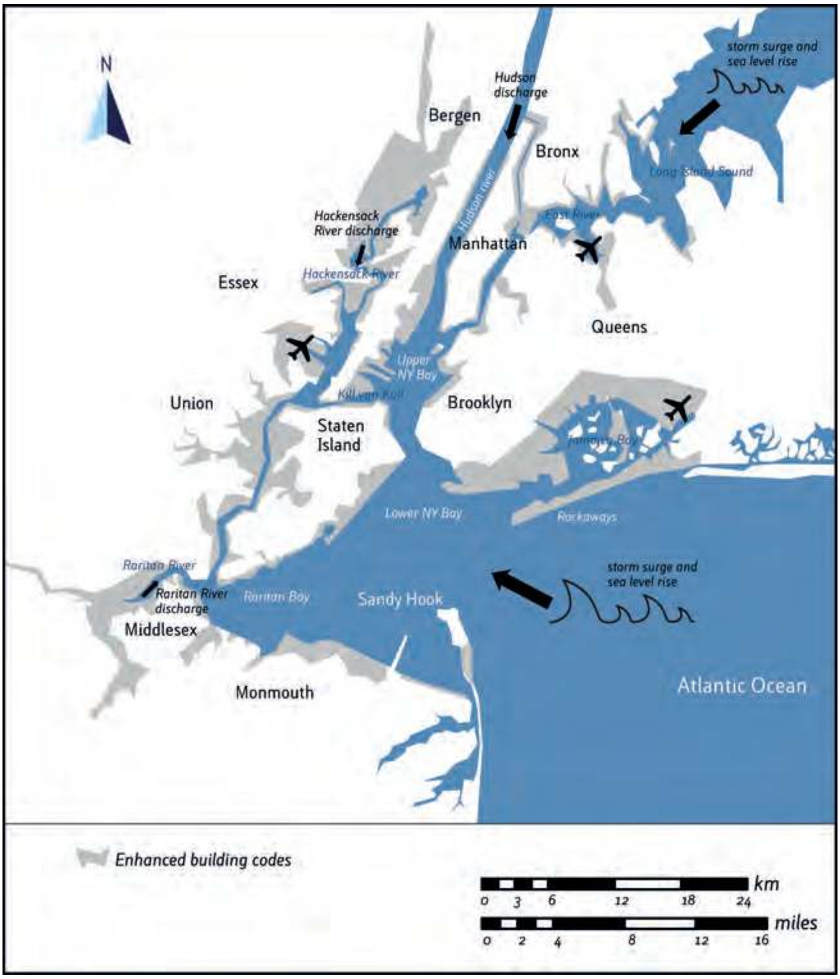

Figure 1.1. Strategy 1a: Resilient Open City.

Strategy 1c: A Hybrid Solution

Strategy 1c (S1c, Figure 1.3) anticipates to the uncertainty of future developments, and combines elements of the Resilient Open City strategies and some local scale protection measures from the barrier strategies (S2a,b,c). Such a Hybrid Strategy aims at keeping options open because of the uncertainty of future scenarios. By keeping all options open, either (a) building codes can be further enhanced in the future with additional local scale protection measures or (b) storm surge barriers can be developed.

Since in a potential barrier strategy, low lying areas behind the barriers are still vulnerable to sea level rise, additional protection measures are needed to protect these low lying areas. Hybrid Strategy 1c (S1c), therefore, starts implementing some local flood protection measures, such as levees and beach nourishment, that are also part of the storm surge barrier strategy. Because these measures are needed anyway, they can be referred to as ‘no regret’ measures. In addition, the locations of future storm surge barriers will remain open space (e.g. park land) such that room is available for those structures. The difference between the local adaptation measures in strategy 1b is that the no regret measures in this strategy include levees located along the coastline, protecting all buildings and infrastructure behind the local levees, whereas in strategy 1b adaptation measures refer to measures only targeted at protecting particular infrastructure. By investing in buildings and infrastructure, the flood adaptation

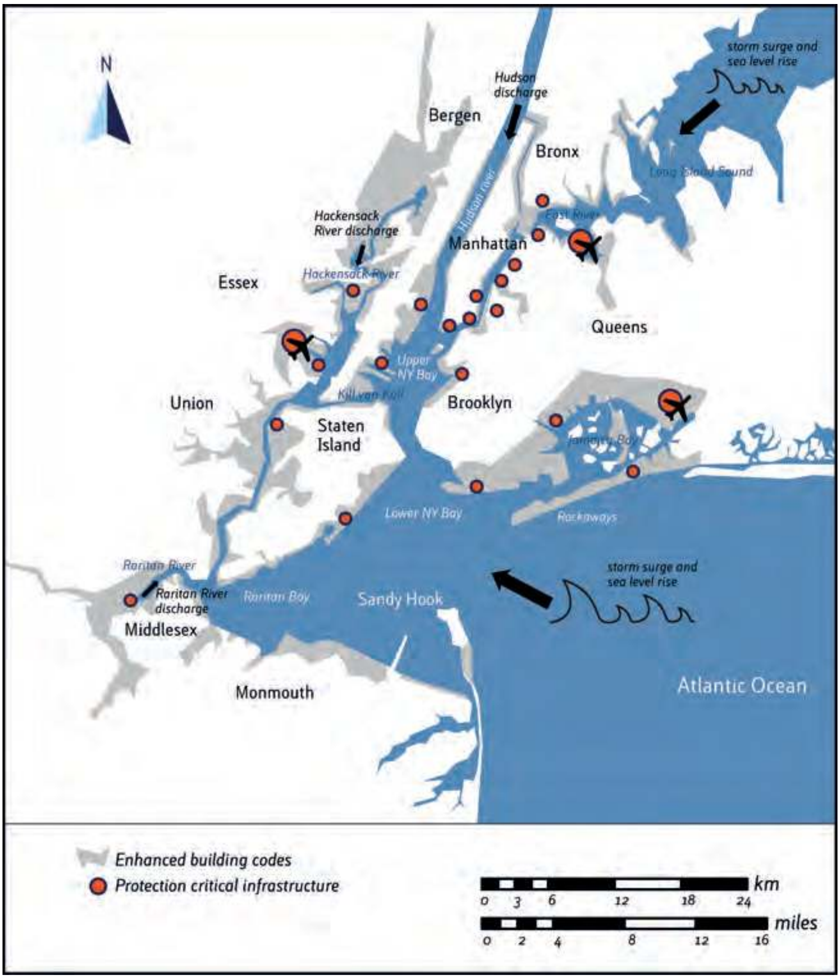

Figure 1.2. Strategy 1b: Resilient Open City+.

measures add value to the city. For example through innovations such as green infrastructure, the NYC waterfront will be developed into a resilient coastal area against storm surges, which is also increasingly attractive to citizens (NYC-DCP, 2011). By only increasing resilience of buildings and infrastructure, parts of the city can still be flooded, but it is assumed this damage will be minor compared to the damage from a hurricane like Sandy. Moreover, since infrastructure will be protected, the economic losses from a storm surge will be limited, with relatively minor business interruptions.

For S1c, A Hybrid Solution, only freeboard building code levels (maximum +4 ft) for new buildings are required in the 1/100 A zone. Higher freeboard levels for new buildings (maximum +6 ft) will be applied in the 1/100 V zone. These building codes only pertain to new structures in the 1/100 flood zone and not in the 1/500 flood zone. In addition, we apply wet flood proofing of +2 ft to existing buildings in the 1/100 A zones. Measures include:

a. 1/100 A flood zone: elevation of the base floor of new houses (+4 ft) above base flood elevation (BFE); wet floodproofing of existing buildings of +2 ft;
b. 1/100 V flood zone: elevation of the base floor of new houses (+6 ft) above base flood elevation (BFE);
c. No-regret measures that strengthen beaches through sand nourishments in The Rockaways;
d. Protect low lying areas with levees, for example in Red Hook, Hoboken, and Manhattan;

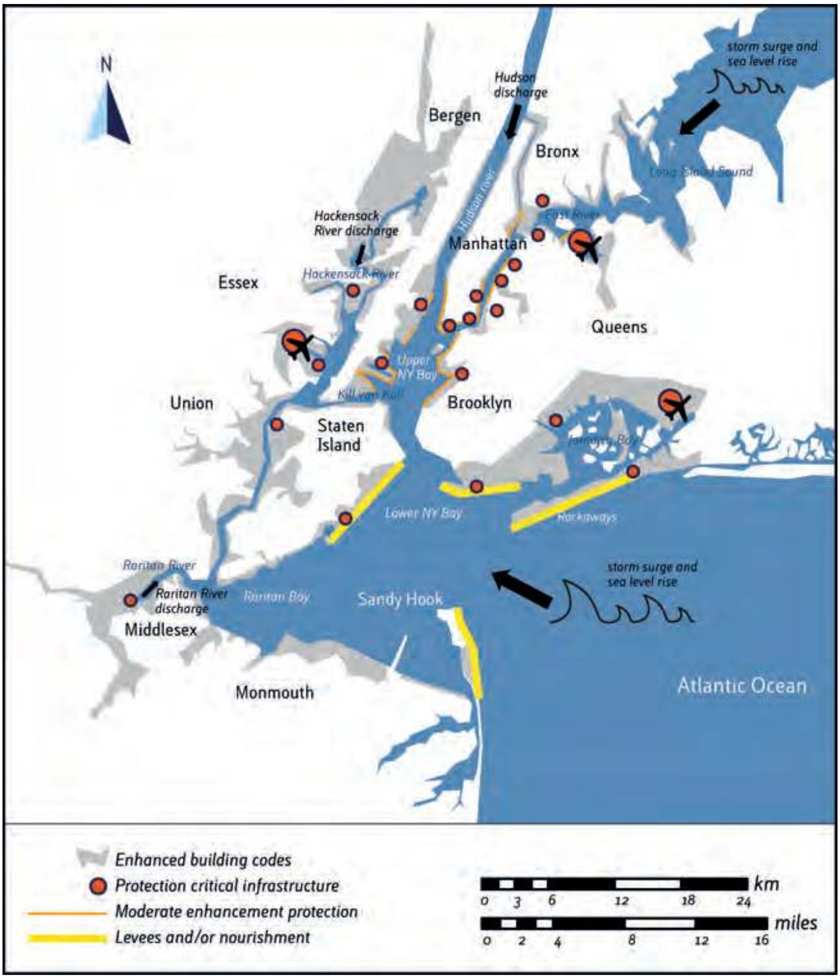

Figure 1.3. Strategy 1c: A Hybrid Solution.

e. Infrastructure enhancements and protection; and
f. Measures that minimize environmental impacts: these pertain predominantly to maintaining salt marshes and wetlands in the Jamaica Bay area.

Strategies 2a, 2b, 2c: Storm surge barriers

Strategies 2a, 2b, 2c, **Storm surge barriers**, aim at lowering flood probabilities as the goal of the measures is to withstand a flood with a certain design probability. Storm surge barriers do not protect people and assets against wind damage, nor do they protect against inland flooding from precipitation. All three strategies have different sets of storm surge barriers at the core and, in addition, protective measures that complement the barriers. These additional measures include levees, beach nourishment, bulkhead upgrade, etc. (see e.g. Aerts *et al.*, 2009). The storm surge barrier strategies are adapted from the proposals made during the 2009 Storm Surge Barrier conference (Hill *et al.*, 2013). Strategy 2a, *Environmental dynamics*, consists of three barriers that would work in concert to close off NYC from the waterways and, in addition, aims to preserve the wetland dynamics of Jamaica Bay. This strategy can be expanded in Strategy 2b, *Bay closed*, by a fourth barrier that closes off Jamaica Bay. Strategy 2c, *NJ-NY connect*, replaces three barriers from Strategy 2b and would reduce the length of the shoreline considerably, thereby protecting a larger area. In the flood protection strategies in this research, each individual protection measure must be designed so that it can withstand what are called 'design water levels'. We have selected a design water level that belongs to a storm like Hurricane Sandy, but assuming additional climate change effects. The design water level is, therefore, composed of different components: maximum surge level belonging to a future Sandy-type storm, wave height, and sea level rise. Maximum surge height has been set to a robust 20 ft above MSL. In addition, we propose here to heighten design levels due to future sea level rise and an additional wave height to 25–30 ft (7.5–10 m). It should be noted that storm water levels vary spatially around New York (Orton *et al.*, 2012), although this effect is small compared to the design level chosen in this study. Moore *et al.* (1981) show, for instance, that water levels for a 1/100 storm vary roughly between 8 ft (Jamaica Bay) and 13 ft (East River between Queens and the Bronx).

Strategy 2a: Environmental dynamics

This strategy starts as Strategy 2a (Figure 1.4), and aims at maintaining the ecosystem dynamics of Jamaica Bay and its salt marshes. Landscape restoration and stabilization is an important means to maintain the 'open' system character of Jamaica Bay in the long term. A 'closed' defense system provides protection for a larger area, but even if it were to be equipped with gates to let water flow through the structure, it would still be a partial morphological and ecological barrier, thereby possibly losing (some) of their important ecological areas (Dijkman, 2007). Therefore, this strategy is

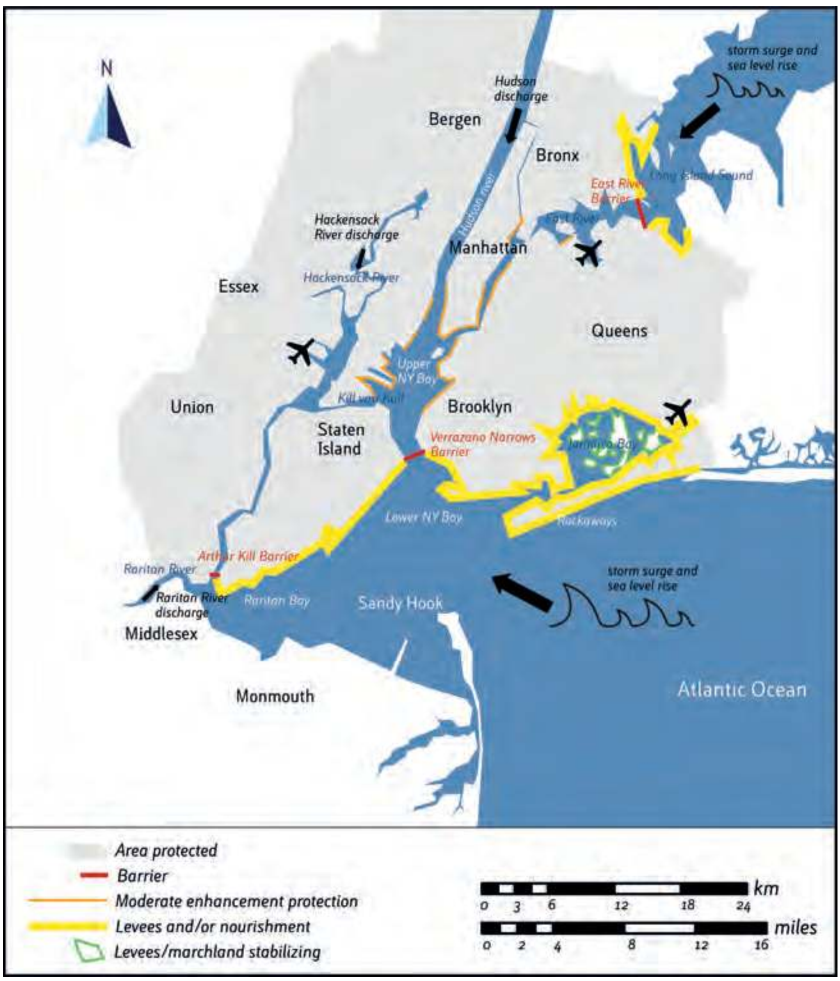

Figure 1.4. Strategy *2a*: *Environmental dynamics.*

designed such that the lower NY Bay will remain open, and the tidal currents of Jamaica Bay Inlet will not be disturbed by a storm surge barrier. Three storm surge barriers will be installed: at Arthur Kill, Verrazano Narrows, and East River. The strategy, furthermore, predominately uses measures that maintain the character of the natural beaches with periodic sand nourishment. Both Coney Island and the Rockaways are not protected by storm surge barriers, but their beaches will be nourished, backed by a berm or artificially created dune of 25–30 ft. Salt marches in Jamaica Bay will be stabilized and restored periodically. The urban areas around Jamaica Bay, as well as JFK airport will be protected by levees. The design height for the levees in the Jamaica Bay area are 2–3 ft lower compared to the regular design level, since surge water levels in the Bay are generally lower than those on the coast near the Rockaways (Moore *et al.*, 1981). Where levees are already in place, they will be upgraded to the new design levels. On the inside (landward side) of the protection system (mainly Staten Island, Manhattan, Brooklyn and the Bronx), low spots will be upgraded by +3 ft, through reinforcing bulkheads, levees, or landfill. This is necessary to accommodate increasing water levels caused by Hudson River discharge during the closure of the barrier system.

Strategy 2b: Bay closed

The strategy continues in Strategy 2b (Figure 1.5) when sea level surpasses +3 ft compared with current MSL. At that point, according to this strategy, it will no longer be viable to maintain the Jamaica Bay wetlands and its salt marshes.

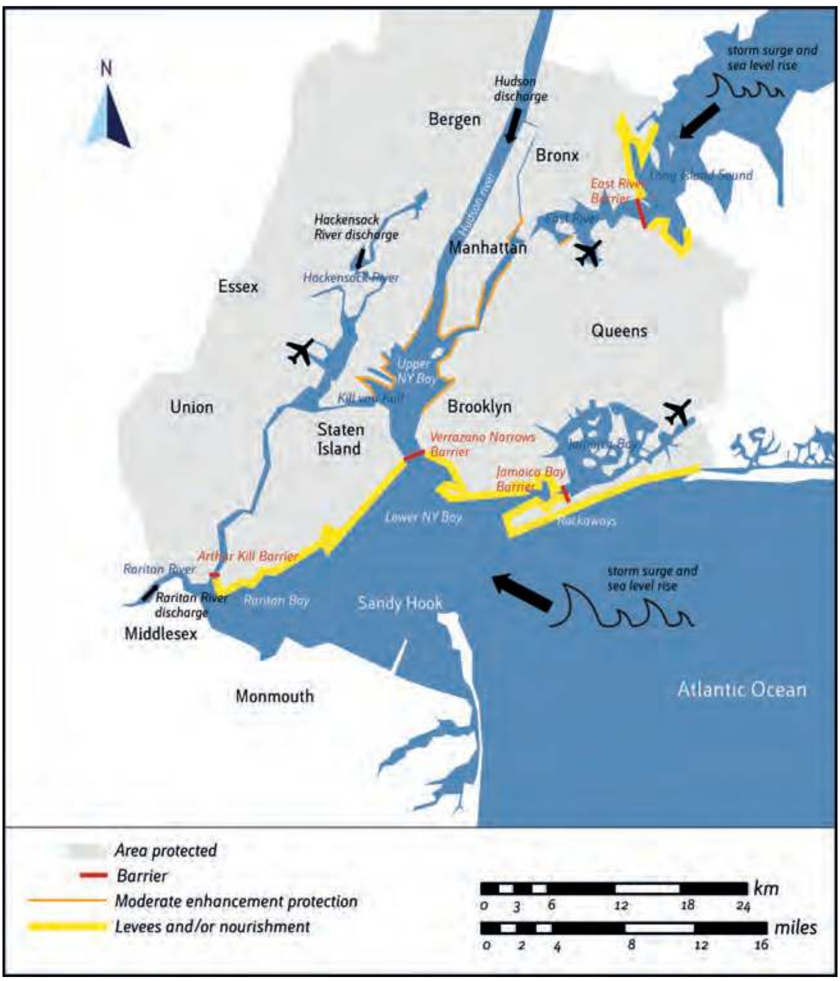

Figure 1.5. Strategy *2b*: *Bay closed.*

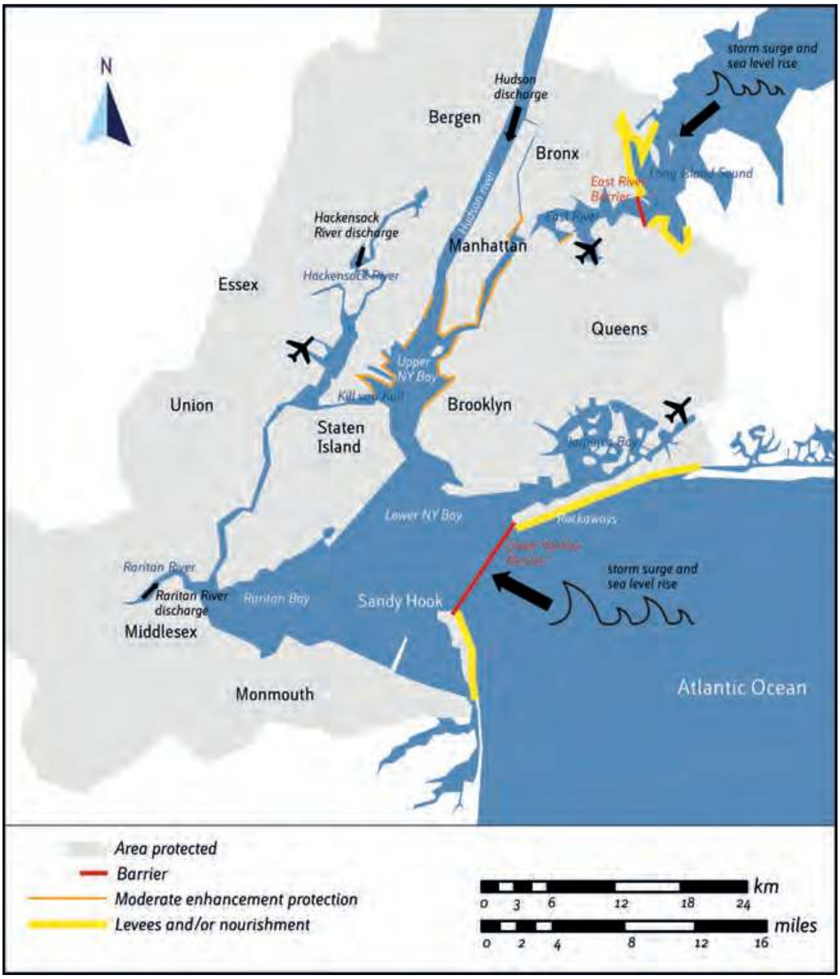

Figure 1.6. Strategy 2c: *NY-NJ connect.*

Hence, large-scale protection works and marshland-stabilizing activities in Jamaica Bay will be cancelled and, instead, an additional storm surge barrier will be installed across the Jamaica Bay Inlet. An additional advantage is that Coney Island and the Rockaways will be directly connected by road or rail infrastructure. As in Strategy 2a, low spots on the inside of the protection system (mainly Staten Island, Manhattan, Brooklyn, and the Bronx), will be upgraded by reinforcing bulkheads, levees, or by landfill.

Strategy 2c: NY-NJ connect

The aim of this strategy is to reduce the length of the coastline of the NYC area as much as possible. The rationale for this strategy is that, by doing this, flood protection costs can be minimized. The three barriers described in Strategy 2b (Arthur Kill, Verrazano Narrows, and Jamaica Bay Inlet) are replaced by one large barrier that connects Sandy Hook in NJ and the tip of the Rockaways in Queens, NY. This strategy protects the largest area, including parts of NJ. Apart from flood protection, the barrier will be constructed with road and/or rail infrastructure that connects NJ with NYC. As in Strategy 1c, lower spots (bulkheads, levees, or landfill) on the inside of the protection system (mainly Staten Island, Manhattan, Brooklyn, and the Bronx) will be elevated by +1–3 ft to accommodate for rising water levels caused by Hudson River peak discharges during a storm event.

Table 1.1. **Total costs for all flood management strategies (all in $ 2012 values)**

	S1a. R. City	S1b R. City +	S1c Hybrid[a]	S2a Env. Dyn.	S2b Bay closed	S2c NJ-NY connect
Total cost NYC	$0.5–4.4 bn	$6.9–11.1 bn	$6.4–7.6 bn	$16.9–21.1 bn	$15.9–21.8 bn	$11.0–14.7 bn
Total cost NJ	$0.2–2 bn	$4 bn	$4 bn	$2 bn	$2 bn	
Total NJ-NYC	$0.7–6.4 bn	$10.9–15.1 bn	$10.4–11.6 bn	$18.9–23.1 bn	$17.9–23.8 bn	$11.0–14.7 bn
Maintenance protection NJ-NYC	*1 mln/yr*	*$2 mln/yr*	*$13.5 mln/yr*	*98.5 mln/yr*	*126 mln/yr*	*117.5 mln/yr*

[a]Cost estimates for Strategy 1c, Hybrid Solution, are described in Appendix L.

1.3 Total costs flood management strategies

Table 1.1 summarizes the estimated overall costs for the six different flood management strategies for NYC, NJ, and the combination of NYC and NJ. Detailed cost estimations of these strategies are provided in papers 2, 3, and 5 of this report. If we focus on the strategies that include protection infrastructure, overall cost for NYC ranges between $6.4–11.1 bn for the Resilient Open City Strategies 1b and 1c and $11–21.8 bn for storm surge barrier Strategies 2a,b,c. When including costs for NJ, the ranges become $10.4–15.1 and $11–23.8 bn for the Strategies 1b,c and Strategies 2a,b,c, respectively. This shows the cost ranges of the Resilient Open City strategy types are generally lower as compared to Strategies 2a,b,c. Furthermore, yearly maintenance costs are higher for the barrier strategies as compared to Strategies 1b,c. The reason part of NJ is included in the cost analyses is that the different barrier strategies also protect parts of NJ (Raritan–Hoboken area). In a comparative analysis of strategies (e.g. a cost benefit analyses, CBA), benefits are often expressed as the reduced flood risk. Since the barriers protect parts of NJ, benefits of reduced flood risk are achieved both in NYC and parts of NJ. Hence, in order to compare costs of storm surge barrier strategies with Resilient Open City strategies, we need to include costs for adaptation in NJ as well. Note that the costs for the barriers strategies are theoretically joint costs for NJ and NYC as they protect large parts of both States. They are here listed under NYC, in order to compare the order of magnitude of costs with the building code costs for NYC.

1.4 Overall Cost of Resilient Open City strategies

The costs for Strategy 1a are relatively low for NYC ($0.5–4.4 bn) and NYC-NJ ($0.7–6.4 bn). This is due to the fact that measures only include those that lower vulnerability of buildings, and not infrastructure. If we take the Strategy 1a, Open Resilient City, as a basis, we may add costs for measures that protect or upgrade (create more resilience of) the critical infrastructure. The total adaptation cost for the various proposed infrastructure utilities in NYC and the Hoboken–Raritan River areas of New Jersey are estimated at $2.9–$6.4 bn (in total $9.3 bn), which are lower than the total estimated adaptation costs for the states of NJ (2012) and NY (2012): $9 bn for NY and $7.4 bn for NJ, respectively, adding up to $16.4 bn. Note, however, that these are very preliminary estimates and, probably, some cost categories for adaptation are missing. For example, adaptation measures for parks and wetlands are not included. These rough estimates, therefore, only provide an indication of the potential size of the required budget for adaption. For NYC only the total costs (building code + infrastructure) would be in the range of $6.9–11.1 bn (Strategy 1b) and $6.4–7.6 bn (Strategy 1c, Hybrid Solution). Strategy 1c is cheaper compared to Strategy 1b, since building codes only pertain to new buildings. Hybrid Strategy 1c also implements protection measures, and the maintenance costs for these additional protections have been set to $13.5 mln/yr.

The three main building code measures considered in this study—elevation, wet floodproofing, and dry floodproofing—are consistent with actual building code policies in NYC. We have estimated the costs of the application of each measure for 2 ft, 4 ft, and 6 ft above the current height of the lowest floor of the buildings. A distinction has been made between the costs of applying the floodproofing measure for all buildings in the 1/100 or 1/500 year flood zones. Current flood-resistant building regulations apply only to the 1/100 year flood zone, but given the expected increase in flood zones due to sea level rise it is relevant to explore floodproofing strategies in the current 1/500 year flood zone. A further distinction that we make is whether the floodproofing measure is applied to existing or new constructions.

The objective of elevating a house is to raise the lowest floor in order to prevent floodwaters from entering the living areas. The elevation of existing buildings can entail leaving the house in its existing position and constructing a new raised floor within the house or by lifting the entire house, including the floor. It is the costs of this latter method that are examined in this study. The costs of this measure are very substantial and range between $2.3 bn and $2.6 bn for the 1/100 flood zone and between $1.3 bn and $1.5 bn for the 1/500 flood zone. The estimated elevation costs for the 1/500 zone reflect only the costs of elevation in that zone, and do not include the costs of elevating buildings in the 1/100 zone. The cost estimates for 4 ft and 6 ft elevation are not much higher than the 2 ft elevation costs, so if this measure were implemented it is probably best to elevate to a high level. However, overall the costs of elevating existing buildings are very high, meaning that it is of interest to explore other floodproofing strategies. Moreover, we estimated costs for elevating new buildings that have been projected to be newly built by the year 2040. The costs of this measure range between $80 mln and $230 mln for the 1/100 flood zone and between $30 mln and $100 mln for the 1/500 flood zone. These costs are substantially lower than the costs of elevating all existing buildings for two reasons: (1) the number of projected new buildings is only a small proportion of the existing building stock; and (2) the average per building costs of elevating new building is much lower than elevating existing buildings.

Wet floodproofing entails modifying parts of a house so that floodwaters can enter but cause only minimal damage to the house and its contents. In our cost calculations we assumed that wet proofing is undertaken when a building is substantially renovated and finish materials need to be replaced anyway. In that case, wet floodproofing costs include adding wall openings for the entry and exit of floodwaters, installing pumps, rearranging or relocating utility systems, moving large appliances, and making it easier to clean-up after floodwaters recede. The costs of wet floodproofing all existing buildings range between $250 mln and $980 mln for the 1/100 flood zone and between $150 mln and $590 mln for the 1/500 flood zone. The costs of wet floodproofing existing houses are substantially lower than the costs of elevating these homes. Wet floodproofing costs are more sensitive to the height up to which the measures are applied than is the case for elevation. The costs of wet floodproofing new buildings range between $65 mln and $260 mln for the 1/100 flood zone and between $30 mln and $110 mln for the 1/500 flood zone.

Dry floodproofing a building means that the flood-prone parts of the house have been made watertight, so that floodwaters cannot enter the building. The costs of dry floodproofing existing buildings range between $640 mln and $980 mln for the 1/100 flood zone and between $380 mln and $580 mln for the 1/500 flood zone. The costs of dry flood-proofing existing houses are substantially lower than the cost of elevating these houses. Dry floodproofing is more costly than wet floodproofing for floodproofing heights of 2 ft and 4 ft, but is about the same for floodproofing up to 6 ft. The costs of dry flood-proofing new buildings range between $170 mln and $260 mln for the 1/100 flood zone and between $70 mln and $110 mln for the 1/500 flood zone. The difference between the total costs of floodproofing these new residential buildings compared with existing buildings only arises because of differences in the number of buildings that are floodproofed.

Future research could examine how these building code strategies can be made consistent with current NFIP and NYC building code regulations; feasibility of the elevation requirements in terms of ensuring adequate building access for disabled people and building connections with streets and utility systems; effectiveness of these measures under a variety of flood conditions; and NYC resident attitudes toward the implementation of these floodproofing measures.

1.5 Storm surge barriers strategies

The costs for the storm surge barrier strategies vary from $16.9–$21.1 bn for Strategy 2a, Environmental Dynamics, to $11.0–$14.7 bn for Strategy 2c, NJ–NY Connect. The latter strategy is relatively cheap since it contains less additional protection measures. The movable parts in a storm surge barrier (sluices, gates, etc.) largely determine costs of the barriers, and empirical data on existing storm surge barriers show the unit costs price of movable parts varies between \$1.9 and \$3.53 bn per km, depending on the types of gates and sluices. Furthermore, the costs of the additional measures are determined by the required length of additional protection measures (levees, beach strengthening, etc.) that complement the storm surge barriers. With Strategy 2c, NJ-NY Connect, the vulnerable coastline is shortened quite dramatically, with the largest protected area in both NJ and NYC behind the two barriers. This means that additional costs are the lowest because fewer additional protection measures are needed. Furthermore, it will be interesting to assess the benefits (reduced flood risk) of Strategy 2c, since it protects the largest parts of NJ, compared to Strategies 2a and 2b. The advantage of Strategies 2a and 2b (with Strategy 2b being a follow up of 2a) is that it aims at leaving Jamaica Bay open as long a possible, without any interference of a large barrier that hinders estuarine flows and sediment transport. It can be an argument to invest more in Strategy 2a (and later on 2b) in order to protect the natural values of Jamaica Bay. However, this needs detailed valuation studies to determine the ecological values of Jamaica Bay, preferably expressing these values in monetary units. In all areas that will be protected with storm surge barriers, no building code measures are required, and only additional protection measures are needed in the low lying areas. These protection measures have two purposes. (1) In the event of a storm surge, with a closure of the barriers, the Hudson and other tributary river still flow in the Hudson Bay. Because Hudson water will be trapped behind the barriers for 24–48 hours (the duration of a storm surge), water levels on the landward side of the barriers will rise with 1 ft. (2) Sea level rise will increase vulnerability in the protected areas. Since the barriers are open during non-storm conditions, future sea levels will rise through this open barrier system, thereby increasing flood risk in low lying areas.

The cost estimates by engineering companies that made the conceptual designs for the barriers are generally lower than those made on the basis of empirical unit cost prices. This can be explained by the additional maintenance costs that were not included in first cost estimates (e.g. East River barrier design), contingencies that were not included in cost estimates, possible surcharges on labor costs that are generally higher in NYC as compared to other locations in the US, and the uncertainty of the length of movable parts. For example, the total length of movable parts in the Outer Harbor barrier in Strategy 2c is 2 km. However, in the conceptual design, as well as in recent expert meeting, the required length of sluices might be longer due to possible flow disturbances of tides. We have, therefore, increased the length of movable parts to 3 km (on a total length of 9.5 km).

The following four main issues related to developing storm surge barriers need additional attention. (1) Permitting and legislation; studies need to assess what permits are needed. (2) Maintenance and institutional issues; this refers to the issue who is maintaining the barriers and who bears the costs for maintenance. (3) Environmental issues; detailed hydrological studies need to show the effect of barriers on water quality, tidal current, and sediment budgets, and impacts on environmental values in Jamaica Bay and NY Harbor. (4) A barrier might fail, and thus studies need to assess what reliability is required (expressed in failure probability). The higher the reliability, the higher will be the final construction costs. These issues are open for future research.

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2. Cost estimates of Strategy Open Resilient City

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2.1 Introduction

An alternative flood risk management strategy for installing storm surge barriers or other types of floodwalls comprises the use of building codes to make structures more resistant to flooding. These building code strategies have a different influence on the flood risk distribution than storm surge barriers or other flood prevention measures. Flood prevention aims to lower the probability that a damaging flood occurs (hazard), while building code strategies aim to limit the potential damage from flooding (vulnerability of the assets exposed). Several studies have shown that considerable flood and storm damage can be saved if more stringent building codes are being adopted in the flood-prone regions in the USA (Burby, 2006; Kunreuther *et al.*, 2009). Aerts and Botzen (2011) have discussed the usefulness of upgrading flood-resistant building codes for NYC in particular, but did not estimate the costs of such strategies, as will be done here.

Here we examine the costs of implementing a variety of flood-proofing measures that can be taken at the building level. In particular, the average costs of these flood-proofing measures will be estimated per individual building type. This provides insight into the average costs that homeowners incur if they take such a measure. Moreover, the total cost of implementing a specific flood-proofing strategy on a flood zone level is estimated. These cost estimates can be interpreted as the costs of implementing a specific building code policy for NYC. The reason for providing these costs on the flood-zone level is that current NYC flood-resistant building codes, as well as the construction rules imposed by the National Flood Insurance Program (NFIP), are defined per flood zone.

2.2 Current NYC flood-resistant building codes

NYC flood-resistant building codes are discussed in detail by Aerts and Botzen (2011), and are briefly summarized here. Minimum building code standards in NYC have been designed by the Federal Emergency Management Agency (FEMA) because NYC participates in the NFIP. This implies that buildings in NYC have to comply with NFIP building regulations. Building codes apply to new structures and substantial improvements of structures that exceed 50% of the value of the building before the work started. Building code policies apply to the 1/100 year floodplains, which are the A and V zones depicted on the Flood Insurance Rate Maps that are designed by FEMA. V zones are coastal zones where the impacts of flood velocity and waves on structures need to be considered in building regulations (Nadal and Zapata, 2010). Such impacts do not need to be considered in A zones. The main requirement by the NFIP is that new constructions in the 1/100 year floodplain need to be elevated to the Baseline Flood Elevation (BFE), which equals the height of the expected water level during a flood that occurs on average once in 100 years.

The NYC Department of Buildings (DOB) can propose building regulations that go beyond NFIP requirements, which can come into effect after approval by the City Council. Since 1983 NYC flood-resistant building codes have become effective. These additional building code regulations for NYC can be divided in three main categories: (1) elevating buildings above the BFE, which is called 'freeboard'; (2) wet floodproofing which aims to minimize the damage once water enters the building; and (3) dry floodproofing which aims to prevent floodwaters from entering the building. Specific requirements can differ per flood zone and building type (Aerts and Botzen, 2011).

Consistent with the NFIP requirements, the NYC building code stipulates that new buildings in NYC have to be elevated to the BFE. These minimum elevation requirements apply to buildings that pose a low hazard to human life (agriculture, temporary buildings and storage facilities) and residential buildings. Stricter elevation requirements apply to certain building types that pose a substantial hazard to human life in case of failure (e.g. schools and power stations), and essential facilities (e.g. hospitals, fire and police stations, shelters, and facilities for national defense), which should, respectively, be elevated by +1 ft and +2 ft higher in the A zone. Building parts that lie below the level of these elevation requirements in the A zone should be wet floodproofed. Alternatively, dry floodproofing can be applied in the A zone, which should prevent water from entering the building during floods with water heights that are up to the elevation requirements per building type. Currently, dry floodproofing is not an option for making buildings with solely a residential use comply with building code requirements, but this is allowed for other building types. An advantage of dry floodproofing is that it is possible to use building space below the BFE.

NYC building codes are stricter in V zones where structures have to withstand high-velocity wave action during floods. In V zones new buildings are elevated on pilings or columns to ensure that waves can flow underneath the building. The requirements for elevation heights are the same as those in A zones for buildings that pose a low hazard to human life and residential buildings (namely, elevate to the BFE). Elevation requirements for building types that pose a substantial hazard to human life in case of failure and essential facilities are for both types +1 ft above the BFE if the floor is located parallel to the direction of the waves, or +2 ft if this location is perpendicular. As in A zones, building parts located below these elevation requirements should be wet floodproofed. A difference with A zones is that wet floodproofing of building types that pose a substantial hazard to human life in case of failure and essential facilities should be implemented up to +1 ft above the elevation requirements. Current regulations do not allow for dry floodproofing in V zones.

After Hurricane Sandy, on 31 January 2013 Mayor Bloomberg announced new measures to allow home and property owners who are rebuilding to meet updated flood standards.[a] These measures include the removal of the "zoning height penalty" as has been proposed by Aerts and Botzen (2011). Before this announcement, elevation of buildings was not always allowed by zoning regulations that put limits on the height of a building. This zoning regulation has been suspended by the Mayor using an emergency executive order. Moreover, the emergency rule requires that new construction or buildings with substantial damage are built at least one foot above the flood elevation that is currently required in the building code. This means that "freeboard" has become required for new residential buildings in the 1/100 flood zone, as has been recommended by Aerts and Botzen (2011).

Types of alternative flood-proofing strategies per building type and flood zone

The costs of alternative flood-proofing strategies for buildings are estimated for three main categories of measures that are applied to a variety of building types and flood zones, as Table 2.1 shows. This table shows the kind of measures we study per building type, for which we use the typology of occupancy types for structures used in the HAZUS flood damage model, which is the main flood risk model in the USA (FEMA, 2009a). The three main measures—elevation, wet floodproofing, and dry floodproofing—are consistent with actual building codes policies in NYC (Section 1.1). The elevation of existing buildings is only applicable to buildings that are not too large to be lifted and, as Table 2.1 shows, is therefore not applied in this study to large apartment blocks and commercial building types. Wet and dry floodproofing of existing buildings is applied to all building types. We realize that, in practice, the option of dry floodproofing of residential buildings would currently not comply with NFIP or NYC building code requirements. Nevertheless, we include this floodproofing strategy in this research since it is may be of interest to explore its potential cost-effectiveness. For new constructions, we assume that all three measures are applicable to all residential building types. Floodproofing of new commercial buildings is not studied here, since we lack reliable projections of the future new commercial building stock. In addition, we do not include agriculture, industrial, religious, government, and education structures in our study of floodproofing measures because we lack reliable cost estimates for

[a]http://www.nyc.gov/portal/site/nycgov/menuitem.c0935b9a57bb4ef3daf2f1c701c789a0/index.jsp?pageID=mayor_press_release&catID=1194&doc_name=http%3A%2F%2Fwww.nyc.gov%2Fhtml%2Fom%2Fhtml%2F2013a%2Fpr044-13.html&cc=unused1978&rc=1194&ndi=1

Table 2.1. Combinations of studied floodproofing measures and HAZUS building types in NYC flood zones

HAZUS (occupancy) building class	Description	Flood-proofing of existing buildings: Elevation	Wet-proofing	Dry-proofing	Flood-proofing of new buildings: Elevation	Wet-proofing	Dry-proofing
	Residential buildings						
RES1	Single Family Dwelling	Yes	Yes	Yes	Yes	Yes	Yes
RES2	Manuf. Housing	Yes	Yes	Yes	Yes	Yes	Yes
RES3A	Duplex	Yes	Yes	Yes	Yes	Yes	Yes
RES3B	Triplex/Quads	Yes	Yes	Yes	Yes	Yes	Yes
RES3C	Multi-dwellings (5 to 9 units)	No	Yes	Yes	Yes	Yes	Yes
RES3D	Multi-dwellings (10 to 19 units)	No	Yes	Yes	Yes	Yes	Yes
RES3E	Multi-dwellings (20 to 49 units)	No	Yes	Yes	Yes	Yes	Yes
RES3F	Multi-dwellings (50+ units)	No	Yes	Yes	Yes	Yes	Yes
RES4	Temporary Lodging	Yes	Yes	Yes	Yes	Yes	Yes
RES5	Institutional Dormitory	Yes	Yes	Yes	Yes	Yes	Yes
RES6	Nursing Home	Yes	Yes	Yes	Yes	Yes	Yes
	Commercial buildings						
COM1	Retail Trade	No	Yes	Yes	No	No	No
COM2	Wholesale Trade	No	Yes	Yes	No	No	No
COM3	Personal and Repair Services	No	Yes	Yes	No	No	No
COM4	Professional/Technical Services	No	Yes	Yes	No	No	No
COM5	Banks	No	Yes	Yes	No	No	No
COM6	Hospital	No	Yes	Yes	No	No	No
COM7	Medical Office/Clinic	No	Yes	Yes	No	No	No
COM8	Entertainment & Recreation	No	Yes	Yes	No	No	No
COM9	Theaters	No	Yes	Yes	No	No	No
COM10	Parking	No	Yes	Yes	No	No	No
Applied in flood zone zone type:		1/100 A and V zone, and 1/500	1/100 A zone, and 1/500	1/100 A zone, and 1/500	1/100 A and V zone, and 1/500	1/100 A zone, and 1/500	1/100 A zone, and 1/500

applying such measures to these building types.[b] We feel that this exclusion does not limit the scope of our study too much since these excluded buildings comprise only about 10% of the NYC building stock in the A and V zones. Elevation is applicable to both A and V zones, while wet and dry floodproofing is only studied for A zones since these stand-alone measures are less effective to cope with high velocity waves in V zones, especially if flood depths are high (FEMA, 2009b).

Table 2.1 shows different heights of implementation of the measures, which reflect a stricter application of current Building Code Regulations. We now can explore the application of each measure for 2 ft, 4 ft, and 6 ft above the current height of existing buildings. It should be realized that, here, this level of implementation is not explicitly related to the BFE in a flood zone. In the case of existing

[b]In terms of the HAZUS typology: IND1 (heavy industrial), IND2 (light industrial), IND3 (food, drugs, and chemicals), IND4 (metals and minerals processing), IND5 (high technology), IND6 (construction), AGR1 (agriculture), REL1 (churches and other non-profit organizations), GOV1 (general government services), GOV2 (emergency response), EDU1 (grade schools), and EDU2 (colleges and universities).

buildings, the level of implementation implies that the flood-proofing measure will be applied up to this particular level (+2 ft, +4 ft, or +6 ft), in addition to the current height of the building. For buildings constructed after the 1983 Building Code came into effect, this implies an additional height of flood-proofing compared with the applied Building Code standards (described in Section 2.2). For buildings constructed before the 1983 Building Code came into effect, this implies an application of flood-proofing measures to buildings that are currently not yet flood-proofed. Exceptions to this are rare cases in which pre-1983 buildings have been built according to flood-resistant Building Code standards because the buildings were substantially improved[c] and, therefore, in accordance with the Code, or in which flood-proofing measures have already been taken voluntarily. For new buildings the level of implementation (+2 ft, +4 ft, or +6 ft) implies that the flood-proofing measure is applied up to that level in addition to the current height of the area where the new building is being sited.

2.3 Cost estimates for elevation

Elevation of existing buildings

The objective of elevating a house is to raise the lowest floor in order to prevent floodwaters from entering the living areas. The elevation of existing buildings can entail leaving the house in its existing position and constructing a new raised floor within the house or by lifting the entire house, including the floor. It is the costs of this latter method that are examined in this study. This method involves separating a house from its foundations, raising the house and temporarily supporting it, and creating a new foundation or extending foundation below the house. This method works well for houses that were originally built on basement, crawlspace, and open foundations. The new foundation can consist of continuous walls, separate piers, posts, columns, or piles. Figure 2.1 shows an example of a house that is substantially elevated using a continuous wall foundation. If houses are built without a basement, crawlspace, or open foundation, but instead have a slab foundation, then both the house and the slab can be lifted, or the house can be detached from the slab and lifted and a new (elevated) slab can be created. More details about these elevation methods can be found in FEMA (2009b).

Figure 2.1. A house that is elevated using a continuous wall foundation (Source: FEMA, 2009b).

Table 2.2 shows the approximate costs of elevating different building types, as reported in FEMA (2009b). These costs are applicable to elevation on both continuous wall and open foundations. These costs include extending utilities and adding or extending staircases. These costs are for lifting houses. If the house has a slab foundation, then it is assumed that it is raised together with the house. A distinction is made between elevation costs for houses with and without a basement or crawlspace because elevation costs are higher for houses with a slab-on grade. Moreover, a distinction is made between the elevation of frame constructions[d] and that of masonry constructions,[e] since elevation costs are higher for the latter.

The cost estimates shown in Table 2.2 are used for estimating the average elevation costs per building type for NYC, as well as the costs of implementing the elevation of all buildings located in the current NYC flood zones. This is done as follows.

[c]This probably applies to few buildings because these regulations for flood-proofing substantially-renovated buildings are commonly side-stepped. These regulations can be side-stepped easily by conducting improvements to existing buildings in several phases, so that each phase costs less than 50% of the market value of the building before that construction phase started. For such renovations, flood-resistant building codes do not apply (Aerts and Botzen, 2011). Moreover, people rarely invest voluntarily in flood-proofing their homes, as discussed in Kunreuther (1996) and Kunreuther *et al.* (2009).

[d]Frame constructions are walls constructed of wood or light-gauge metal studs, with wood, vinyl, or aluminum siding (FEMA, 2009b).

[e]Masonry constructions have walls constructed of brick, stone, or concrete blocks (FEMA, 2009b).

Table 2.2. Approximate costs of elevating a building

Construction type and foundation	Cost in US$ per sq. ft. of the building footprint 2 feet elevation	Cost in US$ per sq. ft. of the building footprint 4 feet elevation	Cost in US$ per sq. ft. of the building footprint 8 feet elevation
Frame construction with a basement or crawlspace	$29	$32	$37
Frame construction with a slab-on-grade	$80	$83	$88
Masonry construction with a basement or crawlspace	$60	$63	$68
Masonry construction with a slab-on-grade	$88	$91	$96

NOTE: in 2009 US$ values.
Source: FEMA (2009b).

First, the MapPLUTO database was used to derive average building footprints (surface areas) per residential building class (according to the HAZUS building typology in Table 2.1). This database contains information on buildings in NYC on a detailed spatial level.[f] Using the building count of the HAZUS model, three census blocks per HAZUS building class were selected containing mostly (>85%) one of the building classes RES 1–RES 6. The buildings located within these census blocks in the MapPLUTO database were grouped and counted according to type and then their surface area was averaged. This resulted in a standard building footprint for each of the residential building classes.

Second, the average building footprint per residential building type is multiplied by the number of this particular type of buildings located in the A and V flood zones, according to the building database from the Office of Emergency Management (OEM) of NYC. The result is the total number of square feet of building footprints per residential housing type in the A and V zones in NYC.

Third, using information from the HAZUS database, a further subdivision of the HAZUS building classes (RES 1–RES 6) is made into masonry or other construction types. In particular, the percentage of masonry and other housing types per HAZUS building class is derived for the NYC flood zones. These percentages are used to calculate per building type how much of the total square feet of building footprints in the A and V zones belong to masonry buildings and how much belong to other building types.

Fourth, using information from the HAZUS database, it has been derived what percentage of NYC buildings on average have a basement. On average, 76% of the buildings have a basement and 24% do not. These percentages are used to calculate per building type in the A and V flood zones how much of the total square feet of building footprints belong to: (1) masonry buildings with a basement (2); masonry buildings without a basement; (3) other buildings with a basement; and (4) other buildings without a basement.

Fifth, the total square feet of building footprints in different zones derived in step four are combined with the elevation costs shown in Table 2.2 in order to estimate the total costs of elevating existing buildings in the A and V zones by 2 ft, 4 ft, and 8 ft. This is done by multiplying the total square feet of footprints of masonry buildings with basements by the corresponding cost estimates in Table 2.2, and the total square feet of footprints of masonry buildings without a basement is multiplied by the elevation costs of masonry constructions with a slab-on-grade, etc. It is assumed that the frame construction elevation costs are representative for non-masonry buildings. The total costs for 6 ft of elevation are approximated by taking the average of total elevation costs for a 4 ft and an 8 ft elevation. A similar analysis as that described in the previous steps was done for the 1 in 500 floodplain in NYC.

Table 2.3 shows the average elevation costs of existing buildings for three main HAZUS building classes: namely, single family dwellings (RES1), manufactured housing (RES2), and duplex housing (RES3A) and triples/quads housing (RES3B). These costs are shown on the basis of the FEMA (2009) cost estimates for the US, as well as for a scaling-up of these cost estimates to reflect higher

[f]It can be accessed via http://www.nyc.gov/html/dcp/html/bytes/applbyte.shtml

Table 2.3. **Average costs per building of elevating existing buildings in NYC floodplains for building classes RES1, RES2, RES3A, and RES3B, using FEMA (2009b) cost estimates (left columns), and scaled-up estimates that reflect higher NYC construction costs (right columns)**

	Costs based on FEMA per building category				Costs scaled-up for NYC per building category			
Elevation level	RES1	RES2	RES3A	RES3B	RES1	RES2	RES3A	RES3B
+2 ft	\$33,239	\$40,550	\$41,337	\$62,029	\$44,208	\$53,931	\$54,978	\$82,498
+4 ft	\$35,464	\$43,499	\$43,861	\$65,816	\$47,168	\$57,854	\$58,335	\$87,535
+6 ft	\$37,319	\$45,958	\$45,964	\$68,971	\$49,634	\$61,124	\$61,132	\$91,732

Table 2.4. **Total costs of elevating existing buildings per flood zone using FEMA (2009b) cost estimates (left columns), and scaled-up estimates that reflect higher NYC construction costs (right columns)**

	Costs based on FEMA per building category		Costs scaled-up for NYC per building category	
Elevation level	1/100 A and V zones	1/500 zone only	1/100 A and V zones	1/500 zone only
+2 ft	\$1,759,058,426	\$1,001,969,917	\$2,339,547,707	\$1,332,619,990
+4 ft	\$1,872,497,344	\$1,065,306,285	\$2,490,421,468	\$1,416,857,359
+6 ft	\$1,967,029,776	\$1,118,086,591	\$2,616,149,602	\$1,487,055,166

NYC construction costs. To derive the latter, a scaling factor of 1.33 was used. This factor reflects the higher NYC construction costs compared with the US average.[g] The increasing costs per residential building class can be explained by the higher average building footprint of these categories. The estimates in Table 2.3 are consistent with the range \$30,000–\$88,000, which represents the costs of actual projects to elevate existing buildings as reported by Jones *et al.* (2006).

Table 2.4 shows the costs of elevating all existing buildings per flood zone for the different elevation heights. The costs of this measure are very substantial and range between \$2.3 bn and \$2.6 bn for the 1/100 flood zone and between \$1.3 bn and \$1.5 bn for the 1/500 flood zone. The estimated elevation costs for the 1/500 zone reflect only the costs of elevation in that zone, and do not include the costs of elevating buildings in the 1/100 zone. The cost estimates for 4 ft and 6 ft elevation are not much higher than the 2 ft elevation costs, as is consistent with the relation between per square feet footprint costs and height shown in Table 2.2.

[g]This estimation has been made by the Manhattan Research Institute. NYC officials have confirmed its adequacy in personal communication.

Elevation of new buildings

Moreover, we estimate costs for elevating new buildings that have been projected to be newly built by the year 2040. This projection is based on population growth estimates per Traffic Analysis Zone (TAZ) developed by the NYC department of city planning (NYC-DCP, 2011). The population projections are at the borough level (5 areas) and were made spatially explicit by NYC-DCP to the level of TAZ zones (1611 areas) using information on current household distributions, the distance to subway stations and existing building, and zoning plans. We assumed growth in households to follow these population growth rates per TAZ zone and translated them into new buildings using borough differentiated percentages (as some new households will settle in existing buildings) provided by NYC-DCP. Lastly, every census block was attributed a growth in buildings similar to the TAZ zone it was located in, to determine the increase in buildings. Only residential buildings are assumed to increase in our projections, which make up 90% of the existing building stock in NYC. Overall, this results in an increase in residential buildings of 14% in the whole of NYC (723,000 to 825,000 buildings).

New buildings in flood zones have to be built at the BFE level. Here, we examine the costs of building higher than that level, which has been called ‘adding

Table 2.5. **Costs of 1 foot of elevation of new buildings with a pile or masonry pier foundation in US$ per square foot of building footprint**

Type of building	Cost in US$ per sq. ft. of building footprint A zone (average quality house)	Cost in US$ per sq. ft. of building footprint Coastal A zone (good quality house)	Cost in US$ per sq. ft. of building footprint V zone (very good quality house)
30 × 50, 1-storey, 1,500 sf.	0.17–0.33	0.23–0.45	0.27–0.54
30 × 50, 2-storey, 3,000 sf.	0.28–0.57	0.39–0.78	0.50–1.00
40 × 60, 1-storey, 2,400 sf.	0.15–0.31	0.21–0.42	0.25–0.50
40 × 60, 2-storey, 4,800 sf.	0.26–0.52	0.36–0.73	0.47–0.94

freeboard'. Jones *et al.* (2006) have estimated the costs of adding freeboard for different foundations types, and expressed these costs as a percentage of the total building costs. This resulted in the following estimates:

- The costs for adding freeboard for pile and masonry pier foundations range between 0.25% and 0.5% per foot of freeboard;
- The costs for adding freeboard for masonry wall foundations range between 0.8% and 1.5% per foot of freeboard;
- The costs for adding freeboard for slab on fill foundations range between 0.8% and 3% per foot of freeboard.

These cost estimates of adding 1 ft freeboard can be translated to costs per square foot of the building footprint using the total building costs as reported by Jones *et al.* (2006, p. 32) for four types of buildings that are constructed in the A zone with either average or good quality materials, or in the V zone using very good quality materials (to withstand wave impacts). These results are shown in Tables 2.5, 2.6, and 2.7. Masonry wall-and-fill foundations are not used in V zones, which is why these elevation costs are not provided for that zone. In V zones open foundations are used. Open foundations consist of individual structural members that support the houses only at key points. In other words, no continuous walls are created around the house in order to allow water to flow underneath the house. These foundations, which consist of piers, posts, columns, or piles, are especially suitable for elevating houses in areas with wave action and high velocity floods (V zones). More details about these elevation methods can be found in FEMA (2009b).

The cost estimates from Tables 2.5–2.7 are used for estimating the costs of elevating new buildings. These tables show that the costs per square foot of building footprint are slightly higher for the elevation of two storey buildings compared with one storey buildings. Given the scarcity of space in NYC, we expect that few new single storey buildings will be constructed in NYC, so we use the elevation costs of only two storey buildings in our cost estimations. For the elevation of new buildings in the V zone, the average of the observed cost range of $0.47–1.00 per square ft of building footprint in Table 2.5 was used to estimate average costs of adding 2 ft, 4 ft, and 6 ft of freeboard for the different residential building classes. The results are shown in Table 2.8. Moreover,

Table 2.6. **Costs of 1 foot of elevation of new buildings with a masonry wall foundation in US$ per square foot of building footprint**

Type of building	Cost in US$ per sq. ft. of building footprint A zone (average quality house)	Cost in US$ per sq. ft. of building footprint Coastal A zone (good quality house)
30 × 50, 1-storey, 1,500 sf.	0.53–1.00	0.72–1.35
30 × 50, 2-storey, 3,000 sf.	0.91–1.70	1.25–2.34
40 × 60, 1-storey, 2,400 sf.	0.49–0.92	0.67–1.26
40 × 60, 2-storey, 4,800 sf.	0.84–1.57	1.16–2.18

Table 2.7. Costs of 1 foot of elevation of new buildings with a fill foundation in US$ per square foot of building footprint

Type of building	Cost in US$ per sq. ft. of building footprint A zone (average quality house)	Cost in US$ per sq. ft. of building footprint Coastal A zone (good quality house)
30 × 50, 1-storey,1,500 sf.	0.53–2.00	0.72–2.70
30 × 50, 2-storey, 3,000 sf.	0.90–3.40	1.25–4.68
40 × 60, 1-storey, 2,400 sf.	0.49–1.84	0.67–2.51
40 × 60, 2-storey, 4,800 sf.	0.84–3.15	1.16–4.37

Table 2.8. Average costs per building of elevating new buildings in the V zone for building classes RES1, RES2, RES3A, and RES3B, using the Jones *et al.* (2006) cost estimates (left columns) and scaled-up estimates that reflect higher NYC construction costs (right columns)

	Cost based on Jones *et al.* per building category				Cost scaled-up for NYC per building category			
Elevation level	RES1	RES2	RES3A	RES3B	RES1	RES2	RES3A	RES3B
+ 2 ft	$1,090	$1,445	$1,237	$1,856	$1,450	$1,922	$1,645	$2,468
+ 4 ft	$2,181	$2,891	$2,473	$3,711	$2,901	$3,845	$3,289	$4,936
+ 6 ft	$3,271	$4,336	$3,710	$5,567	$4,351	$5,767	$4,934	$7,404

Table 2.9 shows the total costs of elevating all new buildings in the V zone, which have been estimated using the same procedure.

For elevation of new buildings in the A and the 1/500 zones we used the average of the costs in Tables 2.5, 2.6, and 2.7 for high quality foundations for coastal A zones, which results in cost per ft of freeboard of $1.72 per ft of building footprint. The lower cost estimates for average quality foundations in A zones are regarded as less realistic for NYC and are, therefore, not applied here. Table 2.10 shows the estimated average costs of adding 2 ft, 4 ft, and 6 ft of freeboard to new buildings for the different residential building classes in the 1/100 (excluding V) and 1/500 zones. Moreover, Table 2.11 shows the total costs of elevating all new buildings in the 1/100 (excluding V) and 1/500 zones. The costs of this measure range between $77 mln and $231 mln for the 1/100 flood zone and between $33 mln and $98 mln for the 1/500 flood zone. These costs are substantially lower than the costs of elevating all existing buildings for two reasons: (1) the number of projected new buildings is only a small proportion of the existing building stock; and (2) the average per building costs of elevating new building is much lower than elevating existing buildings.

2.4 Cost estimates of wet floodproofing

Wet floodproofing entails modifying parts of a house so that floodwaters can enter but cause only minimal damage to the house and its contents. Figure 2.2 shows an example of a wet floodproofed building. By allowing water to flow into the house, hydrostatic pressures exerted by water inside and outside the house can be equalized, which minimizes the risks that the walls of the house collapse.

Table 2.9. Total costs of elevating all new residential buildings in the V zone using the Jones *et al.* (2006) cost estimates (left columns), and scaled-up estimates that reflect higher NYC construction costs (right columns)

Elevation level	Cost based on Jones *et al.*	Cost scaled for NYC
+ 2 ft	$1,175,989	$1,564,065
+ 4 ft	$2,351,978	$3,128,131
+ 6 ft	$3,527,967	$4,692,196

Table 2.10. Average costs per building of elevating new buildings in the 1/100 A and 1/500 zones for building classes RES1, RES2, RES3A, and RES3B, using the Jones *et al.* (2006) cost estimates (left columns), and scaled-up estimates that reflect higher NYC construction costs (right columns)

	Cost based on Jones *et al.* per building category				Cost scaled-up for NYC per building category			
Elevation level	RES1	RES2	RES3A	RES3B	RES1	RES2	RES3A	RES3B
+2 ft	\$2,553	\$3,384	\$2,895	\$4,344	\$3,396	\$4,501	\$3,851	\$5,778
+4 ft	\$5,106	\$6,768	\$5,790	\$8,689	\$6,791	\$9,002	\$7,701	\$11,556
+6 ft	\$7,659	\$10,152	\$8,686	\$13,033	\$10,187	\$13,502	\$11,552	\$17,334

Table 2.11. Total cost of elevating all new residential buildings in the 1/100 A and 1/500 zones using Jones *et al.* (2006) cost estimates (left columns), and scaled-up estimates that reflect higher NYC construction costs (right columns)

	Cost based on Jones *et al.* per building category		Cost scaled for NYC per building category	
Elevation level	1/100 A zones	1/500 zone only	1/100 A zones	1/500 zone only
+2 ft	\$57,991,533	\$24,439,155	\$77,128,739	\$32,504,076
+4 ft	\$115,983,066	\$48,878,310	\$154,257,478	\$65,008,153
+6 ft	\$173,974,599	\$73,317,465	\$231,386,216	\$97,512,229

Allowing floodwaters to enter the house implies that finishes and constructions below potential water heights should be made resistant to flood damage. For example, service equipment (e.g. utility installations) should be built above flood levels, and walls should be built using water-resistant building materials. Moreover, it is advised not to use the flood-prone parts of the house in a way that high-value goods are exposed to flooding (e.g. in a sauna or kitchen). Valuable items should be moved to spaces above potential floodwaters.

Table 2.12 shows the approximate costs of wet floodproofing buildings. These costs have been estimated by FEMA (2009b), and include adding wall openings for the entry and exit of floodwaters, installing pumps, rearranging or relocating utility systems, moving large appliances, and making it easier to clean up after floodwaters recede. The cost estimates in Table 2.12 are applicable to both frame or masonry type of buildings and are provided for wet flood-proofing up to 2 ft, 4 ft, and 8 ft. These cost estimates do not include the costs of the removal of all non-flood damage-resistant materials in existing buildings or replacing finish materials with flood damage-resistant materials. A description of these flood damage-resistant materials can be found in FEMA (2008). We do not include the additional costs of installing these materials in our cost estimates of the strategy of wet floodproofing houses in NYC since it is assumed that wet proofing is undertaken when a building is substantially renovated and finish materials need to be replaced anyway.

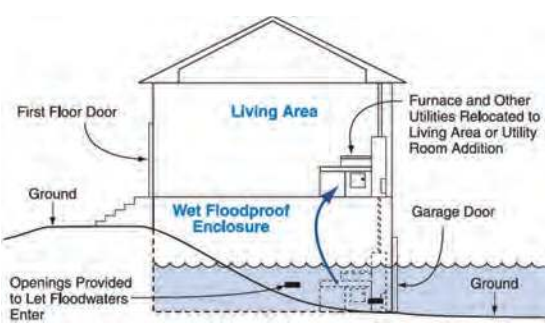

Figure 2.2. Example of a wet floodproofed building (Source: FEMA, 2009b).

The cost estimates shown in Table 2.12 are used for estimating the costs of wet floodproofing per building type for NYC, as well as the costs of wet floodproofing all existing buildings located in the current NYC flood zones.

First, the MapPLUTO database was used to derive average building footprints (surface areas) per residential building class (according to the HAZUS building typology in Table 2.1), by following the methodology that was described in Section 2.3. A different approach had to be followed to estimate

Table 2.12. Costs of wet flood-proofing buildings per foot of wet-proofing height

Existing foundation of a frame or masonry building	Cost in $ per sq. ft. of the building footprint 2 foot above basement floor or LAG[a]	Cost in $ per sq. ft. of the building footprint 4 foot above basement floor or LAG[a]	Cost in $ per sq. ft. of the building footprint 8 foot above basement floor or LAG[a]
Basement	$2.90	$6.00	$17.00
Crawlspace	$2.20	$5.60	Not available

NOTES: In 2009 US$ values.
[a]LAG stands for lowest adjacent grade, which is the elevation of the lowest ground surface that touches any of the exterior walls of a building. Source: FEMA (2009b).

the average building footprints of commercial building classes.[h] This was done as follows. We first estimated the ratio FA/BF of total floor area (FA) (from an NYC-OEM database) to the building footprint (BF) for each residential buildings type. Then using a regression analysis the relation between this ratio and the total floor area has been estimated. Next, the results of this regression equation were used to estimate this ratio (FA/BF) for commercial building type on the basis of the total floor area per commercial building type that we obtained from OEM. Finally, on the basis of these ratios, the average building footprint of commercial building types was derived.

Second, the average building footprints per building type were multiplied by the number of this particular type of buildings that are located in flood zones, according to the building database from NYC-OEM. The result is the total number of square feet of building footprints per residential and commercial building types in the 1/100 A and 1/500 zones in NYC.

Third, the total square feet of building footprints derived in step two were combined with the costs of wet floodproofing shown in Table 2.12 in order to estimate the total costs of wet proofing existing buildings in the 1/100 A and 1/500 flood zones with wet-proofing levels of 2 ft, 4 ft, and 8 ft. This is done by multiplying the total square feet of the buildings in the flood zones with the corresponding cost estimates in Table 2.12 for wet floodproofing buildings with a basement. We used the cost estimates for buildings with basements and not crawlspaces, because most NYC buildings have a basement. Although this may result in a slight over-estimation of the costs, differences between the two cost estimates are small as Table 2.12 shows. Another more pragmatic reason for this choice is that cost estimates for 8 ft wet proofing of buildings with a crawlspace are not available. The total costs for 6 ft of wet floodproofing are approximated by taking the average of the total wet flood-proofing costs for the 4 ft and 8 ft levels.

Table 2.13 shows the average wet floodproofing costs of existing buildings for three main housing types: namely, single family dwellings (RES1), manufactured housing (RES2), and duplex housing (RES3A) and triples/quads housing (RES3B). These costs are shown on the basis of the FEMA (2009b) cost estimates for the US, as well as for a scaling-up of these cost estimates to reflect higher NYC construction costs. As in Section 2.3, a scaling factor of 1.33 has been used to derive the latter.

Table 2.14 shows the costs of wet floodproofing all existing buildings per flood zone for the different heights if wet-proofing measures are taken. The costs of this measure range between $250 mln and $980 mln for the 1/100 flood zone and between $150 mln and $590 mln for the 1/500 flood zone. The estimated wet floodproofing costs for the 1/500 zone reflect only the costs of wet floodproofing in that zone, and do not include the costs of wet floodproofing buildings in the 1/100 zone. The costs of wet floodproofing existing houses are substantially lower than the cost of elevating these homes. Wet floodproofing costs are more sensitive to the height

[h]The reason for this is that there are no census blocks in the MapPLUTO database that contain almost only buildings of one particular commercial class type from which the average footprint could be computed.

Table 2.13. Average costs per building of wet floodproofing houses in NYC floodplains for building classes RES1, RES2, RES3A, and RES3B, using FEMA (2009) cost estimates (left columns), and scaled-up estimates that reflect higher NYC construction costs (right columns)

Wet flood-proofing level	Costs based on FEMA per building category				Costs scaled-up for NYC per building category			
	RES1	RES2	RES3A	RES3B	RES1	RES2	RES3A	RES3B
+2 ft	$2,151	$2,851	$2,440	$3,661	$2,861	$3,792	$3,245	$4,869
+4 ft	$4,451	$5,900	$5,047	$7,574	$5,920	$7,846	$6,713	$10,073
+6 ft	$8,531	$11,307	$9,674	$14,517	$11,346	$15,039	$12,867	$19,307

Table 2.14. Total costs of wet floodproofing existing buildings per flood zone using FEMA (2009b) cost estimates (left columns), and scaled-up estimates that reflect higher NYC construction costs (right columns)

Wet flood-proofing level	Cost based on FEMA per building category		Cost scaled-up for NYC per building category	
	1/100 A zone	1/500 zone only	1/100 A zone	1/500 zone only
+2 ft	$185,726,393	$111,250,098	$247,016,103	$147,962,631
+4 ft	$384,261,503	$230,172,617	$511,067,799	$306,129,581
+6 ft	$736,501,214	$441,164,183	$979,546,614	$586,748,363

up to which the measures are applied than is the case for elevation.

The same methodology has been applied to estimate the total costs of wet floodproofing all new residential buildings that are expected to be newly built until the year 2040. The cost estimates of this strategy are shown in Table 2.15. The costs of wet floodproofing new buildings range between $65 mln and $258 mln for the 1/100 flood zone and between $27 mln and $109 mln for the 1/500 flood zone. The difference between the total costs of flood-proofing these new residential buildings compared with existing buildings only arises because of differences in the number of buildings that are flood-proofed. In other words, the costs of wet floodproofing new buildings in Table 2.16 are lower than those costs for existing buildings because the number of about to be built residential buildings is lower than the current building stock.

2.5 Cost estimates for dry floodproofing

Dry floodproofing a building means that the flood-prone parts of the house have been made watertight, so that floodwaters cannot enter the building (FEMA, 2009b). Figure 2.3 shows an example of a dry floodproofed building. A building can be made watertight by sealing walls with waterproof coatings, impermeable membranes, or supplemental layers of masonry or concrete. Doors and other openings of the building in flood-prone parts of the building must be protected by permanent or removable flood shields. Backflow valves must be installed in sewer lines and drains to prevent floodwaters from entering the building via the sewer system. However, dry floodproofing may not be effective in all flood conditions. For example, high flood depths may create pressure on the walls of the building which may cause the building to collapse. The reason is that if

Table 2.15. Total costs of wet floodproofing new buildings per flood zone using FEMA (2009b) cost estimates (left columns), and scaled-up estimates that reflect higher NYC construction costs (right columns)

Wet flood-proofing level	Cost based on FEMA per building category		Cost scaled-up for NYC per building category	
	1/100 A zone	1/500 zone only	1/100 A zone	1/500 zone only
+2 ft	$48,864,536	$20,592,799	$64,989,833	$27,388,423
+4 ft	$101,099,040	$42,605,791	$134,461,724	$56,665,702
+6 ft	$193,773,161	$81,661,099	$257,718,304	$108,609,262

Table 2.16. Approximate costs of elements of a dry floodproofing project

Type of dry floodproofing measure	Costs are expressed per	Cost in US$
Sprayed-on cement (above grade)[a]	Linear foot of wall covered	$16.80
Waterproof membrane (above grade)[a]	Linear foot of wall covered	$5.70
Asphalt (two coats on foundation up to 2 feet below grade)	Linear foot of wall covered	$12.00
Drainage line around perimeter of the house	Linear foot	$31
Plumbing check valve	Each	$1,060
Sump and sump pump (with backup battery)	Lump sum	$1,710
Metal flood shield	Linear foot of shield surface	$375
Wooden flood shield	Linear foot of shield surface	$117

[a]Cement, membrane and asphalt are alternative sealant methods (source: FEMA, 2009b).

dryproofing is applied then pressure on walls from water rising up on the outside of the building is not balanced by water inside the house. This is a real risk in the case of frame constructions, but less of a problem if buildings are constructed with masonry walls (FEMA, 2009b). Moreover, buoyancy forces may damage the building, especially if flood depths are high and the buildings are not heavy enough to withstand buoyancy. Because of these risks of damage to walls at high flood depths, FEMA (2009b) advises that dry floodproofing in the USA should be applied only up to a flood depth of 3 feet. Nevertheless, we examined the dry floodproofing strategy for NYC up to a height of 6 feet, as we do for the other flood-proofing strategy. It is relevant to study dry floodproofing in NYC for locations with higher flood depths than 3 feet because, in general, buildings in New York are heavier and have a stronger construction than is usual in the US. This implies that in NYC the risk of building collapse in the case of dry floodproofing at high flood depths may be less of a problem.[i] Further research should examine in more detail the effectiveness of dry floodproofing NYC construction types under a variety of flooding conditions, and in particular, flood depths.

Table 2.16 shows the costs of dry floodproofing houses up to a level of 3 feet, as has been approximated by FEMA (2009b) for a variety of cost elements of a dry floodproofing project. The total costs per house will depend on the size of the house, the depth of floodwaters for which the dry-proofing is undertaken, the types of sealants and shield materials that are used, the number of plumbing lines that have to be protected, and the number of door openings that have to be covered by shields.

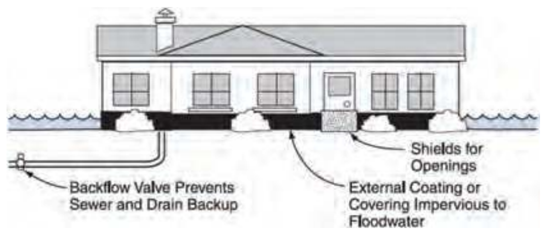

Figure 2.3. Example of a dry floodproofed building (Source: FEMA (2009b).

The cost estimates shown in Table 2.16 are used for estimating the average dry floodproofing costs per building type for NYC, as well as the costs of implementing dry floodproofing of all buildings located in the current NYC flood zones. This is done as follows.

First, the MapPLUTO database was used to derive average building footprints (surface areas) per residential building class (according to the HAZUS building typology in Table 2.1), using the method that was explained in Section 2.3. This resulted in a standard building footprint for each of the residential building classes. The method outlined in Section 2.4 was used to derive building footprints of the commercial building classes. Unlike wet floodproofing and elevation, dry floodproofing costs are not dependent on the building footprint, but instead depend on the perimeter (linear feet of walls covered) of the building. Therefore, for each building class the average perimeter was calculated from the average footprint per building class.[j]

[i] This was confirmed by means of consultations with NYC building specialists.

[j] The perimeter of the buildings was derived by taking four times the square root of the footprints ($4*\sqrt{\text{footprint}}$).

Table 2.17. Average costs per building of dry floodproofing houses in NYC floodplains up to 3 ft for building classes RES1, RES2, RES3A, and RES3B, using FEMA (2009b) cost estimates

Dry flood-proofing level	Costs based on FEMA per building category			
	RES1	RES2	RES3A	RES3B
+3 ft	\$9,361	\$10,519	\$9,858	\$11,691

Second, the average perimeter per building type is multiplied by the number of the particular type of buildings concerned that are located in the 1/100 A and 1/500 flood zones, according to the building database from NYC-OEM. The result is the total linear feet of building perimeter per building type separately for the 1/100 A and 1/500 flood zones in NYC.

Third, the information obtained in the second step was combined with the cost information in Table 2.16, which was done as follows. As Table 2.16 shows, sealing costs dependent on whether cement, a water-proof membrane, or asphalt is used. Consultations with NYC building experts revealed that cement is rarely used for dry-proofing buildings in NYC, and that mostly water-proof membranes or asphalt are used. Therefore, we took the average costs of these latter two methods (\$8.85 per lin. ft) as average sealant costs. Adding to this amount the costs of a drainage line results in an average cost of installing sealing and drainage of \$39.85 per linear foot of a house perimeter. It is assumed that 6 linear feet of flood shields are needed to dry floodproof a single-family dwelling (RES1).[k] For deriving the costs of flood shields, the higher cost estimate for metal flood shields in Table 2.16 was used (\$375 per lin. ft.), rather than the lower costs of wooden shields.[l] This results in an average cost of flood shields per single-family dwelling of \$2,250. The other building types are typically larger than single-family dwellings, which implies that these buildings probably have more openings that need to be shielded. Average flood shield costs for these buildings are assumed to increase proportionally with their average perimeter size relative to the average perimeter of single-family houses; that is, the shielding costs of building type X are 2250 × average perimeter building X/average perimeter of a single-family house. It is assumed that every building needs one sump pump that costs on average \$1,710 per building. Moreover, it is assumed that one set of plumbing check valves is installed per single-family house for a cost of \$1,060, while for the other building types this cost is assumed to increase, on average, proportionally to their relative perimeter size; that is, 1060 × average perimeter of building X/average perimeter of a single-family house. In other words, larger buildings are, on average, likely to have more connections to the sewer system, which results in higher costs for installing backflow valves. Finally, the total costs of dry floodproofing buildings in the NYC floodplains are estimated by multiplying the total number of linear feet of a building's perimeter by the average sealing and drainage costs per linear square foot (\$39.85), and by adding the costs for sump pumps, check values, and flood shields per building per building type, which are multiplied by the corresponding total number of building types in a flood zone according to the NYC-OEM building database. Average dry floodproofing costs per building type are obtained by dividing the total dry-proofing cost per building type by the total number of buildings of this particular type. The resulting average dry floodproofing costs for four main residential building classes is shown in Table 2.17.

The costs in Table 2.17 are shown for a height of dry floodproofing of 3 ft, as is consistent with the FEMA (2009b) cost estimates that served as input for these calculations. These cost estimates are adjusted for dry floodproofing heights of 2 ft, 4 ft, and 6 ft, using the following approach. The cost for check valves, the sump pump, and the drainage system used to remove floodwaters leaking in the house are taken as fixed costs per house, and do not depend on the desired dry proofing height. However, sealing costs and costs for flood shields

[k]This is consistent with having, on average, two door-openings per single family home.

[l]NYC building experts have confirmed that wooden flood shields are not commonly used; thus it is more appropriate to use the costs of metal shields.

Table 2.18. **Average costs per building of dry floodproofing houses in NYC floodplains up to 2 ft, 4 ft, and 6 ft for building classes RES1, RES2, RES3A, and RES3B, using FEMA (2009b) cost estimates (left columns), and scaled-up estimates that reflect higher NYC construction costs (right columns)**

Dry flood-proofing level	Costs based on FEMA per building category				Costs scaled-up for NYC per building category			
	RES1	RES2	RES3A	RES3B	RES1	RES2	RES3A	RES3B
+2 ft	$8,290	$9,286	$8,717	$10,294	$11,026	$12,350	$11,594	$13,690
+4 ft	$10,433	$11,753	$10,999	$13,089	$13,876	$15,631	$14,629	$17,408
+6 ft	$12,576	$14,220	$13,281	$15,884	$16,726	$18,912	$17,664	$21,126

are assumed to increase with the desired height of dry floodproofing. The costs of sealing and flood shields for dry-proofing of 2 ft, 4 ft, and 6 ft are computed by multiplying the costs for 3 ft by a factor of, respectively, 2/3, 4/3, and 2. Table 2.18 shows the resulting average dry floodproofing costs of existing buildings for three housing types: namely, single family dwellings (RES1), manufactured housing (RES2), and duplex housing (RES3A) and triples/quads housing (RES3B). These costs are shown on the basis of the FEMA (2009b) cost estimates for the USA, as well as for a scaling-up of these cost estimates to reflect higher NYC construction costs, as was done in Sections 2.3 and 2.4.

Table 2.19 shows the costs of dry floodproofing all existing buildings per flood zone for the different heights after dry-proofing measures are taken. The costs of this measure range between $640 mln and $980 mln for the 1/100 flood zone and between $380 mln and $580 mln for the 1/500 flood zone. The estimated dry floodproofing costs for the 1/500 zone reflect only the costs of elevation in that zone, and do not include the costs of dry floodproofing buildings in the 1/100 zone. The costs of dry floodproofing existing houses are substantially lower than the cost of elevating these houses. Dry floodproofing is more costly than wet floodproofing for flood-proofing heights of 2 ft and 4 ft, but is about the same for flood-proofing up to 6 ft.

The same methodology has been applied to estimate the total costs of dry floodproofing all new residential buildings that are expected to be newly built until the year 2040. The cost estimates of this strategy are shown in Table 2.20. The costs of dry flood-proofing new buildings range between $170 mln and $260 mln for the 1/100 flood zone and between $70 mln and $110 mln for the 1/500 flood zone. The difference between the total costs of flood-proofing these new residential buildings compared with existing buildings only arises because of differences in the number of buildings that are flood proofed. In other words, the cost of dry floodproofing new buildings in Table 2.20 are lower than those costs for existing buildings because the number of about to-be-built residential buildings is lower than the current building stock.

2.6 Summary: costs of Strategy 1a, Open resilient City

Table 2.21 summarizes the costs for Strategy 1a Open resilient City. The table shows the total costs for elevating, wet floodproofing, and dry floodproofing all buildings (existing or new). Of course, it is not realistic to elevate all existing building, nor is it feasible to dry proof all buildings. Nevertheless, the table provides interesting insight into the order of magnitude of the total costs for implementing building codes, which lies between $0.5 bn for 'wet

Table 2.19. **Total costs of dry floodproofing existing buildings per flood zone using FEMA (2009b) cost estimates (left columns), and scaled-up estimates that reflect higher NYC construction costs (right columns)**

Dry flood-proofing level	Cost based on FEMA per building category		Cost scaled-up for NYC per building category	
	1/100 A zone	1/500 zone only	1/100 A zone	1/500 zone only
+2 ft	$477,753,289	$283,873,352	$635,411,874	$377,551,559
+4 ft	$606,025,771	$360,299,296	$806,014,276	$479,198,064
+6 ft	$734,298,253	$436,725,240	$976,616,677	$580,844,570

Table 2.20. **Total costs of dry floodproofing new buildings per flood zone using FEMA (2009b) cost estimates (left columns), and scaled-up estimates that reflect higher NYC construction costs (right columns)**

Dry flood-proofing level	Cost based on FEMA per building category		Cost scaled-up for NYC per building category	
	1/100 A zone	1/500 zone only	1/100 A zone	1/500 zone only
+2 ft	$128,759,576	$53,869,990	$171,250,236	$71,647,087
+4 ft	$163,258,937	$68,376,561	$217,134,387	$90,940,826
+6 ft	$197,758,299	$82,883,131	$263,018,537	$110,234,565

floodproofing +2 ft' to $4.4 bn for 'elevating all buildings with +6 ft'.

2.7 Cost estimates of Strategy Open Resilient City+

Flood adaptation costs for critical infrastructure

The Resilient Open City+ strategy aims at implementing floodproofing and elevation measures in zones that are currently classified as the 1/100 and the 1/500 flood zones. These measures are applied to existing and new buildings; again, the '+'refers to additional measures needed to protect critical infrastructure. Since a lot of vulnerable infrastructure remains unprotected in Strategy 1a, Strategy 1b Resilient Open City+ aims at enhancing resilience of critical infrastructure, such as power-plants, subways, water treatment plants, airports, etc. This is performed using local scale adaptation measures that protect these facilities.

We use the proposed adaptation measures and their costs provided by the infrastructure companies and authorities, such as elevating or sealing tunnel entrances, small scale levees or the hardening of power lines. Large-scale storm surge barriers are not considered. Table 2.22 provides an overview of adaptation cost for the various proposed infrastructure utilities in NYC and the Hoboken – Raritan River areas of New Jersey. The total costs are estimated at $2.9 –$8.4 bn (total: $11.3 bn), which are lower than the total estimated adaptation costs for the states of NJ (2012) and NY (2012): $9 bn for

Table 2.21. **Summary of all building code costs for NYC of Strategy 1a Open resilient City (in $ 2012 values)**

	[Costs $ bn]	[Costs $ bn]	[Costs $ bn]
Elevation	**1/100 A and V zones**	**1/500 zone only**	**Total**
Existing buildings +2 ft,+4 ft, +6 ft	$2.3–$2.6 bn	$1.3–$1.5 bn	$2.6–$4.1 bn
New buildings +2 ft,+4 ft, +6 ft	$0.08 – $0.2 bn	$0.03–$0.1 bn	$0.1–$0.3 bn
Total			*$2.7–$4.4 bn*
Total ($ 2012 values)			**$2.9–$4.7 bn**[a]
Wet floodproofing			
Existing buildings +2 ft,+4 ft, +6 ft	$0.25–$1 bn	$0.15–$0.6 bn	$0.4–$1.6 bn
New buildings +2 ft,+4 ft, +6 ft	$0.06–$0.26 bn	$0.03–$0.1 bn	$0.09–$0.36 bn
Total			*$0.5–$1.96 bn*
Total ($ 2012 values)			**$0.5–$2.0 bn**[a]
Dry floodproofing			
Existing buildings +2 ft,+4 ft, +6 ft	$0.6–$1 bn	$0.4–$0.6 bn	$1–$1.6 bn
New buildings +2 ft,+4 ft, +6 ft	$0.17–$0.26 bn	$0.07–$0.1 bn	$0.24–$0.36 bn
Total			*$1.24–$2 bn*
Total ($ 2012 values)			**$1.3–$2.1 bn**[a]

[a]All summary cost tables are in US$ 2012 values. Indexing was applied using the Construction Cost Index from ENR (Engineering News-Record, http://enr.construction.com/economics). The CCI annual growth rate was set to 2.4%, on May 2nd 2013.

Table 2.22. **Overview of adaptation costs for various utility companies for NYC and the Hudson coasts of NJ (all in $ 2012 values)**

		Power utilities	
Name of utility company	**State**	**Flood adaptation measures [$bn 2012]**	**Adaptation description**
PSE&G	NJ	1–2 [a]	Protect substation, relocate wire underground, etc
Consolidated Edison	NY	1.25 [c]	raising sub stations, local barriers, pumps, relocate wire underground
Long Island Power Authority	NY	>0.5[b]	Reinforced foundations, Higher strength steel infrastructure, undergrounding new transmission lines, New flood resistant substation equipment
Jersey Central Power & Light	NY	>0.2 [a,i]	new substation building, new circuits, replacing underground cables
		Transport infrastructure	
Name of utility company	**State**	**Flood adaptation measures [$bn 2012]**	**Adaptation description**
MTA	NY	∼2 [g,k,l]	e.g. protect floodgates at tunnel entrances, vertical roll-down doors, vent closures, inflatable bladders, replace copper wires, upsized fixed pumps
NJ Transit Rail	NJ	0.35–0.8[f,h]	Flood control Hoboken, Secaucus Junction and Bay Head stations, seawall, protect electrical substations
PAUTH. NY-NJ/PATH	NJ-NY	>0.1	Steel gates in tunnels, Move control panels to higher elevation, new pumps, seawall[d,e,k]
Amtrak	NY-NJ	0.27[h]	design of a high-density signaling system, Rebuilding the Kearney, N.J., electrical substation
		Other	
Name of utility company	**State**	**Flood adaptation measures [$bn 2012]**	**Adaptation description**
Waste water treatment and drinking water		0.61–0.81 [j]	Flood protection, power backup systems (*no climate change addressed*)
Health center		N/A	Install secondary power supplies
TOTAL NYC/NJ			**$9.3 bn ($2.9 bn, NJ + $6.4 bn, NYC)**

[a]http://www.njspotlight.com/stories/13/01/10/rate-counsel-urges-utilities-to-take-cost-benefit-approach-to-grid-upgrades/
[b]http://www.wnyc.org/articles/wnyc-news/2012/dec/20/state-officials-mull-end-lipa/
[c]http://www.coned.com/documents/2013-rate-filings/$1-Billion-Storm-Investments.pdf
[d]http://hoboken.patch.com/articles/port-authority-estimates-sandy-damage-at-300m
[e]http://www.nj.com/hudson/index.ssf/2013/02/nj_transit_and_developer_lcor.html
[f]http://newyork.cbslocal.com/2013/03/13/nj-transit-approves-17-million-to-continue-post-sandy-repairs/
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[i]https://www.firstenergycorp.com/content/fecorp/newsroom/news_releases/jcp-l-to-invest--200-million-in-2013-to-enhance-customer-service.html
[j]http://mediamatters.org/blog/2013/01/04/fox-news-bogus-hunt-for-pork-in-sandy-bill-cont/192035
[k]http://www.nydailynews.com/new-york/mta-exploring-inflatable-expandable-devices-seal-tunnels-article-1.1208561
[l]http://www.cityandstateny.com/storm-proofing-the-mta/

Table 2.23. **Summary of costs for Strategy 1b Open Resilient City+ (all in $2012 values[a])**

	Elevation [$ bn]	Wet flood-Proofing [$ bn]	Dry flood Proofing [$ bn]
Cost applying building codes NYC	$2.9–$4.7 bn	$0.5–$2.0 bn	$1.3–$2.1 bn
Costs infrastructure measures NYC	$6.4 bn	$6.4 bn	$6.4 bn
Total Costs Strategy 1b, Resilient City + (NYC)	**$9.3–$11.1 bn**	**$6.9–$8.4 bn**	**$7.7–$8.5 bn**
Costs infrastructure measures NJ		*$3 bn*	*$3 bn*
Costs applying building codes NJ	*$$1 bn*	*$1 bn*	*$1 bn*
Grant Total NJ+NYC Strategy 1b, Resilient City +	***$11.3–13.1***	***$10.9–12.4 bn***	***$11.7–12.5 bn***

[a]All summary cost tables are in US$ 2012 values. Indexing was applied using the Construction Cost Index from ENR (Engineering News-Record, http://enr.construction.com/economics). The CCI annual escalation rate was set to 2.4%, on May 2nd 2013.

NYS and $7.4 bn for NJ, respectively, adding up to a total of $16.4 bn. Note, however, that these are very preliminary estimates, and probably some cost categories for adaptation are missing. For example, adaptation measures for parks and wetlands are not included. These rough estimates, therefore, only provide an indication of the potential size of the required budget for adaption, and we can assume the adaptation costs for protecting and resilience measures of infrastructure in the NYC-NJ Hudson area lies somewhere between $11.3 bn and $16.4 bn.

Power utilities. In response to the storm, Con Edison is exploring approximately $1 bn in storm protection measures that include (ConEd, 2013): reconfiguring network boundaries, separating flood and non-flood areas ($100 mln), relocating overhead lines underground ($200 mln), hardening electric and steam production facilities with new walls and flood barriers ($165 mln), and protecting 13 substations in low-lying areas against floods ($240 mln). These efforts are all expected to take 3 years of construction works. Additional flood protection costs for PSE&G, to protect substations located in coastal flood zones are estimated at $1–2 bn. On top of the hundreds of millions spent on Hurricane Sandy relief and repair efforts, JCP&L has announced plans to invest nearly $200 mln in 2013 to expand and strengthen its existing infrastructure. Planned projects include a new substation, building new circuits, replacing underground cables, inspecting and replacing utility poles, and ongoing vegetation management programs (Firstenergycorp, 2013).

Before Hurricane Sandy, LIPA launched a flood adaptation program of $500 mln over 20 years to prepare the utility network for (future) flooding (LIPA, 2012). The program aimed at minimizing damage caused by severe storms, and creating more resilience by minimizing outage times. Concrete proposed measures to reduce the electrical transmission and distribution system exposure to flooding include: equipment repositioning to mitigate flooding issues, reinforcing foundations to support critical equipment, and undergrounding new transmission lines.

Transport. While repairing damaged tunnels, tracks signals, and stations, adaptation measures can be implemented to increase resilience. For example, flood adaptation plans in Hoboken are being considered, and the NJ government has proposed building a local seawall to prevent flooding and upgrading the Hoboken terminal with flood prevention measures. The MTA and Port Authority are considering gates to close tunnels in case of a storm or, alternatively, inflatable plugs (NYD, 2012) that can seal tunnels entrances in case of a flood event. Inflatable plugs cost about $0.4 bn each. The costs of steel gates cost about $45 mln per tunnel (NYD, 2012). Other measures include elevating subway entrances and ventilation grates, hardening electric equipment and signals, increasing pumping capacity, and installing local flood protection measures.

It is difficult to estimate the additional adaptation costs for the transport organization as the MTA. Some adaptation costs for the MTA will be mainstreamed in the clean up and restoration costs that are estimate at $5.1 bn (CaS, 2013). On the Federal scale, '. . . half of the \$10.9 bn of the federal budget of Sandy repairs, is earmarked for projects aimed at reducing future damage, hence beyond just repairing the systems.' (CaS, 2013). We, therefore, take a conservative estimate of 40% from the estimated MTA repair costs, labeled as the additional adaptation costs, for proofing MTA facilities for future flood risk, estimated at ~\$2 bn.

Other. For waste water and drinking water infrastructure, cost estimates for repair and cleaning waste and pollution, and for improving drinking water, are estimated at \$0.61–\$0.81 bn for the states of NY and NJ (MM, 2013). However, these estimates do not take into account the impact of future climate change. For the whole of the US, climate adaptation measures for drinking water and waste water facilities would cost between \$448 and \$944 bn up to 2050 (MM, 2013).

Summary costs of Strategy 1b Open Resilient City+

Table 2.23 summarizes the costs of Strategy 1b Open Resilient City+. The table adds the range of costs for building code measures for all buildings (existing or new) with costs for protecting infrastructure. The table shows the order of magnitude of the total costs for implementing building codes with the adaptation cost for upgrading infrastructure. The range of costs lies between \$10.9 and \$13.1 bn, dependent on the combination of measures.

These figures are without adaptation costs in the NJ Hoboken–Raritan river area. The total cost for adaptation in NJ is estimated by the State of NJ at \$7.4 bn (NJ, 2012). Note that these cost are not labeled 'adaptation' but 'mitigation and prevention costs'. Table 2.23 shows the total cost of adaptation measures for infrastructure only. For the Hoboken–Raritan area in NJ these costs are estimated at \$2.9 bn. Furthermore, we also need an estimate of the costs of implementing building codes in the NJ area. Using the USGS NLCD land cover dataset (USGS, 2001), we have compared the urban area flooded in NJ counties (Bergen, Hudson, Essex, Union, Middlesex, and Monmouth) with the urban area of NYC flooded by Hurricane Sandy. The total developed area flooded by Sandy in NYC boroughs and NJ counties was calculated (see Appendix K). The results show that in NJ around 128 km^2 of urban area was affected, compared to 96 km^2 in NYC. This indicates that in NJ roughly 1.33 times the amount of urban area is at risk compared to NYC. Assuming similar types of buildings in NJ and in NYC, this would mean that the costs of implementing building codes in NJ will be about 1.33 times the cost of implementing them in NYC. However, because there is much uncertainty around these numbers, we assume a conservative estimate of the adaptation costs for implementing enhanced building codes in NJ to be \$1 bn. Adding adaptation costs for infrastructure with the cost for building codes results in total adaptation costs for NJ of \$4 bn. This lies well within the range of the total estimated adaptation costs for the whole Sate of NJ of \$7.4 bn (NJ, 2012), whereas our estimate of \$4 bn only pertains to the area in NJ that would be protected by storm surge barriers.

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3. Cost estimates of flood protection and resilience measures

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Developing a flood management strategy that either aims at enhancing building codes (Strategy 1b, c, Resilient City) or relies on storm surge barriers (Strategies 2a,b, and c), is not sufficient; additional flood protection measured are needed to fully protect the NYC and NJ. There are numerous examples measures appropriate for protecting the NYC coastline, but these need to be tailored with designs that address numerous guidelines and boundary and permit requirements. Such detailed analyses are not feasible in the present research, and therefore we have categorized the main types of additional flood protection measures as those that can complement either the Resilient Open City Strategy to a new Hybrid Strategy 1c or the storm surge barrier strategies. We have broadly indicated where those measures could be implemented (See Appendix I). These flood protection categories are linked to two shoreline characteristics: (1) geomorphological characteristics of the coastline and (2) urban density and land-use type. The combination of morphology and land use types broadly characterizes the coastline in 10 different segment types, which can be linked to the flood protection measure that is required for each coastal segment. The coastal morphological types and land use types are listed in Appendix I.

As with the cost estimate of storm surge barriers, many factors determine the final maintenance and construction costs of additional flood protection measures, such as floodwalls, dams, and beach nourishment. Similarly, costs also depend on planning and engineering costs, material costs, labor costs, and costs for permits, management, and maintenance.

3.1 Floodwalls

The T-wall and the L-wall are pile-founded structures that consist of a reinforced concrete wall and a base with steel pile cut-off (Figure 3.1). Steel or concrete piles are placed towards the protected and flood sides and are the main components that support the concrete wall and base. The purpose of the steel sheet piling is to provide a seepage cut-off beneath the wall. T-walls are typically considered for a floodwall system in cases where there is a potential for barge or boat impact, or where there is a potential for foundation instability due to hydraulic loading (USACE, 2008).

Bos (2008) provides the costs of different types of concrete floodwalls for the New Orleans East polder. The costs were derived from historical construction costs (Table 3.1). Note that the construction costs of levees or floodwalls are differently priced than the construction costs of storm surge barriers. Levees are initially built for a shorter lifetime than barriers and need an upgrade every 10–30 years. A barrier has a lifetime of 100–150 years. An upgrade of the levees is applied, at the end of each decade, to keep pace with the rising sea (Wei-Shiuen and Mendelsohn, 2005). It is assumed that this method of dynamic adaptation is most profitable for NYC because the construction costs are spread over years.

3.2 Earth filled and armored dikes in high-density urban areas

A dike is defined as an earth-filled levee body with a seal of stone or asphalt. This design can cope with considerable wave overtopping without the risk of a levee breach. The flexible asphalt increases the costs of the levee system, but also reduces the risk of a breach during storm and overtopping conditions. Dijkman *et al.* (2007) selects a levee design with slopes of 1:6 at the surge side. Such a slope is cost-effective for wave energy dissipation. The inner slope chosen is at 1:4, which is a safe value considering overflow and soil mechanical stability (Hillen

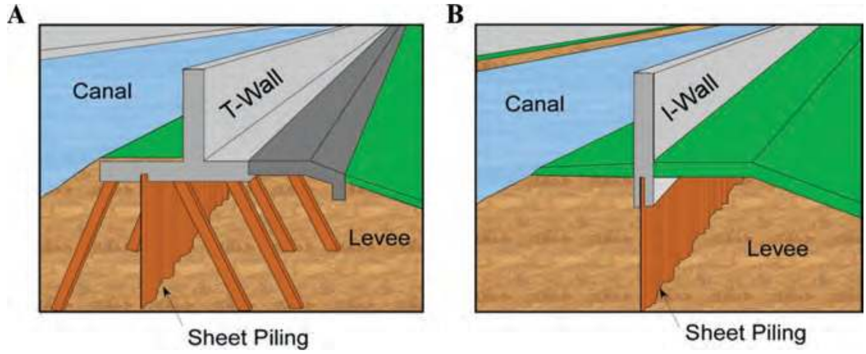

Figure 3.1. Two types of floodwalls applied in New Orleans (adapted from Nelson, 2010).

et al., 2010). Studies by Dijkman (2007), Hillen *et al.* (2010), and Jonkman *et al.* (2013) provide an overview of alternative levee costs for New Orleans and other locations. A reinforced dike is similar to an earthen dike, except that it is constructed of horizontal layers of earth wrapped with woven geotextile or steel sheet piles for added support. Reinforcement allows for steeper side slopes, allowing less fill and a smaller footprint. The reinforcement also provides for erosion resistance on the side slopes.

Dijkman (2007) determined unit cost prices for New Orleans levees to be €5 mln to €8 mln per kilometer for a meter (3 ft) dike heightening. Upgrading existing dikes is seen as construction costs because the costs are not yearly and the levees have to be reconstructed in a sense. Dijkman (2007) estimated the price for upgrading existing dikes at $27.1 mln/km. A complete new 30 ft hurricane levee in water for New Orleans cost between $40 and $85 mln/ km depending on the height of the levee (Dijkman, 2007).

Annual dike maintenance costs per linear kilometer of dikes are reported to range from $0.028 mln in Vietnam (Hillen 2008) and US$ 0.14 mln in the Netherlands (Hillen *et al.*, 2010). The variability in costs is largely because maintenance in the Netherlands is well organized and has high political priority. This is not the case in many other countries where maintenance programs are less rigorous. To a lesser extent, local factors such as labor and material costs influence the maintenance costs.

3.3 Retrofitting bulkheads in high-density urban areas

In many locations, the NYC shoreline is fortified with wooden bulkheads, essentially retaining walls

Table 3.1. Costs for T-walls and L-walls (adapted from Bos, 2008)

Type of floodwall	$/Ft	€/m	M€/km	height (m)	costs in M€/km per m heightening
7-Foot High L-Wall with 6-Foot Wide Monoliths	3200	7874	7.87	2.13	3.7
8-Foot High T-Wall with 8-Foot Wide Monoliths	3400	8366	8.37	2.44	3.43
10-Foot High T-Wall with 8-Foot Wide Monoliths	4100	10089	10 09	3.05	3.31
12-Foot High T-Wall with 11-Foot Wide Monoliths	5100	12549	12.55	3.66	3.43
14-Foot High L-Wall with 11-Foot Wide Monoliths	6300	15502	15.50	4.27	3.63
16-Foot High L-Wall with 11-Foot Wide Monoliths	7000	17224	17.22	4.88	3.53
18-Foot High L-Wall with 13-Foot Wide Monoliths	8300	20423	20.42	5.49	3.72
20-Foot High T-Wall with 14-Foot Wide Monoliths	9900	24360	24.36	6.1	3.99
22-Foot High T-Wall with 16-Foot Wide Monoliths	10800	26575	26.58	6.71	3.96
24-Foot High T-Wall with 17-Foot Wide Monoliths	12202	30020	30.02	7.32	4.1
26-Foot High L-Wall with 6-Foot Wide Monoliths	14600	35925	35.93	7.92	4.54
28-Foot High L-Wall with 6-Foot Wide Monoliths	15500	38140	38.14	8.53	4.47
30-Foot High L-Wall with 6-Foot Wide Monoliths	16800	41339	41.34	9.14	4.52

Figure 3.2. Example of vinyl bulkheads (adapted from Ecobuilders, 2012).

that are generally made of steel or wood, and stretch 10–20 ft below the water surface and at least 4 feet above. They were built to prevent soil erosion and flooding, and to maintain sufficient navigation width. Many of the bulkheads are more than 50 years old and bulkheads are often in poor condition. Many sections will require replacement because of age, oxidation, and damage through collision with ice and floating debris. The replaced bulkheads will often be higher than the old construction, and can be made of wood or vinyl (Figure 3.2) or concrete. Wooden bulkheads are usually the least expensive, and consist of pilings being driven for the supports.

In some areas, bulkheads are replaced by armored grades. An example is the shoreline stabilization project at Floyd Bennett Field. This shore had an old bulkhead located in Jamaica Bay, Brooklyn, and the goal of the project was to prevent future erosion of the coastline by installing a new stone embankment. The existing steel sheet pile bulkhead was removed and replaced by a grading of the bank slope. After the removal and grading, stone protection was developed on the graded bank (Figure 3.3). The costs of this project were estimated at >$400,000 (2010 values) (DEC, 1997).

We apply a unit cost range between $10 and $41 mln/km, depending on whether the retrofitted bulkhead is developed in low- or high-density urban areas. The maximum number is derived from the unit cost price of L-shaped floodwalls of 30 ft. because bulkheads are often located in high-density urban areas with high-value property, and retrofitting is a combination of fill and developing a floodwall.

3.4 Mixed highway and floodwall in high-density urban areas

This measure partly elevates existing roads along the coastline to create a road on top of a levee. This measure may disturb a large ground area because the road prism could extend considerably to either side of the existing road embankment (Figure 3.4). As with the earthen dike, the water side of the embankment would need to incorporate armoring measures to address potential erosion and scour. Additionally, the design would need to incorporate measures, such as a precast-concrete open-bottom culverts, to convey storm water and allow pedestrian and wildlife passage.

Another option is to elevate the road on stilts, without a fill, and create space underneath the road, for example, for car parking and storage; the water side of the elevated roads needs to be closed with a floodwall. An example for such an option is the FDR drive in Manhattan (Figure 3.5), for which several plans have been developed, such as the East River Blue Way plan (www.eastriverblueway.org). We apply a unit cost price of $70 and $80 mln/km, which is about twice the price of a high L shaped floodwall.

3.5 Mix of levees and landfill in medium to highly-urbanized areas

Coastal areas with medium to high density built up areas, mixed land use (varying from residential to commercial or industrial), and overall hardened straits or bulkheads comprise a common coastal type in NYC. For example, the East River side of Brooklyn, the South Bronx, and parts of western Staten Island are examples of such a coastal type. For developing coastal protection measures, detailed studies are needed to determine the most optimal solution. In some areas, old bulkheads will be replaced, or shorelines will be strengthened. Some areas have buildings on the shore, and a small floodwall is needed to prevent floodwaters entering the land. An example of a design where a small scale levee has been integrated in the water front is presented in Figure 3.6. Other areas are either more open or need simple landfill. Although this mixed class of flood protection encompasses a mix of measures, we here apply a relatively high unit cost price of $50 mln/km, which is much

Figure 3.3. New graded bank protected by stones replaced the old steel bulkhead at Floyd Bennett Field, Jamaica Bay, Brooklyn (source: Ap Construction, 2012).

higher than the unit cost price of upgrading a levee estimated by Dijkman (2007) of $27.1 mln/km. However, since this is medium-to-high urban density area land prices are higher, and there is a lack of space to develop levees and the possible retrofitting of existing buildings to incorporate the levee system.

3.6 Earth filled dikes in low-density urban areas

Low-density urban areas with relatively large areas of green space and wetlands can be protected with a combination of relatively cheap earth-filled levees (e.g. Nordenson *et al.*, 2010). As it is expected that flow velocities are low in these areas, a seal of stone or asphalt is not necessary to prevent erosion. The design has shallow grades to allow for the maximum environmental values. We apply a low unit cost price of $10 mln/km

3.7 Beach nourishment

Ocean currents move sand from Montauk Point in the east toward NYC in the west, which overall causes coastal erosion. According to Leatherman and Allan (1985), most of the Long Island southern coasts have been eroding over the period 1834–1979, with some exceptions where groins or jetties have been installed. Coastal erosion also occurs in the northern part of the New Jersey shores, from Sandy Hook to Asbury Park. Historic mean erosion rates were about 2.6 ft/yr (0.8 m/yr) between 1836 and 1985 (Gornitz, 2000). Some research also suggests that a seawall and groin complex near Sea Bright (NJ) has increased erosion rates at Sandy Hook (Psuty

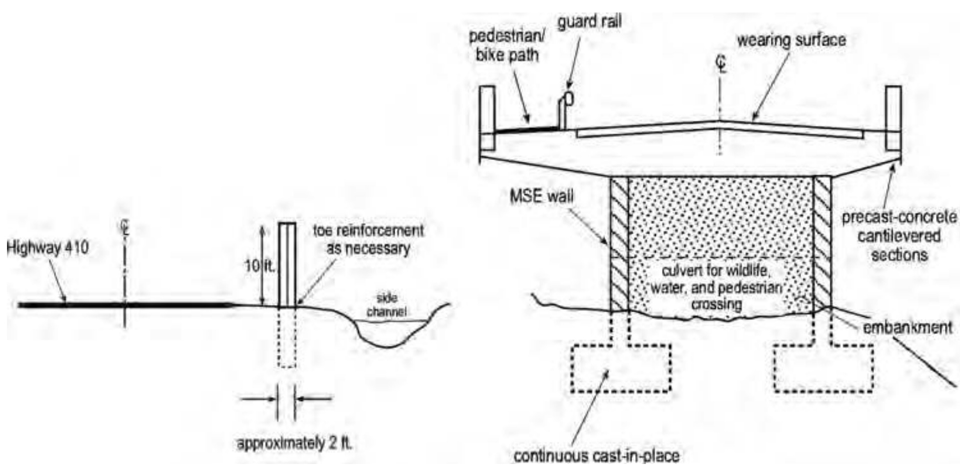

Figure 3.4. Highway with sheet pile floodwall (*Left*); elevated cantilevered highway (*Right*) (source: WSDT, 2012).

Figure 3.5. WXY proposes transformation of Manhattan's East River waterfront, with tidal pools and salt marshes creating a soft edge for the waterfront (source: WXY architects; www.eastriverblueway.org).

and Namikas, 1991). Most of the southern coasts of Long Island (Rockaways, Coney Island) and New Jersey consist of flood-exposed barrier islands.

For these areas, beach nourishment already is a frequently implemented measure to restore sandy parts in order to protect the city from floodwaters (Gornitz *et al*, 2002). Sand comes from offshore sand bars, usually within several kilometers of the beach, at depths of around 10–20 m below present mean sea level. The sand is closely matched with the original beach sand, in terms of mean grain size and overall size distribution. The U.S. Army Corps

Figure 3.6. A proposed pedestrian and bicycle bridge at 14th Street forms a security and flood barrier for a substation while connecting to the waterfront (source: WXY architects).

of Engineers uses a methodology to estimate the volumes of sand needed to nourish a beach. This volume depends on beach profiles, profile depth, and the length of the shoreline. Especially during the last 10–20 years, nourishment projects have increased because of increased availability of federal funds, and shifts in management from hard shoreline protection to nourishment. The lifetime of a beach nourishment project ranges between 25–50 years, with initial and periodic costs. About 81 mln m^3 (106 mln cy) of sand has been nourished on NY beaches in the period 1960–2007 (WC, 2012). Groins, jetties, or breakwaters can be co-developed with beach nourishment and have the goal to reduce wave impact.

Future beach nourishment is necessary to anticipate climate change and sea level rise. Gornitz (2000) reports that the erosion rates for NY beaches could increase 3 to 6 times by the 2050s, and 4 to 10 times by the 2080s, relative to the 2000s. To compensate for these losses, Gornitz (2000) calculates that an increase of 4.4–18.7%, and 5.4–25.6% of additional sand volumes would be needed by the 2050s and 2080s, respectively, to offset increased erosion. A possible challenge is the limited availability of sand to meet future demands.

The USACE (2006) reports on beach nourishment costs for Long Beach Island, with a length of 18,000 ft (5830 meters). The plan includes redeveloping a berm with a width of 33 m (~110 ft) at an elevation of 3.3 m (10 ft) with a dune crest of 5 m (15 ft) in elevation (all to NDVG). The total sand fill quantity is 2.17 mln m^3 (2.85 mln cy), including overfill and tolerance, and will add between 30–130 m (100–400 ft) of new beach to the existing beach at NDVG. Periodic nourishment, estimated at $0.41 mln m^3 ($0.54 mln cy) every 5 years (~ $3.5 mln) is planned in order to maintain the new beach profile. The total costs of the sand fill are estimated at $18.6 mln, excluding new groins, bulkheads, and sea walls. When including 12 new groins and reconditioning existing groins, the total costs may rise to $42.4 mln for the 5.8 km of coastline. These totals include contingencies of 15%. When taking the $18.6 mln as a lower estimate and the $42.4 mln as a higher estimate, the total initial coasts of this nourishment can be estimated at $3.2–7.3 mln/km, with a lifetime of 30 years and additional yearly costs of $0.6 mln/km. The volume cost of nourishment sand is $7–18/cy (USACE, 2006).

Valverde *et al.* (1999) studied the nourishment on the US East coast. In the period 1960–1996 $1.3 bn was spent on nourishment projects, funded by both federal and non-federal sources. For the future, Aerts *et al.* (2009) have roughly estimated the volumes of sand necessary for beach nourishment in NYC sandy coasts, for a sea level rise of ~20 cm and an accelerated sea level rise of 80 cm, with 4 and 17 mln m^3/yr of sand, respectively. At an average price of $8/$m^3$ ($10/cy) this would result in $3.2–13.6 bn over a period of 100 years. Leatherman (1989), however, concludes that the cost of beach nourishment for New York from a 50 to 200 cm rise in sea level by 2100 is estimated to be $0.7–2.6 bn, which is considerably lower.

Nourishment with hidden dike

In order to additionally protect nourished beaches, Athow (1976) suggests not only nourishing beaches in the Rockaways but backing this up by a floodwall in order to prevent erosion and withstand future hurricanes. Such a technique has been recently applied in the coastal city of Noordwijk in the Netherlands. The dunes at this location will be extended by adding new sand from the sea bottom until he beach reaches an elevation of +8.5–10 m (+25–30 ft) above MSL. However, a new dike will be placed inside this new system of dunes. Additionally, the beaches in front of the dunes will be nourished to raise the coastline, creating a smooth transition from the widened dunes to the existing beach (SEO, 2006). The 'dike in dune' project in Noordwijk (Figure 3.7) costs about €45 mln (2006 values) for dune widening and a 'hidden levee' within the dune with a length of 1.1 km (0.7 mile). The unit cost price is, hence, $45 mln/km, without periodic beach nourishment to maintain the beach and the dune profile.

3.8 Nature restoration and augmentation

Jamaica Bay remains one of the largest and most productive coastal ecosystems in the Northeastern United States, and includes the largest tidal wetland complex in the New York Metropolitan Area (Figure 3.8). The area is important for migrating birds and more than eighty fish species (USDI, 2007). Jamaica Bay's tidal marshes also provide flood

Figure 3.7. **Model of a dike within a dune and beach strengthening project in the beach resort Noordwijk in the Netherlands (*Top*) (Adapted from: http://www.kustvisie.nl/noordwijk.php). Photo of the dike within dune project in Noordwijk, just after completion (*Bottom*) (adapted from: http://www.hooijmans-noordwijk.nl/keuze/dijkaanzee.html).**

protection for nearby businesses and residences, and play an important role in buffering flood inundation volumes and in reducing wave impacts during extreme flood events.

It has been recognized that Jamaica Bay's tidal wetlands are rapidly disappearing, and that between 1924 and 1999 half of the Bay's vegetated marsh islands disappeared (USDI, 2007). From analyses

Figure 3.8. Area where wetland restoration measures can be implemented in combination with traditional levee and floodwalls: Jamaica Bay Unit of the Gateway National Recreation Area (source; http://www.digplanet.com/wiki/Jamaica_Bay_Wildlife_Refuge).

of satellite imagery, it appears that on the marsh islands tidal creeks are expanding and vegetated areas are transforming first into mud flats and then to sand flats as they disappear. The reason for this trend is probably a combination of a reduced inflow of sediment through the channeling of overland flow into sewers, and the hardening of the coastline that also reduces sediment flows in combination with increased nutrient flow from four major water treatment plants. Already, marsh island restoration is being seen as an important measure to balance out marsh island loss. Such measures are continuously needed in the future to preserve the natural values.

Wetland and salt marsh restoration can be effective for stabilizing existing wetlands because they serve as flood protection and shoreline erosion control for the Bay's surrounding homes and businesses. They dissipate wave energy, minimize storm surge, and provide flood-risk reduction benefits. The idea behind marshland stabilization is to stabilize the wetlands through preventing further degradation and, in addition, creating new wetlands. The measures include mechanical supply of sediment to the marshland islands for a longer time period. This sediment is used for plugging and filling the marshlands (restoration) or separating open water into compartments in order to reduce wind fetch and, thereby, limit the erosion process (stabilizing) (Figure 3.9). Small cranes and barges bring sediment into the area, e.g. from the foreshore. On top of the sand fill, the accumulation of plant detritus will naturally add another half an inch per year

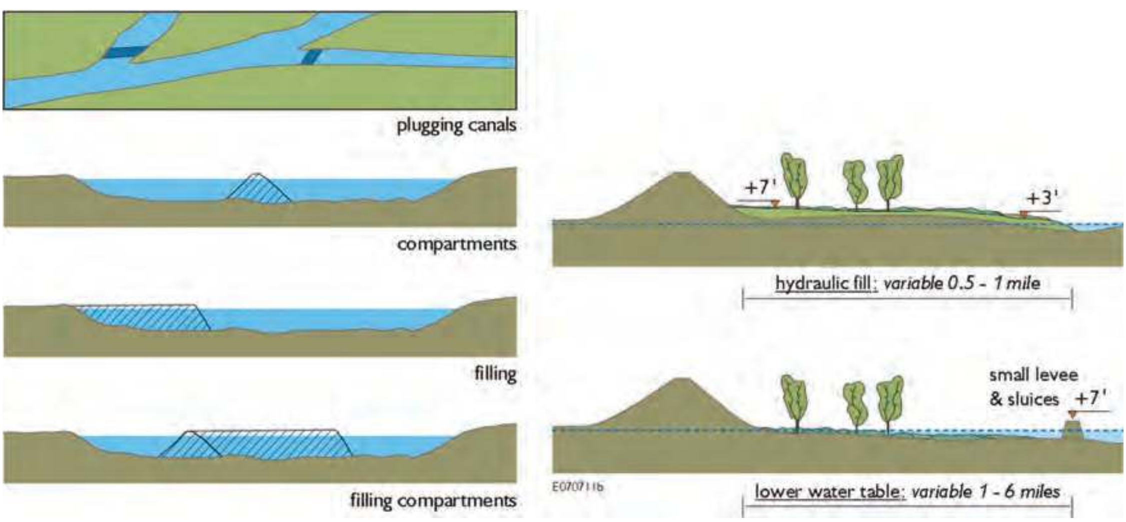

Figure 3.9. Overview of which fetch reduction measures and canal plugging for marshland stabilization (*left*). Fill and the development of small ridge or levees to reduce flood impacts (*right*). Adapted from Dijkman, 2007.

Table 3.2. Summary table with overview of costs for different flood protection measures (all in $ 2012 values)

	LEVEE			FILL		
	Total costs ($ mln/km)	Cost per meter heightening ($ mln/km)	Maintenance costs levee ($ mln /km)	Costs Fill ($/cy)	Costs ($mln/m^2)	Maintenance costs marshland ($ mln /m^2)
1 Flood T-wall (24 ft)	15–30[a]	4.5[a]	0.1[b]			
1 Flood L-wall (30 ft)	30–50[a]	4.7[a]	0.1[b]			
2 Dike	27[a]	8[a]	0.1[b]			
2 Hurricane dike	65[b]	9 [b]	0.1[b]			
3 (Retrofit-) bulkhead	41	8[a]	0.1[b]			
4 Mix highway & floodwall	70–80		0.2[b]			
5 Mixed levee	50	8[a]	0.2			
6 Flood protection low density	10	4[a]	0.05[b]			
7 Beach nourishment	7		0.1[d]	12		
7 Hidden levee + nourishment	30–45	8[a]	0.1			
8 Marshland stabilization					3.6[b]	0.07[b]
9 Land-fill				50[c]		

[a]Bos (2008).
[b]Dijkman (2007).
[c]Personal com. Perkins (Appendix H).
[d]USACE (2006).

(Dijkman, 2007). This work will be continued every year during the forthcoming decades in order to achieve a new natural equilibrium that will sustain itself despite sea level rise. In order to minimize the impact from waves and surges, surge reduction measures can be implemented, for example, at regular intervals (roughly every few miles) culverts are built in a traditional levee or ridge-levees to allow water, sediment and nutrient exchange (Figure 3.9).

Currently, the U.S. Army Corps is working in the Jamaica Bay area with the Port Authority of New York and New Jersey, the National Park Service (Gateway), the New York City Department of Environmental Protection, the New York State Department of Environmental Conservation, National Resources Conservation Service, and the New York/New Jersey Harbor Estuary Program. For example, to restore Yellow Bar Hassock marsh island, 375,000 cubic yards of dredged sand was pumped on the island to maintain the proper elevations of the marsh island. The sand was dredged from the Ambrose Channel (See Section 4.4), part of the Army Corps' New York/New Jersey Harbor Deepening Project. Usually, this sand is dumped into the ocean; but instead it is now used for marshland restoration.

Dijkman (2007) estimates that marshland stabilization and marshland creation for the New Orleans area costs between $1.9 and $3.6/m^2.

3.9 Landfill of parkland in high-density urban area

This measure refers to (partly) elevating parkland and other low density areas to create an elevated waterfront, but with a very shallow grade, so the views of the waterfront remain, as well as accessibility. An example of such an area is Battery Park, where these requirements are important. Landfill is expensive, because of the transport costs of bringing fill material into urban areas. Prices of alternative fill materials, other than sand, depend on market prices and availability. Price can go up to $50/cy.

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4. Storm Surge Barriers for NYC and NJ

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4.1 Introduction

Here, we provide an overview of the existing storm surge barrier designs that were presented at the 2009 conference 'Against the Deluge: Storm Surge Barriers to Protect New York City' (Hill *et al.*, 2013). Each of these designs is discussed using criteria for a conceptual barrier design by Dircke *et al.* (2011). Furthermore, we provide an overview of the construction and maintenance costs of existing barriers. Finally, an overview of required additional protection measures and their associated costs is presented.

In March 2009, the conference "Against the deluge: Storm Surge Barriers to Protect New York City" was organized in NYC. A key issue discussed during this conference was to explore the feasibility of developing storm surge barriers to protect the city from flooding in times of high water levels. Storm surge barriers or closure dams are engineering structures in rivers or estuaries to protect urbanized areas with high values of economic assets from flooding. Storm surge barriers can have movable gates to allow for shipping and tidal flows, which are closed during an extreme flooding event. Non-navigable barriers only allow for the inflow and outflow of water discharge. Closure dams are fixed structures that permanently close off a river mouth or estuary, and with such a structure water is discharged through, or pumped over, a closure dam. Since storm surge barriers are expensive, most existing storm surge barriers were implemented after a flood disaster occurred. After a flood event, risk perceptions are generally high (Botzen *et al.*, 2009) and policy makers can more easily justify large expenses for flood protection to the public. For example, the Thames Barrier in the UK and the Delta Works in the Netherlands were developed after the major flood in 1953. The most recent barriers were installed in New Orleans after Hurricane Katrina in 2005 (e.g. Dircke *et al.*, 2011; Hillen *et al.*, 2010).

Storm surge barriers have a number of advantages and disadvantages that are important to recognize. An advantage, for example, is that in the event of a permanent closure of estuaries through constructing a barrier the length of the coastline is reduced. Therefore, the required height of floodwalls behind the barrier can be reduced, which reduces the cost for the heightening or maintenance of the levees behind the barrier (Hillen *et al.*, 2010). Moreover, a barrier system can provide a comprehensive protection of all the buildings and infrastructure in the City, and prevent flood casualties. This is in contrast to Building Code measures which are often targeted only at certain specific structures (Aerts and Botzen, 2011). In addition, a multiple barriers system that closes different parts of an estuary or lagoon may be used to provide environmental benefits by increased capacity to flush the estuary area. This is achieved by independently opening and closing different barriers, depending on factors like tide and wind direction. By closing the barriers, the ability of the wind to drive water out of the lagoon is enhanced, which increases the turnover of water and disperses pollutants (Linham and Nicholls, 2010).

The main disadvantages of a barrier system are the huge construction and maintenance costs. In addition, movable barriers also require simultaneous investment in flood warning systems, which provides information on when to close the barrier (Linham and Nicholls, 2010). Furthermore, the morphology and environmental values of the estuary or river system can be affected in terms of interrupted water salinity, temperature, suspended matter, and nutrients (Munaretto *et al.*, 2012). The latter issue could play a role in designing a barrier system for the NYC Harbor area. However, the salinity regime of the harbor and sediment flow dynamics could be altered by installing the barriers, which is likely to impact fish and shellfish distribution (Swanson *et al.*, 2009). Another indirect effect on flood risk management is

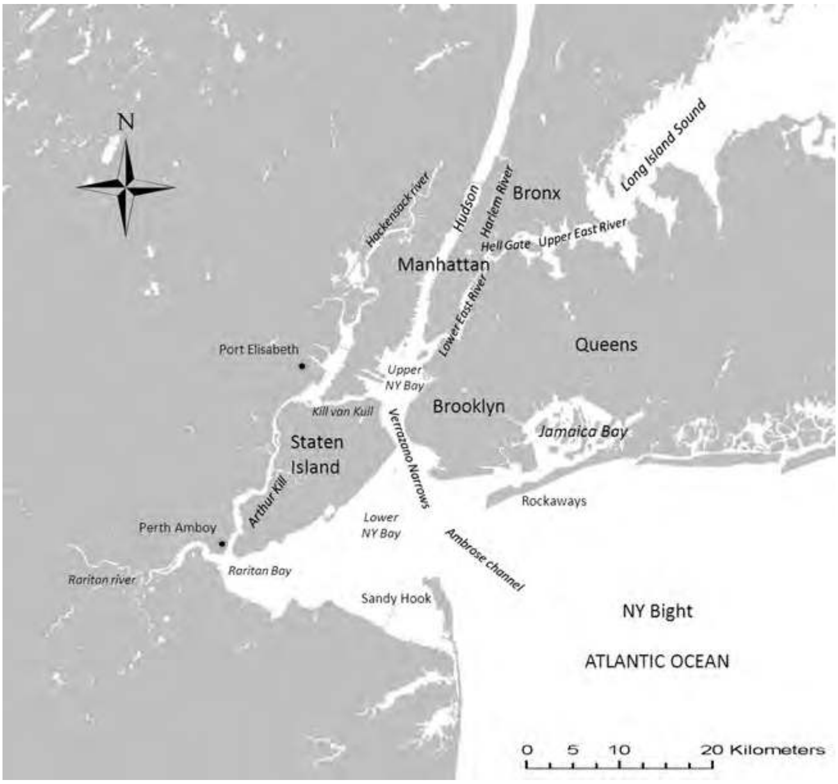

Figure 4.1. **New York City and surrounding waters.**

that flood risk perceptions and investment in damage prevention may decrease after barriers have been installed, which can cause a steady increase in the exposure to flooding behind the barriers system as a result of economic growth. This has been called "the levee effect" and implies that additional flood risk management and awareness strategies may be needed to prevent extensive flood damage if a barrier system fails during extreme flood conditions (Botzen *et al.*, 2012).

4.2 Geographical and hydrological characteristics

Hydrological considerations for barriers

Numerous descriptive and modeling studies have described the hydrology and hydrodynamic circulation of the Hudson Estuary, the NY Harbor area and the NY Bight (for an overview, see Blumberg *et al.*, 1999). The New York Harbor (Figure 4.1) is located at the mouth of the Hudson River, which discharges to the ocean via New York Bay and the Verrazano Narrows. This area is bounded by Brooklyn in the east and Staten Island in the west. The second connection of the Hudson River/New York Bay to the Atlantic Ocean is via the East River and Long Island Sound.

Long Island Sound (LIS) is an estuary of about 165 km with a mean depth of 20 m (Table 4.1). Its main opening to the Atlantic Ocean lies to the east, with a tidal transport of about 40,000 m^3/s (Bowman, 1977). The estuary has a serious water quality problem in the summer due to high-nutrient wastewater discharges into the upper East River (Bowman, 1977; NYC-DEP, 2008). The lower East River, from the Battery (Lower Manhattan) to Hell Gate, connects New York Harbor with the western LIS and is also shaped by tidal currents. The East River is about 12 km long and is narrower and deeper than the LIS estuary. The upper East River, which is about 13.5 km in length, is shallower and wider than the lower East River. It encompasses several bays and islands and has a shipping channel with an average depth of about 11 m below mean low water (MLW). In the northeast of Manhattan, the Harlem River connects the East River at Hell Gate to the Hudson River at Spuyten

Table 4.1. Overview of hydraulic conditions of important rivers, channels, and estuaries

	Freshwater inflow	Long Island Sound (between Whitestone and Throgs Neck Bridges)	Lower East River	Harlem River	Arthur Kill, Perth Amboy	Narrows	Rockaway inlet	Ambrose Channel
Mean depth in m and *(ft)*[b,e]		20/*(61)*	11/*(33)*		12/*(36)*	30/*(90)*		
Max. Depth of channel in m and *(ft)*[d,e]		∼34/*(109)*		7/*(20)*	16/*(48)*	33/*(102)*	7/*(20)*	17/*(53)*
Distance across channel in m		750–1500	850	∼180	500 – 750	1600–1800	1700	
Volume of tidal transport in m^3/s[a]		40,000	6,700	330		41,000		
Max. Tidal current in m^3/s[c,g]		1–2.6	1.5–1.8		1.1–1.3	1.1–2.4	2.2–3.0	1.4–2.6
Mean discharge of Hudson in m^3/s[g]	600							
Mean discharge of other fresh water sources in m^3/s[g]	114							

[a]Bowman (1977) Nutrient distributions and transport in Long Island Sound. *Est. Coastal Mar. Sci.* 5: 531–548.
[b]Jay, D.A. & M.J. Bowman (1975) *The physical oceanography and water quality of New York Harbor and western Long Island Sound.* Mar. Sci. Res. Center. Tech. Rep. #23. State University of New York, Stony Brook, NY. pp. 71.
[c]US Coast and Geodetic Survey (1956) *Tidal Current Charts, New York Harbor.* US Department of Commerce, Rockville, MD.
[d]Hugh S. Lacy1, Anthony DeVito, and Athena C. De Nivo (2009) Geotechnical Aspects of Three Storm Surge Barrier Sites to Protect New York City from Flooding. in *ASCE Proceedings of the 2009 Seminar Against the Deluge: Storm Surge Barriers to Protect New York City.*
[e]Ronan, A.D. (2009) Student Designs of Storm Surge barriers for the New York Metropolitan Area, in *ASCE Proceedings of the 2009 Seminar Against the Deluge: Storm Surge Barriers to Protect* New York City.
[f]Atlantic Boating Almanac (2004), Vol. 2: Cape Cod, MA to Sandy Hook, NJ.
[g]Blumberg *et al.* (1999).

Duyvil. The Harlem River is about 11 km in length. Other important waterways are the Kill Van Kull waterway (to the west of Staten Island), which becomes the Arthur Kill between Upper New York Bay and Raritan Bay. It is both a commercial and recreational waterway (Figure 4.1). In the outer New York Bay, the Ambrose Channel is the main shipping channel between Sandy Hook (NJ) and the Rockaways, Queens. The channel has a depth of about ∼20 m.

The highest freshwater inflow to the NY Bay area is provided by the Hudson River. The river has a length of 507 km that originates at Lake Tear of the Clouds in the Adirondack Mountains and drains a watershed of about 35,000 km^2. The long-term annual mean discharge is about 600 m^3/s, with a peak discharge in April (mean monthly flow ∼1,200 m^3/s). Minimum flows occur in August (discharge ∼190 m^3/s). The largest recorded monthly discharge was 1,900 m^3/s, measured in 1960. The Hudson River has an average depth of 10–15 m (Geyer and Chant, 2006) and is influenced by the ocean tide, which can propagate upstream about 300 km. Other fresh water sources are from water treatment plants and storm-water runoffs (e.g. Rosenzweig *et al.*, 2007). Blumberg *et al.* (1999) estimated a runoff of 114 m^3/s, from 110 effluents of wastewater treatment plants in their hydrodynamic modeling framework. Additional runoff can be produced by rainfall runoff.

Estuarine circulation and environmental issues

The current regime of the Hudson estuary is a partially mixed estuary, influenced by the tidal mixing of fresh and salt waters. Although the vertical gradient varies considerably during the neap and spring tides, there is always a horizontal salinity gradient (Geyer and Chant, 2006). Even during slow flow conditions, the horizontal gradient drives salt water to penetrate 70 km north of NY harbor (Geyer and Chant, 2006). Furthermore, the horizontal salt water gradient drives the estuarine circulation, which is characterized by a deep landward flow at the bottom (against the direction of the river flow) and a seaward flow of water at the surface (Bowman, 1977; Geyer and Chant, 2006). This gravitational circulation is an important issue to consider when designing storm surge barriers. As the circulation is essential to biological productivity (e.g. fish migration) and the flushing characteristics of the harbor, surge barriers should be designed so that their influence on the circulation is minimal (NYC-DEP, 2008). Blumberg *et al.* (1999) simulated the annual circulation pattern of the NY harbor area (Figure 4.2), with net flows defined as the difference between the surface layer flow (Q_u) and the lower layer flow (Q_l). Figure 4.2 shows a general flow from the Hudson in the NY Bay area, as well as a net flow from Long Island Sound into the NY Bay area. The net flow continues through the Narrows into the NY Bight (Blumberg *et al.*, 1999). Once outside the Sandy Hook–Rockaways transect (Figure 4.1), the estuarine flow forms a coastal current that flows south along the New Jersey Coast (Blumberg *et al.*, 1999). In addition, it is important to note the 3-hour difference in Long Island Sound low/high tides and New York Harbor low/high tides. This time difference leads to large hydraulic gradients and, hence, the large currents of $> \sim 2$ m^3/s in the East River and over 3 m^3/s at Hell Gate (Figure 4.1) at the junction of the East and Harlem Rivers (Table 4.1).

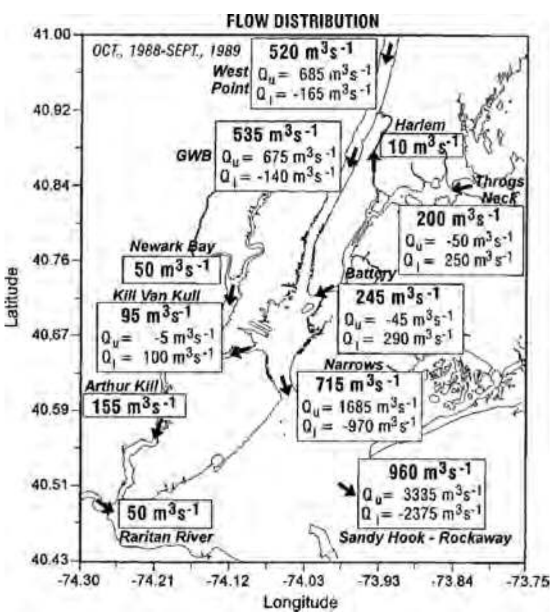

Figure 4.2. **Annual circulation pattern in New York Harbor in 1988–1989 (Adapted from Blumberg *et al.*, 1999).**

The harbor receives a significant sediment load from the Hudson River with an average of 1 mln t/yr (Hydroqual, 2007). Siltation problems occur in the lower Hudson estuary where the river widens as it empties into New York Harbor and Lower New York Bay. Furthermore, on the southern coast of Long Island, a westward migration of sand and a northward migration along the New Jersey coast contribute further sedimentation problems to the NY Bay area, which requires periodic dredging to maintain the depth of navigation channels. In relation to this issue, there are problems with the disposal of dredged material containing pollutants. Tidal currents drive sediment transport, which could be changed by installing storm surge barriers, especially if sills are placed in deep channels, serving as foundations for moveable barrier gates (Bowman, 2009).

It is important to note that the proposed storm surge barriers and their foundations must be designed to withstand the water pressure load reversals in circulation, which will occur when a large storm leaves the region. The barriers must also be designed to accommodate tide levels, which were formerly high at storm surge but will reverse and become extremely low. Also, design water levels must consider the water impounded upstream due to the Hudson River flow.

Geological considerations for barrier design

The selection of the specific foundation types for storm surge barriers will depend on the soil conditions and allowable bearing pressures of geological formations at the chosen locations. In addition, the design loads from the tide gate structure, including overturning moments, tensions, and mass stability, will influence the final design of a barrier. Other design aspects to consider are under-seepage, seismic loading and liquefaction, environmental considerations, vessel impact, and ice developing in the river during the winter months.

Deep foundations are most likely the best option to support the tide gates because such foundations are applicable in deep water and to the weak soil conditions at locations where storm surge barriers have been proposed (Lacy *et al.*, 2009). Such foundations can consist of piles, caissons, large prismatic, or cylindrical caisson walls sunk with internal dredge. In addition, anchor pilings or underwater slope stones are needed to stabilize the concrete sills or bases. Stone-faced embankments that are founded on competent material may be suitable for on-shore portions and limited shallow water sections if a permanent constriction of river flow is permitted.

Figure 4.3. **Location of calculation nodes of Moore *et al.* (1981) inside and outside Jamaica Bay.**

4.3 Design water levels for barriers and levees

Storm surge protection measures, such as surge barriers and levees, are needed to attain a certain protection level for NYC. This section describes the estimated required height of the barriers and levees system needed to withstand waterlevels that are associated with the conditions of a future hurricane 3, thus, including climate change and sea level rise (e.g. Lin *et al.*, 2012). In order to determine the required height of the flood protection measures, we first need to determine the design water level. The design water level is composed of different components, which together determine the necessary height of the protection system: storm surge level + sea level rise + wave overtopping + barrier effect + river discharge.

Waterlevels outside the barrier system

Storm surge water levels. There are several studies that have estimated surge levels for a future 1/100 hurricane for NYC above mean sea level conditions (e.g. Lin *et al.*, 2010; Lin *et al*, 2012; Moore *et al.*, 1981). Simulations with the ADCIRC model by Lin *et al.* (2012) show that the 1/1,000 (exceedance probability $P = 0.001$), 1/500 ($P = 0.002$), 1/100 ($P = 0.01$), and 1/50 ($P = 0.02$) storms at the Battery result in storm tide heights of, respectively, 3.48 m (11.4 ft), 3.12 m (10.2 ft), 2.03 m (6.7 ft), and 1.61 m (5.3 ft) This storm tide corresponds to the total water level above mean sea level, including the storm surge, and the astronomical tide. The effect of wave run/up and riverine flow is small in NYC, and thus not considered by Lin *et al.* (2012). Their estimates are somewhat lower compared with the often quoted figures reported first by Moore *et al.* (1981), who estimate water levels of 2.62 m and 3.26 m (compared with NAVD88) for 1/100 and 1/500 year events, respectively. The most extreme water level measured in the NYC area at the Battery was due to hybrid storm Sandy in October 2012, measuring 11.3 ft (3.4 m) above NAVD88 (mean sea level), considerable higher than the recorded previous highest water levels dating back to 1992 and 2011 (Hurricane Irene) with about 1.3 m.

For the Jamaica Bay area, design water levels have to be adjusted, since existing research shows that storm surge levels are lower than surge levels along the coastlines of the Rockaways or Coney Island (e.g. Moore *et al.*, 1981). Figure 4.3 shows several nodes from Moore *et al.* (1981) inside, and outside Jamaica Bay, and Table 4.2 shows the stillwater levels for these nodes for various return periods (relative to NGVD, an old datum). In general, surge elevations are about 0.45 m (1.5 ft) lower in Jamaica Bay (nodes with numbers >100) for a 1/10 storm and up to 1 m (~3 ft) lower for a 1/1000 storm. We, therefore, assume that the design heights for levees in the Jamaica Bay area, in a strategy that aims at a continued open access to the ocean through the

Table 4.2. Stillwater levels (ft NGVD) for the calculation nodes of Moore *et al.* (1981)

Nodes/ return time	10	50	100	200	500	1000
7	7.3	9	9.7	10.7	12.2	13.3
8	7.3	9	9.7	10.7	12.2	13.2
9	7.4	9	9.8	10.8	12.2	13.3
10	7.4	9.1	9.9	10.8	12.3	13.4
109	5.7	7.1	7.8	8.6	9.7	10.6
110	5.8	7.1	7.8	8.6	9.7	10.6
113	6.1	7.3	8.1	8.8	9.9	10.8
114	5.9	7.2	8	8.7	9.8	10.7
117	5.8	7.2	7.9	8.6	9.7	10.6
134	5.9	7.2	7.9	8.7	9.7	10.6
118	5.8	7.2	7.9	8.6	9.7	10.6

Rockaway inlet, can be about 0.7 m (∼2 ft) lower as compared with levees or dunes along the Rockaway coastline. The design level inside Jamaica Bay will be ∼6–7 m (∼18–22 ft).

Sea level rise

Climate change and sea level rise scenarios have been extensively described by the NPCC (2009). Climate change projections indicate that, by the end of the century, NYC may face an increase in baseline rainfall of 5–10% and a rise in sea level of at least 0.31–0.58 m (12–23 inches) (NPCC, 2010). The rise in sea level is very uncertain, and sea level rise may be considerably higher if ice caps, such as the Greenland Ice Sheet, melt more rapidly than current model studies project. For such a scenario, NPCC (2010) provides a 'rapid ice melt sea level scenario' of 1.0–1.4 m (41–55 inches).

Rising water levels through barrier closure. The additional surge water levels, outside the barrier system, caused by the closure of the barriers are confirmed by several studies. Kim *et al.* (2009) has studied the effects of a surge barrier by assuming a wind field for Hurricane Donna, which came ashore on Long Island as a Category 1 hurricane in 1960 (see Appendix E). They used the Estuarine hydrodynamic model called the Coastal and Ocean Model (ECOMSED), which is a three-dimensional, time-dependent, estuarine, and coastal circulation model that was originally developed by Blumberg and Mellor (1987). When using Strategy 2b (see paper 1), water-levels outside the barriers would rise by +0.2 m at Sandy Hook up to 0.14 m at Willets Points near the western end of Long Island Sound. Bowman *et al.* (2005) simulated rising water levels for Strategy 2a (see paper 1) assuming a synthetic storm that has 1.6 times the strength of Hurricane Floyd in 1999. Using the ADCIRC hydrodynamic model water levels rose by +0.3 m outside the closed East River barrier and only +0.04 m up to 0.08 m rise in water levels at the Narrows Barrier. The assumption of adding 0.3 m (+1 ft) of water due to the barrier closure seems to fall well within the range of simulated water levels.

Wave overtopping and leakage. During storm conditions, wave overtopping and leakage may cause some rise in water levels behind the flood protection system in the absence of a system failure. The additional elevation of storm surge barriers or levees may reduce the effects of wave overtopping. However, most existing studies on designing storm surge barriers and levee systems for NYC have neglected the effect of wave overtopping.

Tidal influence. Even though tidal ranges vary across the shores of NYC and tidal dynamics vary through time, we here assume that an average tidal range has a peak of +1 m (3 ft) above mean sea level.

Water-levels inside the flood protection system

The water levels on the inside (landward side) of the barrier system may also rise through rainfall and river runoff behind the closed barriers. Bowman *et al.* (2005) have examined the peak runoff for the New York City harbor during the passage of a

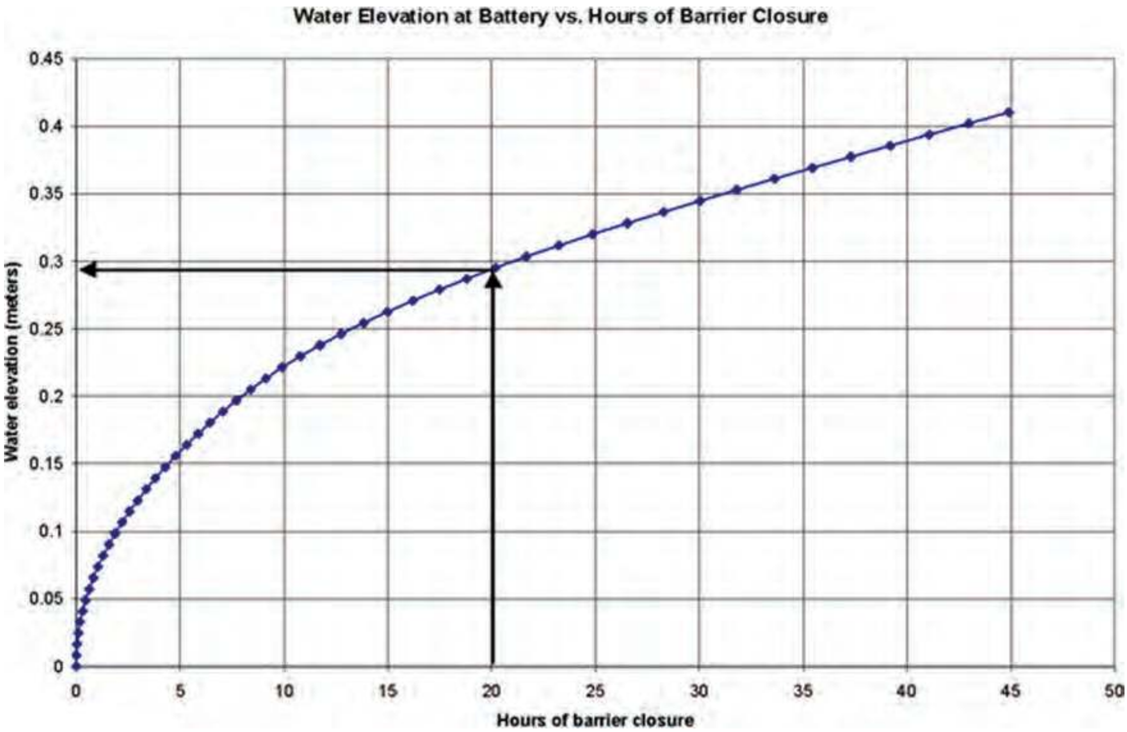

Figure 4.4. Rising water levels behind the closed barrier system at the Battery in relation to the hours of barrier closure (adapted from Bowman *et al.*, 2005).

synthetically simulated version of Hurricane Floyd, which passed through the area in 1999. A small runoff peak of 0.36 m (14 inches) high appears, and occurred a few hours after the peak surge levels had dropped. This small peak can be attributed to the effect of rainfall runoff from New Jersey rivers directly into the waterways. Hereafter, another small runoff peak of 0.14 m (6 inches) lasts for about 2½ days, and could be attributed to the runoff from the Hudson River. Bowman *et al.* (2005) applied different methods to calculate the effects from runoff behind the closed barrier system on water levels. When assuming a closure of 20 hours, and weather conditions that belonged to Hurricane Floyd, they estimate a rise in water level inside the barriers of about 0.3 m (12 inches). If the barriers were closed much longer, then water levels would not significantly rise, as Figure 4.4 shows (Bowman *et al.*, 2005).

Final design water levels

If all maximum values of the components that determine surge water levels during extreme storm conditions are added up, then we arrive at a required height for the protection system of at least 5–6 m (15–18 ft). However, most barrier designs prepared for the 2009 storm sure barrier conference have taken a higher design water level of 6.7 m (20 ft) as a basis, which was based on information by NYC-OEM (2009). In addition, almost all barrier designs have added another 2–3 ft of water level for sea level rise, and 1–2 ft was added to account for rising waters outside the barrier when it closes. Some designs added another 2–3 ft to accommodate wave overtopping (Table 4.1). This results in barrier designs with a total height between 7.5–10 m (25–30 ft), which seems to be a very robust elevation for a design protection level of 1/100.

We, therefore, assume that all other flood defenses that need to be installed in conjunction with the barriers systems also must have a design elevation of 7.5–10 m (25–30 ft). This is higher than the surge height simulations by Lin *et al.* (2012) and Horton *et al.* (2010). Nevertheless, this design elevation can be justified because it anticipates rising water levels due to sea level rise, effects of closed barriers, wave impacts, and spillover, which are all not included in the simulations by Lin *et al.* (2012) and Horton *et al.* (2010). Furthermore, the assumption of a design height of 7.5–10 m (25–30 ft), seems reasonable when reviewing older flood protection systems and barriers that have been built in the area. For example, the design water levels of the New Bedford Hurricane Barrier is ~8.6 m (20.5 ft) above mean sea level, and was determined by adding a 5.8 m (17.4 ft) surge to a coincident mean high water level of 1 m (3.1 ft).

4.4 Designs of storm surge barriers and additional measures

The description of storm surge barriers to protect NYC from flooding are based on the conceptual designs that were made for the conference 'Against the Deluge, Storm Surge Barriers to Protect NYC from Flooding' (Hill *et al.*, 2013). The designs were made by different engineering firms: Parsons Brinckerhoff, US; Camp Dresser & McKee, US; Halcrow, UK; and Arcadis, the Netherlands. The barrier located at the Rockaway Inlet, which has been proposed to protect JFK Airport, has not yet been designed by an engineering firm; only rough designs were made by freshman students from the Cooper Union (Ronan, 2009) and older designs are described by Athow (1976).

Table 4.3 shows the main design criteria that have been outlined by Dircke *et al.* (2011). Based on these criteria, the next section briefly summarizes the characteristics and considerations for each barrier design. The most important function of storm surge barriers is retaining high water levels in times of storm. Furthermore they allow access for shipping and to some degree, for the discharge of water and/or ice. In addition, environmental, ecological and social impacts can play a role and should be addressed in a barrier design. The design criteria are listed in Table 4.3. Section 3 provides a global overview of additional protection measures for NYC coastlines that are not protected by each of the two barrier strategies. These measures include, for example, levees, bulkheads and beach nourishment. These measures need to be developed such that they achieve a protection standard that is equal to the protection standard of the barriers.

Arthur Kill storm surge barrier

Figure 4.5 shows the conceptual design of the Arthur Kill barrier, made by Camp Dresser & McKee (Murphy and Schoettle, 2009). The Arthur Kill barrier has a span of approximately 500 m (0.31 mile), and contains two navigational locks and multiple flow control gates.

Hydraulic boundary conditions & safety. Arthur Kill is a commercial and recreational waterway influenced by the tide that runs between Upper New York Bay and Raritan Bay. Murphy and Schoettle (2009) based their design on hydraulic loadings of a Category 3 hurricane, with an associated surge height of 4.39 m (14.4 ft). Several other factors that were used to determine the required height of the barrier: splash of the overtopping of waves of +2.43 m (+8.0 ft) and localized tidal elevation of 1.68 m (+5.5 ft). This results in a minimum elevation of the barrier of approximately 8.53 m (28 ft) (Murphy and Schoettle, 2009). Swinging tidal gates are incorporated in the barrier to allow for the passage of the tidal flow. In terms of safety and reliability, there is a potential for an electrical power failure during the event of a hurricane. To ensure continued operation of the barrier during such a failure, equipment will be available to provide emergency power. The design will have to meet the requirements to withstand a magnitude 5 earthquake that occurs once in every 100 years.

Navigation

The channel has moderate to heavy commercial and recreational marine travel, and is classified as a "navigable waterway" by the United States Coast Guard (USCG). For this reason, the design is such that it incorporates a dual lock structure. This enables transportation for vessels through the barrier even if the barrier is closed (Murphy and Schoettle 2009). The locks are designed such that they enable to pass an S-Class Container Ship, the largest ship with approximate dimensions of 335 m (1,100 ft) in length, a beam width of 42.6 m (140 ft), and a depth of 10.7m (35 ft). A smaller parallel lock can be used by other vessels.

Siting

The location for the Arthur Kill barrier was chosen south of the Outerbridge Crossing (Appendix 1). At this site, grades of the coastline rise rapidly near

Table 4.3. Description of the main design criteria for the four NYC storm surge barriers (Dircke *et al.*, 2011). 'N/A' means the criteria has not been addressed in the design

Main gate type		Arthur Kill Lock with gate	Verrazano Sliding rotating sector gates	Upper East River Flap gates	NY-NJ Outer Harbor Floating rotating sector gates
		Barriers			
Design Category	**Design criteria**				
Hydraulic boundary conditions & Safety	*Current surge water level (1/100)*	4.39 m (+14.4 ft)	6.4 m (+21 ft)	6.71 m (+22 ft)	
	Sea level rise scenario	N/A	0.9 m (+3 ft)	0.61 m (+2 ft)	
	Current and waves	2.42 m (+8 ft)			Gates in parked position must be largely unaffected by waves and flow.
	Tidal influence on elevation	High water: 1.68 m (+5.5 ft)	Normal tide: 0.9 m (+3 ft)		
	Effect of closing barrier	N/A	0.3 m (+1 ft)	0.61 m (+2 ft)	N/A
	Overtopping and leaking	Overtopping not permitted, additional height of barrier is partly based on overtopping	Overtopping and leaking permitted.	Overtopping has negligible effect on water level.	Overtopping and leaking permitted.
	Hydraulic head		7.6 m (+25 ft)	7.4 m (24 ft)	
	Total height	8.53 m (+28 ft)	8.53 m (+28 ft)	8.23 m (+27 ft)	10 m (+30 ft)
	Reverse flow/head conditions	N/A	Discharge of the Hudson-, Passaic and Hackensack Rivers.	N/A	Discharge of the Hudson-, Passaic Raritan- and Hackensack Rivers.
	Water depth > 10 m	Yes	Yes	Yes	Yes
	Span	500 m *(0.31 mile)*	1,820 m *(1.13 mile)*	1,360 m *(0.84 mile)*	9,540 m *(5.92 miles)*
	Reliability	Emergency power during power-failure	Structural reliability: 10^{-4}/yr	Proven technology	
	Ship colliding	N/A	Addressed for further study	Minimal impact: Flap gates lie at bottom	
	Wind sensitivity	N/A	N/A	Minimal impact: Flap gates lie at bottom	Gates must withstand high winds.
	Earthquake	Resist earthquake of a magnitude 5	N/A	N/A	
	Discharge of ice		Discharge of ice needs further investigation	Minimal: Flap gates lie at bottom	
	Closure time	Reliable as it is a proven technology	Closure reliability: 10^{-3}/yr	Reliable as it is a proven technology	Reliable as it is a proven technology similar to St Petersburg barrier
Navigation	*Clearance height*	Unlimited clearance	Unlimited clearance	Unlimited clearance	Unlimited clearance
	Clearance width	42.8 m *(160 ft)*	262 m *(860 feet)*	No limitations	Width: 200 m *(600 ft)*
	Tidal current	Current flow velocity due to tidal variation: 1.4 -2 knots	Sufficient wet cross section to reduce increasing flow velocities	No interuption	
Siting	*Geology*	Substructures in bedrock. Research needed to assess under-seapage.	Foundation in deep sand deposits. Measures reducing under-seapage needed.	Deep foundations necessary. Prevention of seapage.	
	Road/ railway	Pedestrian and bicycling linkage. Location near important transportation hubs.	Not a requirement due to nearby bridge	Not a requirement due to nearby bridges	Potentially facilitate an alternative transport route.
Environment	*Impact upon landscape*	Steep shore gradients at the sides	Little impact: parks at both sides of barrier	Additional levees needed	Great impact
	Sediment	Barrier will have impact on sediment flow	Provide sediment transport	Siltation of sill may cause maintenance problems	1 mln tonnes sediment each year. Onshore wave pattern produce continual drift of material. Both should be taken into account.
	Erosion	Sediment aggradation and degradation will be modified	N/A	No interruption of sediment flow	
	Water quality	Loss of flow will create a modification of the nutrient flux.	Sufficient wet cross section set at 50% of current wet cross section	Could improve through gate operation	Decline of tidal flow should be minimized and if necessary stimulated by active gate management.
	Fish passage	Research needed on barrier impact on federally- and state-listed fish and wildlife.	N/A	No interruption	Barrier openings should be adequate for the passage of organisms.
	Jurisdiction	Probably joint ownership by NJ and NY	N/A	N/A	

Continued

Table 4.3. *Continued*

		Barriers			
Main gate type		Arthur Kill Lock with gate	Verrazano Sliding rotating sector gates	Upper East River Flap gates	NY-NJ Outer Harbor Floating rotating sector gates
Other	*Corrosion/salt conditions*		N/A	Must be durable in marine environment. Replacement of gates and hydraulic cylinders every 30–40 years	Appropriate selection of materials to resist corrosion
	Safety/terrorism	N/A	N/A	N/A	N/A
	Maintenance	Favorable/proven technology (Dircke *et al*, 2011)	All three types of gates are relatively easy to maintain	Replacement of gates and hydraulic cylinders every 30–40 years	

the shores in both Tottenville and Perth Amboy, so additional levees are not necessary to prevent flooding on the sides. Furthermore, the selected location provides a broad area of protection behind the barrier. Locations more to the north of the channel would have less impact on marine traffic, but would have left a substantial area of Staten Island and New Jersey unprotected. Deep foundations will be

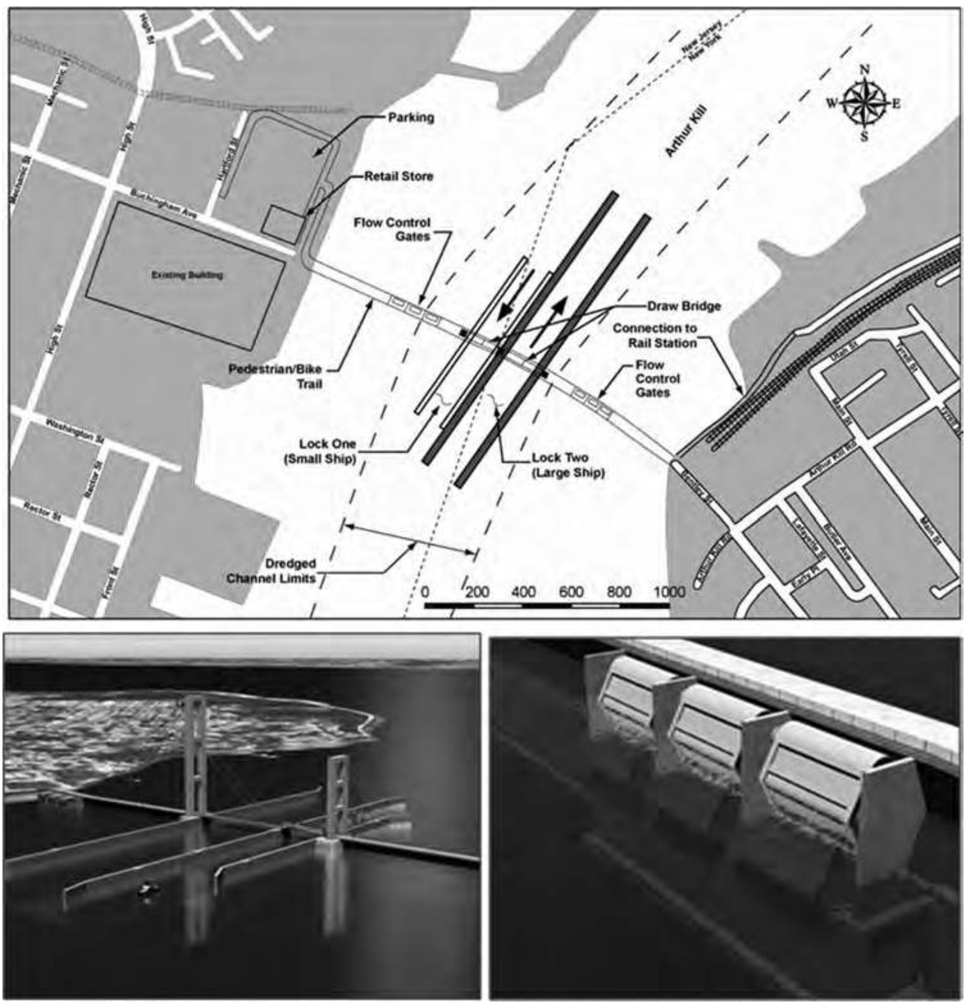

Figure 4.5. Location of the Arthur Kill barrier (*top*). Design of the Arthur Kill barrier with lock (*down-left*) and tidal gates (*down-right*) (source: Camp Dresser & McKee).

required at this location, requiring the bedrock or be supported by piles driven into the bedrock (Lacy *et al.*, 2009). A deep cutoff may be needed to prevent underseepage failure and to ensure sediment is not conveyed from below the structures.

Environment

The design addresses issues such as loss of flow, which could create modification of the nutrient flux, sediment flow and stagnation of water. This is the reason for installing tidal gates. Furthermore, the barrier location is known for the presence of federally and state-listed fish and wildlife. Although no disturbance of wildlife through the barrier is foreseen, further exploration on the subsurface in both Arthur Kill channel and on the shores is necessary. A cutoff wall is needed to ensure sediment is not conveyed from below the structures.

Social issues and legislation

The Arthur Kill barrier would require extensive environmental permitting, involving an environmental assessment under the National Environmental Policy Act (NEPA). Regulatory agencies that are likely to be involved would be the US Environmental Protection Agency, the New York City Department of Environmental Protection (NYCDEP), the New York State Department of Environmental Conservation (NYSDEC), New Jersey Department of Environmental Protection (NJDEP), the US Army Corps of Engineers (USACE), US Coast Guard, the Federal Emergency Management Agency (FEMA), and the US Fish and Wildlife Service.

Transport, infrastructure and other issues

The concept of the barrier includes a pedestrian and a bike lane. The enhanced mobility between Staten Island and New Jersey can increase commercial and recreational development. The nearby Tottenville Train Station provides access to Manhattan via the Staten Island Ferry. Maintenance should include testing the opening and closing of the gates and locks, sediment removal, debris removal, testing the emergency power supply, and testing of the navigational lighting. Narrowing of the Arthur Kill with a barrier will increase flow velocity caused by tidal variations. This is expected to exceed 2 knots (~4 m^3/s) and can then possibly be used for power generation (Murphy and Schoettle, 2009).

Figure 4.6. An artist's impression of the Verrazano Narrows barrier (source: ARCADIS, Jansen and Dircke, 2009).

Verrazano Narrows storm surge barrier

This conceptual design on the Verrazano Narrows storm surge barrier (Figure 4.6) was made by the engineering firm Arcadis (Jansen and Dircke, 2009). This design is a combination of sliding sector gates and lifting gates types, which have already been used in the Netherlands. The structure has a total span of approximately 1,820 m (6,000 ft).

Hydraulic boundary conditions and safety

The Verrazano Narrows is a tidal-influenced straight that separates Staten Island and Brooklyn. The Verrazano barrier is designed to withstand a surge generated by a category 3 hurricane, with a corresponding height of 6.4 m (+21 ft). To determine the required height of the barrier several other factors were taken into account: an additional elevation of 0.9 m (+3 ft) for normal tide, an expected sea level rise for the next 100 years of 0.9 m (+3 ft), and the effect of closing the Narrows of 0.3 m (+1 ft) additional rising water levels outside the barrier. Arcadis designed the barrier in a way that overtopping and leaking is reduced to a minimum, allowing a maximum water level behind the barrier of 2.13 m (7 ft) above mean water level. Janssen and Dircke (2009) made a simple calculation to estimate the volume of water storage behind the barrier by multiplying the surface of the NY Bay area (1.5×10^9 ft^2) by 7 ft of allowed rising water level. They estimate that 50% of this storage will be used by river discharge and other freshwater sources. The other 50% can be used to store leakage from the three barriers that close the Bay area. The hydraulic head is based on a water level difference of 7.6 m (25 ft).

Other functions that have been addressed in the conceptual design are the allowance of free discharge of river water and ice and the prevention of

Table 4.4. Specifications of the movable parts of the Verrazano Narrows barrier

	Depth	Width	Height
Sliding sector gates	19.8 m	262 m	Unlimited
2 lifting gates	12.2 m	50.3 m	29.5 m
16 lifting gates	12.2 m	39.6 m	13.7 m

the interruption of transported sediment as much as possible. These functions require an adequate wet cross section and flow opening. The wet cross-section is set at 14,399 m^2 (155,000 ft^2). Ship collision is a serious threat for barriers that are situated in heavily trafficked waterways: a solution for this problem has yet to be designed. Failure of the closure procedure deserves serious attention in the final design with a reliability of 10^{-3} per closure.

Navigation

The Narrows is a busy and important waterway, which forms the main connection for shipping between New York Bay and the Atlantic Ocean. The barrier was designed to allow for navigation by the world's largest container ship, The Emma Maesk, which needs a minimum depth of 20 m (66 ft), a minimum width of main gate opening of 262 m (860 ft) needed for safe passage, and an unlimited clearance height. A set of sliding sector gates is designed to provide passage for such ships. To facilitate passage for smaller ships two additional gates are provided. The specifications of the movable parts of the barrier can be seen in Table 4.4.

A general problem is the potential for a significant increase in the flow velocity in the proximity of the openings in the barrier. This is caused by the bottle-neck that the permanent barrier creates, despite its sluice gates (Lacy *et al.*, 2009). Any design should seek to maintain a maximum degree of openness, in order to limit the potential for an increase in current velocity. For this reason, Jansen and Dircke (2009) minimized increase flow velocities through the openings by providing sufficient wet cross-section. The danger of ship collisions should be further investigated, as the sector gates are sensitive to these collisions. If future research indicates that the collision risks are too high, then a floating sector gate or flap gates have to be selected instead of sliding sector gates.

Siting

Jansen and Dircke (2009) selected a location north of the Verrazano Bridge because of the availability of (non-urbanized) parkland at both shores and more favorable topography (steep shores), which minimized the need for land-based levees. In addition, Lacy *et al.* (2009) argue that the existing bridge piers and stone protection berms would provide a good start for the barrier system at this location. This location would also be an option according to Jansen and Dircke (2009), who propose two other alignments in this area, including one close to the Verrazano Bridge. The other alignments are half a mile to the north of the Verrazano Bridge (as in the current design) and close to a mile north of the Verrazano Bridge. The foundations for the barrier will be embedded in deep sand deposits overlying the hard Gardiners Clay formation (Figure 4.7). Deep cutoff sheeting or other means will be necessary to block under seepage below the barrier structure, and to avoid failure during extreme tidal surges (Lacy *et al.*, 2009).

Environment

A decrease in tidal flows because of the new storm surge barrier will most likely have an influence on the water quality in the bay. The precise consequences are difficult to predict, and additional research is needed. To provide sufficient tidal flow, the wet cross-section of the barrier design is set at 50% of the present wet cross section. This is accomplished by a large number of lifting gates that together with the sector gates provide a large wet cross-section. It is estimated that the tidal volume will be reduced by approximately 5%.

Transport, infrastructure, and other issues

A transportation route is not seen as necessary because the barrier is located half a mile North of the Verrazano Bridge. The maintenance of the movable parts of the barrier is very important to

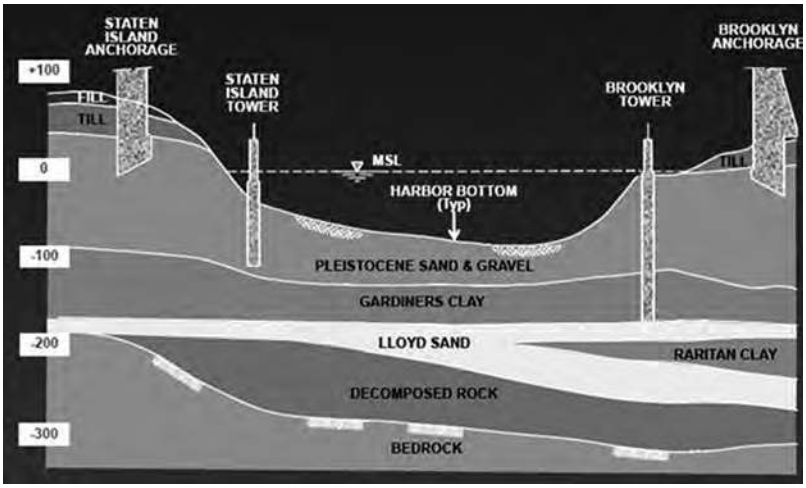

Figure 4.7. The Narrows Geological Section with the main pillars of the Verrazano-Narrows Bridge close to the proposed storm surge barrier location (adapted from Lacy *et al.*, 2009).

sustain a closure reliability of 10^{-3}. The selected gate types of the barrier are relatively easy to maintain. Additional studies are necessary to determine the precise requirements for the wet cross-section and shipping dimensions. Several other factors, like soil condition, current, waves during a hurricane and the maximum design water level in the NY harbor can influence the design of the barrier, and have to be further investigated.

East River storm surge barrier

The conceptual design of the East River storm surge barrier (Figure 4.8) was developed by Parsons Brinckerhoff (Abrahams, 2009). The design uses hydraulic operating flap gates and has a span of approximately 1,360 m (4541 ft).

Hydraulic boundary conditions and safety. The design of the barrier is based on a hurricane return period of 100 years. This corresponds to an expected sea level rise of 6.71 m (+22 ft). With an additional 2 ft for sea level rise caused by climate change and another 0.61 m (2 ft) for water pushed up against the barrier, the total height of the barrier is 8.23 m (27 ft). The wave height is not incorporated in this calculation and overtopping water during a storm is anticipated to have a negligible effect on the East River water level. Each flap gate has a width of 30 m (~90 ft), so, in total, 90 gates are

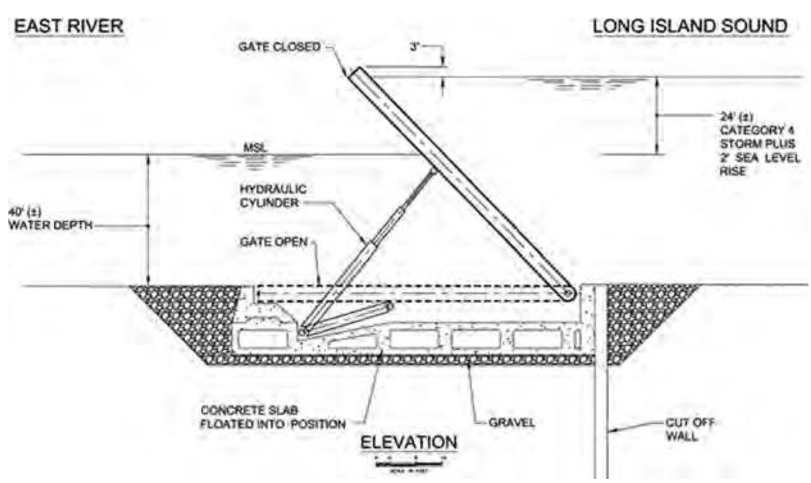

Figure 4.8. Design of the East River storm surge barrier (source: Parsons Brinckerhoff, Abrahams, 2009).

needed to span the Upper East River. Future studies may look at lower designed barriers that allow more overtopping, resulting in lower construction costs (Abrahams, 2009).

Navigation. The waterway is heavily trafficked by commercially (large) vessels and by recreational boats. The gates would be operated by hydraulic cylinders that would normally lie under water in their closed position, and, therefore, have a minimal impact on marine traffic navigation. The gate elements can be fabricated off-site and will be floated in place. In this way there would be minimal impact to marine navigation during construction works (Abrahams, 2009).

Siting. The East River is a 25.6 km (16 miles) long tidal estuary that extends from the southern tip of Manhattan Island to Throgs Neck to the North of Long Island. The main channel at the barrier location is about 10–12 m (~40 ft) deep at low water, and varies between 300–1400 m wide. The Upper East River bathymetry show a high variability of water depths and channel widths and the siting of the barrier is a tradeoff between, on the one hand, a narrow channel, but a less protected area, or, on the other hand, deeper water and a wider channel but a larger protected area. Further East from Throgs Neck, the channel is too wide, and a barrier would be too costly. Abrahams (2009), therefore, selects a location between the Whitestone and Throgs Neck Bridges (between Queens and the Bronx) as the preferred location for the barrier. This site is confirmed by alternative siting by Ronan (2009). The waterway close to both bridges is characterized by water depths between 21 and 24 m (70–80 ft), depths that would significantly complicate the design and construction of a barrier. However, between these two locations, the river widens and the water depths are more uniform and shallow, with maximum depths of approximately 12 m (40 ft), matching the minimum navigation channel depth (Abrahams, 2009). A barrier further south near Wards Island might be considered, but this would leave most of the East River unprotected, including LaGuardia Airport and Rikers Island (with the location of a jail with 15,000 inmates).

Appendix A shows the possible barrier location extending between Willets Point/Fort Totten and Throgs Point. Gradients rise rapidly near the shore at Willets Point/Fort Totten, while at Throgs Point, a land-based barrier would have to extend some distance inland before reaching higher ground. A cut off may be needed on land in the low-lying elevations area between Willets Point/Fort Totten and Bayside, Queens. Abrahams (2009) stressed that the selection of this site was based on a very conceptual level of analysis as a potential crossing site. Considerable further analysis is needed to address many additional requirements.

The geology varies across the Long Island Sound, and the barriers placed on the Queens side would likely need to have different foundations from the Bronx side. Near the Throgs Neck Bridge, the foundations will require support beneath the very deep soft organic clay deposit below most of the crossing. In areas where the sand and gravel deposit is at a shallow depth, a deep cutoff will be needed to prevent under-seepage failure during a storm event. Local ground improvements may be required, as well as a hydraulic cutoff to prevent piping failure (Lacy *et al.*, 2009).

Environment. One beneficial aspect of the barrier could be its function to increase water quality through flushing the water of NYC harbor. The East River is a tidal estuary that is characterized by having poor water quality due to the lack of flushing action, particularly in the summer. Bowman (1977) and Hill (1994) report that there is a potential benefit if the tide gates could be installed in the East River in order to only allow tidal flow southward from Long Island Sound to New York Harbor. This suggests that a tidal barrier on the East River would be used to flush the harbor system to increase water quality.

Transport, infrastructure and other issues. A transportation route is not regarded as an important side function of the barrier, because the barrier is located in between two bridges. In terms of maintenance, the perimeters of the gates can be sealed for maintenance, so it would be possible to de-water the area below the gates for maintenance. The hydraulic cylinders as well as the gates have to be replaced every 30–40 years (see also Van der Meer, 2006). A possible alternative are inflatable flap gates, as are being developed in Venice (Figure 4.9). This design is, however, also more costly. Although this proposed concept is based on current proven technology, the location and impacts of an East River Barrier will require significant additional study. Moreover,

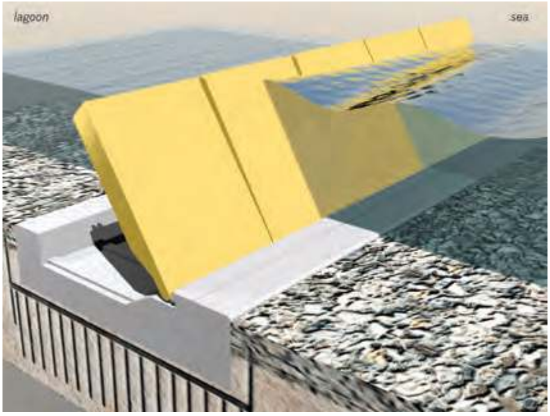

Figure 4.9. **Artist impression of the inflatable flap gates of the Venice-MOSE barrier (source: www.boxbarrier.com).**

Van der Meer (2006) states that the stability of hydraulic driven gates is greater than inflatable gates and, therefore, is more suitable to protect the city from larger differences in storm surge levels.

The Jamaica Bay storm surge barrier

Strategy 2b builds on Strategy 2a by developing a fourth barrier (Figure 4.10) at the entrance of Jamaica Bay to protect JFK Airport. A barrier at the Rockaway Inlet would have a span of about 1730 m (1.08 mile), and would be difficult to construct because the elevation of the nearby Rockaway beach (~3 m/10 ft) is lower than the elevation of a Category 3 Hurricane storm surge (8 m/26 ft)). Without additional floodwall protection, the barrier would do little to protect all of the communities around Jamaica Bay as well as John F. Kennedy International Airport (Ronan *et al.*, 2009). In addition, the southern shore of Brooklyn, including Coney Island, would not be protected by the proposed Rockaway Inlet and Verrazano barriers. Here also, additional floodwalls or shore protection enhancements are necessary to protect the same area as in Strategy 2a. Additional protection works are needed further East, for areas on Long Island, or Nassau.

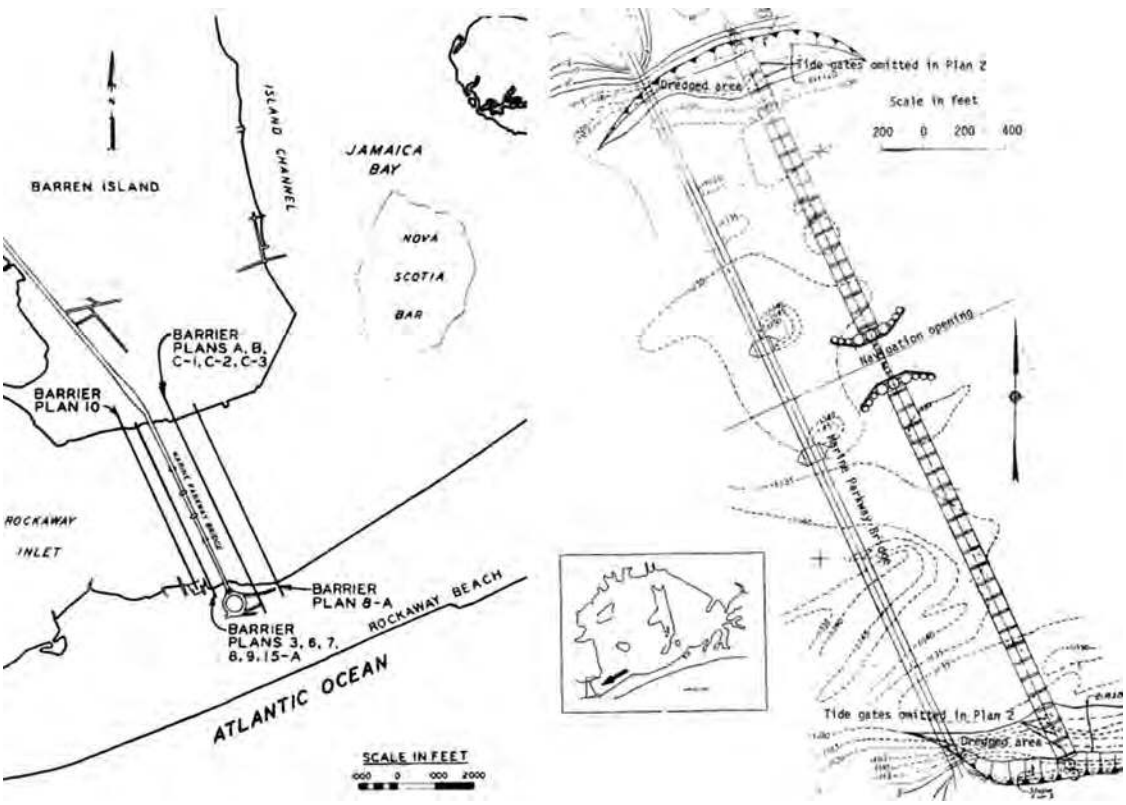

Figure 4.10. **Possible location for Jamaica Bay barrier designs (*left*) (adapted from Athow, 1976). A possible design for a Jamaica Bay barrier (*right*), with an ungated navigation channel and tide gates on the flanks of the channel (adapted from Leendertse and Liu, 1975).**

In 1968, The Army Corps of Engineers proposed an 18 ft high and 12 ft wide "hurricane barrier" across the Rockaway Inlet. The wall has a few gates that create a 600-foot opening for navigation. The cost of this design was roughly estimated at US$ 200 mln (2010 values) (PANYC, 1968). An extensive study by Athow (1976), using both physical and mathematical models, evaluated various barrier designs on their (a) effect on water levels inside Jamaica Bay, (b) flow velocities at the navigable gates, and (c) effects on waterquality in the Bay. Tests involved barrier designs with 35 and 40 gates, as well as an (ungated) navigable opening of 200–300 ft. Depending on the width of the ungated opening and the depth of the sill in the navigation channel, surge heights in the Bay were reduced by 2–3 ft, using the 1950 hurricane conditions as input for the simulations (see also Appendix G). The maximum surge height during that event was +8.4 ft above msl (Athow, 1976). Furthermore, some designs did change the tide phase characteristics of the Bay, and flow velocities in the Rockaway Inlet were increased. In addition, Leendertse and Liu (1975) reviewed the same barrier designs on their effect on water quality in the Bay area. They concluded that barriers would not have a significant impact on chloride concentrations or biochemical oxygen demand (BOD), although, the circulation is affected by the various barrier designs.

Very preliminary conceptual designs were discussed in Ronan (2009). Some ideas addressed the need for a barrier which minimizes the visual impact because of the low-lying surrounding landscape. For this, a fully-submerged barrier similar to the one being constructed in Venice would be an option, but such a design was considered too expensive. Other ideas for a design suggested installing an offshore energy dissipation device instead of a barrier (Ronan, 2009). Another idea is to develop a new bridge-barrier connecting the western end of the Rockaway peninsula to the Coney Island peninsula. The bridge-barrier consists of 78 piers, ranging in height from 16–45 m and spaced at 60 m intervals, that house 154 horizontal radial gates and support a four-lane roadway. The axes about which the gates pivot are embedded in the channel bed between each pair of piers (Ronan, 2009).

In addition to the barrier, a pivoting boardwalk could be designed along the entire length of the Rockaway Peninsula to protect the existing coastline. The boardwalk is approximately 19 km (12 miles) long and 10 m (36 ft) wide. In the event of storm surge, the boardwalk segments are 'pivoted to an angle of 60° from the horizontal and supported by a series of gears and support members stored in underground vaults along its length'. The protective boardwalk should be connected to the Verrazano Barrier (Ronan, 2009).

New-York New-Jersey Outer Harbor storm surge barrier

The conceptual design of the NY-NJ Outer Harbor barrier (Figure 4.11), was developed by the engineering company Halcrow (Padron and Forsyth, 2009). The barrier has a span of approximately 9.5 km (5.94 miles). The largest part of the barrier, approximately 7.5 km (4.69 miles), consists of a land-based berm. The remaining movable parts are two sets of floating radius sector gates, a lifting gate, and non navigational tidal sluices.

Hydraulic boundary conditions & Safety. The Outer Harbor barrier will protect the entire New York estuary, and will replace the three smaller gates in the Arthur Kill, Verrazano Narrows and Rockaway Inlet. The most important advantage of this design is that it protects a larger area of New York City against floods. The barrier is designed to withstand a Category 3 Hurricane with a surge defense height of 9 m (30 ft). With an average depth of 15 m (50 ft) below mean sea level, the overall height of the barrier is about 10 m (30 ft). The gates must withstand high winds and large waves. The design includes floating rotating sector gates to allow for shipping and easy maintenance. However, a disadvantage of the floating gates is that they are sensitive to dynamic wave forces and flow-induced oscillation (Padron and Forsyth, 2009).

Navigation. The New York Bight, between Sandy Hook and the Rockaway Peninsula, is the principal entrance to New York City Harbor, and is one of the busiest waterways in the US. Two channels pass through the Bight. The main channel, Ambrose Channel, is about 600 m (2,000 ft) wide and 15 m (50 ft) deep at mean low water. The second channel, called the Sandy Hook Channel, is less deep, with a depth of about 10 m (33 ft) and being used by smaller boats. The design consists of two sets of floating radius sector gates, which

Figure 4.11. **Causeway over sluice and barrier system (*Top*); navigable floating sector gates at the Ambrose channel (*bottom*) (source: CH2 m).**

allows for a large gate span and no clearance height limitations, which can close of the Ambrose Channel. The width of each of those main gates is 182 m (600 ft). The vertical lifting gates that close off the Sandy Hook channel have the disadvantage that they have a limited clearance height for shipping. Considering the importance of New York Harbor, it is critical that during construction and operation the barrier does not interfere with vessel traffic.

Siting. To span from Sandy Hook to Rockaway without the use of embankments seems almost infeasible. There are several options to connect the navigable parts of storm surge barriers. When considering currents and wave climate in the New York Outer Harbor, only an armor rock or concrete armor

Figure 4.12. **Plan showing the extent of the causeway and berms forming the gateway barrier (adapted from Padron and Forsyth, 2009).**

units are feasible options to connect the moveable parts of the barrier. Comparing these two alternatives, this design uses armor rock to reduce costs. It is assumed that construction material would be brought into the New York area via sea, either by barge or ship (Padron and Forsyth, 2009). Considering the significant length of land areas either side of the proposed barrier, then levees, berms, or the raising of existing highways would be required to increase the land elevation sufficiently high to avoid flooding at the rear ends of the barrier. However, the barrier system is not intended to fully prevent flooding across its flanks in the event of a severe surge event.

Environment. The construction of a new barrier will have a significant effect on tidal flows and affect current patterns. Water quality may be affected and siltation patterns may change. Recreational usage may be impacted to some extent. To alleviate these effects, studies would be required to determine the wet cross-section of the barrier. Decline of tidal flow should be minimized, and can be positively stimulated by active gate management. Sluices in sets of 10, each about 24.3 m (80 ft) wide, are incorporated in the barrier design to provide the required capacity. An influence on the hydrodynamics of the harbor is the Hudson River, which does not only supply river water, but also around 1 million tons of sediment each year. In addition, coastal sand transport produces a continual littoral drift of material from Montauk Point to Rockaway (east to west). Therefore, additional research is needed to determine the feasibility of the barrier to increase the flushing capacity of the barrier. For example, partial closing of the barrier could force currents to flush parts of NY Bay. In addition, new inlets through the sand bars of the Rockaways and Sandy Hook could operate in concert with the operation of sluices to enhance flushing capacity.

Transport/ infrastructure and other. A combination of a road along the causeway and partly through tunnels will be constructed. This would provide access for personnel and maintenance. This road would also act as an additional river crossing for citizens of New York. The sector gates are stored in dry docks, allowing all maintenance to be carried out in dry conditions. The lifting gate has the advantage that when lifted out of the water, the gate is easily accessible for maintenance. An option would be to develop a tunnel all the way under the barrier system that would be covered by a dike. This would save construction material for the dike.

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5. Cost estimates of Storm Surge barriers for NYC and NJ

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5.1 Construction cost of existing storm surge barriers

The costs of storm surge barriers can broadly be divided into three main categories. The first category is the one-time construction costs of the barriers. The second category is the periodic costs of maintenance and operation. The third category is the costs of additional protection measures, such as levees or beach nourishment. Here we discuss each of the main cost categories using data from existing storm surge barriers and protection works.

There are many factors that influence the construction costs of storm surge barriers, and each location has its own functional requirements that determine the final design of a barrier, and hence the cost. Hillen *et al.* (2010), Jonkman *et al.* (2013) and Dircke *et al.* (2011) state that the construction costs of a storm surge barrier are largely determined by its share of the movable parts of the design: more gates or a shipping lock can sharply increase the costs. Furthermore, geographical and hydrodynamic requirements, such as 'span' or 'hydraulic head', determine, respectively, the size and the required strength of the design, and may also increase costs (Hillen *et al.*, 2010).

Table 5.1 shows an overview of existing storm surge barriers around the globe with their specific construction and maintenance costs. Table 5.1 shows that barriers with a large span or a higher number of movable parts are indeed the most expensive barriers, ranging from about \$80 mln for a small barrier in Stamford, USA, to \$6.9 bn for the large St. Petersburg barrier in Russia. Using the information from Table 5.1, the cost per unit meter width has been estimated at between \$0.04 and \$2.37 mln/m. The range is dependent on span and gate types. For example, floating rotating sector gates, such as those which have been used for the Maeslantkering in Rotterdam (the Netherlands) or the St Petersburg barrier (Russia), are more expensive than vertical lifting gates. This range is a bit wider compared with the results by Jonkman *et al.* (2013) and Hillen *et al.* (2010), who estimated a unit construction cost range of between \$0.5 and \$2.7 mln/m. However, they did not include the smaller barriers in the U.S, which are apparently relatively cheap per unit meter.

Furthermore, note that some cost figures include additional floodwalls that are much cheaper per unit width as compared with the unit meter cost of the movable parts of the barriers. For example, the total length of the St. Petersburg barrier is 25.4 km with a total cost of the project of around \$6.9 bn. However, only 1700 m of the total barrier project consist of movable parts, such as gates and sluices. For barriers where the span of the movable parts is smaller than the total span, we subtract the cost for the dam from the total costs. For the older US hurricane barriers we can extract the cost for the dam by looking at the difference between the Fox Point hurricane barrier and the New Bedford storm surge barrier. Both have a span of the movable parts of 50 m. The total construction costs are \$87.6 and \$110.9 mln, respectively. The difference is ∼\$23 mln, which can be attributed to the length of the New Bedford storm surge barrier, which has a 2.3 km longer dam as compared with the Fox point barrier. The unit cost price for this dam is thus \$23/2.3km = \$10 mln/km. For the newer barriers (constructed after 1990), we use the cost prices by Dijkman (2007) and Bos (2008) of \$85 mln/km for a Hurricane Dike. For the IHNC barrier, we use the unit cost price from Bos (2008) for a 30 ft wall of \$50 mln/km.

If we examine the distribution of the construction cost of the IHNC barrier developed in New Orleans (Arcadis, 2006; Figure 5.1), it appears that 68% of the total construction costs have been allocated to constructing the lock with gates. This estimate

Table 5.1. Overview of existing storm surge barriers and their characteristics and costs (costs in US$, 2012 price levels)

Name barrier	Gate type	Country	Constr. Years	# Nav. sector gates	# Non nav. (tidal-) gates	# Lock	Span movable parts (m)	Total width (m)	Gate height (m)	Head (m)	Closure time (min)	Construction costs ($mln)	Costs ($ mln/m)	Movable parts parts ($ mln/m) [1]	O&M costs ($ mln/yr)
Hollandse Ijssel Barrier[5,12,14,23]	Vertical lifting	NL	1954–1958	2		1	110	110	11.5	3.5	30	127	1.15	1.15	2
Fox Point hurricane barrier[15,16,21]	Vertical rotating	USA	1961–1966	3	2		50	300	12	6	30	87.6	0.29	1.7	0.5
New Bedford storm surge barrier[15,21]	Horizontally. moving sector	USA	1961–1966	2			50	2774	18	6	12	110.9	0.04	1.66	N/A
Stamford Hurricane barrier[15,21]	Flap	USA	1965–1969	1			30	866	10.5	5	20	81.7	0.09	2.43	N/A
Thames barrier[7,9,21]	Rotating sector	UK	1974–1982	6	4		530	530	17	7.2	60	1883	3.55	3.55	13
Eastern Scheldt barrier[5,7,10,12,21]	Vertical lifting	NL	1974–1986		62	1	2400	2400	14	5	60	5227	2.18	2.18	20
Hartel barrier[5,7,11,22]	Vertical lifting	NL	1993–1996	2		1	170	170	9.3	5.5	50·	185	1.09	1.09	2.4
Maeslant barrier[5,7,12,21]	Floating sector	NL	1989–1997	2			360	360	22	5	90	852	2.37	2.37	15
Cardiff Bay[26,27]	Sluice/lifting	UK	1994–2000	3	5	1	100	1100	7.5	3.5	30	340	0.31	3.0	15
Ramspol[5,7,13,21]	Inflatable rubber dam	NL	1996–2002				240	240	8.2	4.4	60	171	0.71	0.71	1.1
Ems[4,7,19,21]	Rotating sector	Germany	1998 -2002	2	5		476	476	10.5	3.8	30	376	0.79	0.79	6.3
St Petersburg Barrier[3,8,24]	Floating sector/vertical lifting	Russia	1984–2011	3	64		1700	25400	23.5	5	45	6953	0.27	3.53	
Seabrook barrier[7,18,21]	Vertical lifting/sector	USA	2005–2011	2	2		130	130	8	4	15	165	1.26	1.26	2.1
IHNC barrier[2,7,17,18]	Sector/vert. lifting	USA	2005–2011	3			250	2800	8	4	10	1,0	0.45	3.49	2.5
Venice MOSE[6,7,20,25]	Inflatable flap	Italy	2003- today	78		3	3200	3200	15	3	45	6125	1.91	1.91	12.8

Continued

Table 5.1. *Continued*

[1]For barriers where the span of the movable parts is smaller than the total span, we subtract the cost of the dam. For the old US hurricane barriers we use a unit cost price of US$10 mln/km. For the newer barriers (constructed after 1990), we use the cost prices by Dijkman (2007) of US$40 mln/km. For the IHNC barrier, we use the unit cost price from Bos (2008) for a 50 ft wall of US$ 36 mln/km.
[2]http://www.usace-isc.org/presentation/Construction%20Mgmt/Project%20Controls%20for%20New%20Orleans%20Surge%20Barrier_Stirm_Paul.pdf. Prices of only the movable parts (excluding floodwalls) is estimated at $673 mln.
[3]Cost of whole project, including sea walls: http://www.halcrow.com/Our-projects/Project-details/St-Petersburg-Flood-Barrier-Russia/.
[4]http://www.vncold.vn/Modules/CMS/Upload/13/Science/H4_EMS_Barrier(Germany)_23_02_09/H4_EMS_Barrier(Germany).pdf.
[5]http://www.deltawerken.com/Hollandse-IJssel-storm-barrier/322.html.
[6]Munaretto, S., Vellinga P., & Tobi, H. (2012) Flood Protection in Venice under Conditions of Sea-Level Rise: An Analysis of Institutional and Technical Measures. Coastal Management, 40, 355–380.
[7]Hillen *et al.* (2010).
[8]Cost of movable parts is estimated at 80% of the total price: ~ $5,561 mln.
[9]See Appendix D.
[10]http://www.omroepzeeland.nl/nieuws/oosterscheldekering-blijft-huzarenstukje.
[11]Rijkwaterstaat (1992) Tracenota Europoortkering. http://www.scribd.com/doc/76807878/106/Bediening-en-onderhoud-kering.
[12]IenM (2011) Vaststelling van de begrotingsstaat van het Infrastructuurfonds voor het jaar 2012. Total operation and maintenance for 4 storm surge barriers is 43.9 mln Euro per year.
[13]www.wgs.nl/publish/pages/6850/05-1_jaarverslaggeving.pdf.
[14]http://www.deltawerken.com/Hollandse-IJsselkering/56.html.
[15]http://www.wunderground.com/blog/JeffMasters/comment.html?entrynum=1993.
[16]http://www.pbn.com/Providence-transfersbarrier-to-Army-Corps,48223.
[17]http://www.nola.com/politics/index.ssf/2011/03/southeast_louisiana_flood_prot.html.
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[19]http://home.teleos-web.de/hkoerber1/Meyer-Werft/Emssperrwerk.htm.
[20]http://www.telegraph.co.uk/news/worldnews/europe/italy/3629387/Moses-project-to-secure-future-of-Venice.html.
[21]Dircke *et al.* (2011).
[22]RWS (2007) Waterloopkundige berekeningen TMR 2006 Benedenrivierengebied. RWS RIZA rapport 2007.017.
[23]www.scribd.com/doc/83762881/17/Stormstuw-Hollandsche-IJssel.
[24]http://www.nce.co.uk/news/water/st-petersburg-flood-barrier-swing-through-the-sea/5210173.article.
[25]http://en.wikipedia.org/wiki/MOSE_Project.
[26]Van der Meer (2006).
[27]http://www.guardian.co.uk/society/2005/jan/05/environment.welshassembly.

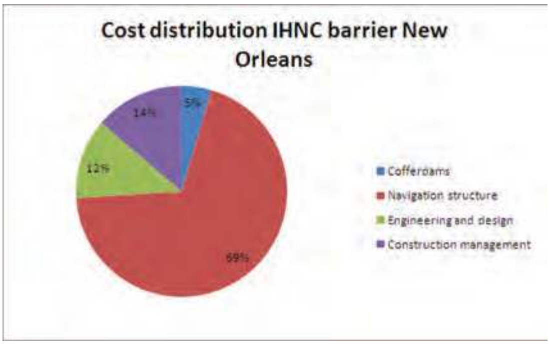

Figure 5.1. Main construction cost categories of the storm surge barrier in New Orleans (adapted from Arcadis, 2006).

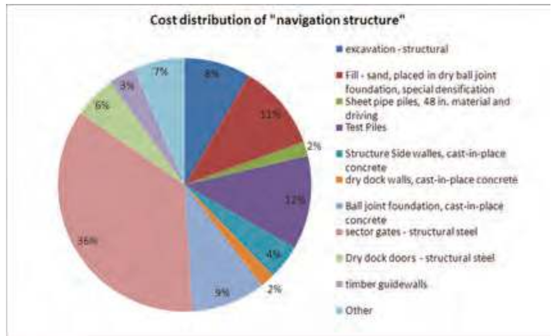

Figure 5.2. Distribution of cost categories of the movable parts of the IHNC storm surge barrier in New Orleans (adapted from Arcadis, 2006).

is somewhat lower than the estimate of 80% provided by Padron and Forsyth (2009). We, therefore, also calculated the cost per unit meter width of *only* the movable parts. This number was then divided by the span of the movable parts. The price range per unit meter is less between $0.71 mln/m for the inflatable rubber dam of Ramspol to $3.53 mln/m for the IHNC barrier in New Orleans. From Table 5.1, it follows that the most expensive barriers are the structures with sector gates ($2.37–3.53 mln/m), except for the older New Bedford barrier. However, there are some exceptions to this, such as the Ems Barrier. Flap gate structures, like the MOSE barrier in Venice and the Stamford barrier, have a unit cost price of $1.9–2$ mln/m. For vertical lifting gates (without a sluice combination), prices per unit km vary more between $1.15–2.18 mln/km.

Research by Hillen *et al.* (2010), using data from existing barriers, state that functional requirements 'span' and 'head' have the largest influence on the total construction costs. In order to have an idea of which functional requirements have a large influence, we conducted an OLS regression in SPSS (Appendix C). Several functional requirements such as 'span', 'hydraulic head', and 'navigation width', were included as explanatory variables in the regression, in order to estimate their influence on total costs. This analysis shows a significant correlation between the 'span of movable parts' of the barriers and the cost of the movable parts. A multiple linear regression with the predictors 'head' and 'span' of movable parts shows that 90% ($r^2 = 0.901$) of the variance in the cost of movable parts can be explained with these two independent variables.

Because the number of observations is low in this regression analysis, it is too premature to estimate future costs of barriers from these relations with span and head, but one could conclude that a wider span and head means higher costs, although costs can vary depending on the gate type and other functional requirements. For example, with respect to the gate type, barriers with a lot of steel structure, such as floating rotating sector gates used in Rotterdam or St. Petersburg, are more costly. In addition, deep navigation channels and extreme storm conditions may lead to gate types that are required to withstand high pressure gradients caused by the difference between the surge level outside the barrier and the inner water levels ('hydraulic head'). Some gates which are relatively cheaper, such as mitre gates, are from an engineering point of view often not feasible solutions in these conditions, and a barrier design will most probably use more expensive lifting gates or sector gates.

If other main cost categories for the IHNC barrier in New Orleans are examined, then it appears that management, design, and the placement of cofferdams each represent 14%, 12%, and 5% of the total construction costs, respectively (Figure 5.2). When further breaking down the costs of the navigation structure of the IHNC barrier in New Orleans, the largest share of all cost sub-categories can be attributed to the steel sector gates. For example, the two steel door sector gates of the IHNC barrier need 8,500 tons of structural steel at $10,500/ton (2006 values). Including 25% contingencies, the costs for the gates amount to $111 mln, around

36% of the cost ($313 mln) of the whole navigable gate structure.

5.2 Maintenance and operational costs of existing storm surge barriers

The maintenance of storm surge barriers pertains predominantly to conserving the gates, the hydraulic components, the electronic system, and the computer system to lift or close the gates. In addition, costs need to be reserved for personnel to operate the barrier and for conducting periodical inspections. Maintenance costs are dependent on the type, size, and location of a barrier. For example, if a barrier is (partly) situated under water, with, for instance, flap gates, maintenance will include efforts to either dry-dock gates with cofferdams or remove the gates and maintain them on dry docks on the side. This may result in high maintenance costs, and in the case of decoupling gates, it means that the barrier does not have its full protection level. The removal of gates for maintenance will mostly take place in periods when there is a less chance of a storm surge. In addition, maintenance works can hinder navigation, and hence may lead to additional costs.

Table 5.1 shows the range in maintenance cost for different barriers, varying from $0.5 mln/yr for a small barrier in Providence to more than $20 mln/yr for large storm surge barriers in the Netherlands. Nicholls *et al.* (2007) suggest that the maintenance costs for movable barriers can be estimated at approximately 5–10% of the invested capital. Applying this rule would result in minimum operation and maintenance costs of between $3 mln/yr and over $100 mln/yr, which are relatively high when comparing historical cost figures from existing barriers in Table 5.1. The total maintenance costs of the new storm surge protection system in New Orleans are estimated to be $18.2 mln/yr, of which $4.6 mln/yr is for the operation and maintenance of the two new storm surge barriers (SLFRA, 2011).

5.3 Contingencies of the costs of storm surge barriers

Evaluations of mega engineering projects show that construction costs are often difficult to estimate precisely. This can be explained by several factors. First of all, the techniques used in these projects are often new, never used before, which often leads to unexpected additional costs. Secondly, owing to the length of the projects, many historical projects, as in Table 5.1, have suffered insecure financing regimes because of political changes or national (or global) financial fluctuations (Munarreto *et al.*, 2012; Goemans and Smits, 1984). Arcadis (2011) lists several financial uncertainties that may cause an upward deviation from the original estimated costs: (1) increased time to acquire environmental permitting, (2) increased costs related to real estate acquisition, and (3) design changes through additional and unforeseen requirements.

Table 5.1 shows that the duration of the construction works varies between 4 years and decades. The St. Petersburg barrier project, for example, has been suspended for several years because of funding problems, and total construction time lies in the period 1984–2014. During the Oosterschelde surge barrier project, Goemans and Smits (1984) advised to budget at least for an additional 30% contingencies at the start of the new (similar) projects. However, when reviewing the INHC barrier construction process, Arcadis (2011) state that the original budget estimates have been increased by 25% from an initial estimated $1 bn to $1.25 bn. Thus, despite the original calculation, already 25% of contingencies were included in each of the cost categories (except for management and administrative activities).

5.4 Cost estimates of storm surge barrier strategies for NYC and NJ

The engineering companies that made the conceptual designs for the barriers during the barrier conference in 2009 (Hill *et al.*, 2013) made an estimate of the costs of the barriers. Some of these costs are mentioned in the design reports, and some provided the price estimation during additional presentations. These estimations range from $1.1 to 6.4 bn for the different barriers and are presented in Table 5.2. The costs for the Jamaica Bay barrier were not provided. Note that the costs of the East River barrier originally was presented as $1.5–1.7 bn (Appendix 2b). However, during specialist interviews with the designers (Appendix H), it appeared that an additional 25% must be included over the 100 years lifetime of the barrier to replace the hydraulic cylinders of the flap gates. The costs, hence, rise to $1.9 – 2.1 bn.

If we apply the historical unit cost prices derived from Table 5.1, we arrive at the following calculations. For the Arthur Kill barrier we apply the unit prices of $1.9–$2.18 mln/m, based on the unit cost

Table 5.2. Construction and maintenance costs for storm surge barrier strategies for NYC (in $ 2012 values)

	Barrier	Total span (m)	Span nav. parts (m)	Cost estimation Engineering firms: Construction (US$ bn)	Cost estimation Engineering firms: Maintenance (US$ mln/yr)	Cost estimation based on historical analyses (Table 5.1): Construction (US$ bn)	Cost estimation based on historical analyses (Table 5.1): Maintenance (US$ mln/yr)
Strategy 2a:	Arthur Kill	500	500	1.1		0.6–1.1	5.5
'Environmental	Verrazano Narrows	1820	1820	6.4	75	4.3–6.4	41
dynamics'	East River	1360	1360	1.9–2.1		2.6–3.0	31
Total				**9.4–9.6**[a]		**7.5–10.5**[a]	**77.5**[a]
Strategy 2c:	East River	1360	1360	1.9–2.1		2.6–3.0	31
'NY-NJ Connect'	Outer Harbor	9540	2500	5.9	72	6.5–9.4	72
Total				**7.8–8.0**[a]		**9.1–12.4**[a]	**104**[a]
Strategy 2b:	Arthur Kill	500	500	1.1		0.6–1.1	5.5
'Bay Closed'	Verrazano Narrows	1820	1820	6.4	75	4.3–6.4	41
	East River	1360	1360	1.9–2.1		2.6–3.0	31
	Jamaica Bay	1730	1730			4.1–6.1	39
Total				**9.4–9.6**[a]		**11.6–16.6**[a]	**116.5**[a]

[a]All summary cost tables are in US$ 2012 values. Indexing was applied using the Construction Cost Index and the Skilled Labor Index from ENR (Engineering News-Record, http://enr.construction.com/economics).

price of both vertical lifting gates derived from historical data (Table 5.1). For the East river barrier, we apply the higher unit price of $1.9–$2.18 mln/m based on the historical construction costs for flap gates. For the Jamaica Bay, Verrazano Narrows and the Outer harbor barriers, we apply higher unit costs prices of $2.37–$3.53 mln/m, as they include more complex designs (party) with sector gates. Note that for the Outer harbor barrier, this range only applies to the span of the movable parts (2000 m). However, the outer Harbor barrier may have the largest impact on environmental values and may largely disturb tidal flows, water quality and sediment budgets. In this context, Padron and Forsyth (2009) write additional 'studies would examine the size, number and location of navigable gates and control sluices' (p.226, Hill *et al.*, 2013). This means the length of movable parts of this barrier might increase, which will increase the costs of this barrier dramatically. We, therefore, add 25% in length of movable parts to a total length of 2500 m (high costs: $2.5 \times 3.53 =$ $8.8 bn). For the remaining span of the levee (7040 m), we apply the maximum unit cost price for hurricane levees by Dijkman (2007) of $85 mln/km, resulting in $0.6 bn total construction costs to be added to the costs of the movable parts of the Outer Harbor barrier.

When examining Table 5.2, it appears that overall, the original cost estimates of the engineering companies are all within or close to the costs ranges based on the historical estimates. The Arthur Kill barrier costs were estimated at $1.1 bn, which lies at the upper end of the historical range. The costs for the Verrazano Narrows barrier were originally estimated at $6.4 bn, which is also at the upper end of the historical range. For the East River barrier, we added cost for a one time replacement of the hydraulic cylinders based on a meeting with the responsible engineering firm Parsons Brinckerhoff (Appendix H). They estimate the replacement of the cylinders at 25% of the initial construction costs of $1.7 bn (see Appendix B), leading to a total cost between $1.9–2.1 bn. However, such replacement could be needed twice during the 100 year lifetime of the barrier, which then would lead to a total cost price of $2.3–2.5 bn. This is partly within the range of the estimations based on historical cost numbers. The costs estimations for the Outer Harbor barrier by the engineering company are well within the range of estimations based on historical data.

Given the rough estimations, the global design and the very preliminary stage of this process, the estimates seem overall reasonably robust. However, the number must be treated with care and are surrounded by large uncertainties. For example, the cost number for the East river barrier can increase when re assessing the tons of structural steel needed for constructing the gates. For example, in the cost calculation used for the East River barrier (Appendix B), 5000 tons of structural steel were used at a unit price of $12,000. This is would cover the material required for 90 flap gates that span the East river (see Section 5). However, for the IHNC barrier in New Orleans, 8,500 tons of steel was used at a unit price of $10,000 for only 2 sector gates (ARCADIS, 2006).

Maintenance cost

Only Jansen and Dircke (2009) estimate the maintenance costs for the Verrazano barrier to be about $75 million annually. This confirms the number provided for the existing St Petersburg barrier of $72 mln, which can be applied to the NY–NJ outer harbor barrier. The Outer harbor barrier and the Verrazano barrier consist for a large part of movable elements and will probably have relatively high maintenance cost. If we, however, look at the historical maintenance costs per unit km, it appears that those costs are lower. For example, the maintenance costs for the Thames barrier are about $13 mln/yr (Appendix C) with 80 full-time employees, which is 23 mln/yr/km. In addition, the maintenance costs for the IHNC barrier in New Orleans are about $10 mln/yr. These differences can be explained by the complexity of the design, the numbers of movable parts, and the span of the barrier. We, therefore, apply a lower estimate of $11.5 mln/yr for the maintenance of the relatively small Arthur Kill barrier as 50% of the maintenance costs of the Thames barrier, and $23 mln/yr per km of movable parts for the other barriers. For the NY–NJ outer harbor barrier, we apply the number from the St Petersburg barrier of $72 mln/yr

Cost of additional measures

Closing NYC's waterways from New York City is not enough to protect NYC against high water levels. Some parts of the coast, because they are too low, will still be exposed after the construction of the barriers and floodwaters may bypass the barriers. For these areas, beach nourishment, levees, dikes and other additional measures will need to be installed. Or, existing protection measures will need to be retrofitted to attain the required design water level height of 25–30 ft. In addition, discharge of the Hudson River and other freshwater sources will raise water levels behind the storm surge barriers in case the barriers are closed during a storm surge event. The water level may rise by ∼1 ft; thus, coastal areas behind the barriers in each strategy will need to be raised until they at least reach a height that is 1 ft higher than the current height of the coastline.

Based on analyses of the current length of coastal morphological types and current protection measures, we may estimate the additional costs of flood protection measures. These measures and associated costs are needed to complete each of the two surge barrier strategies (Table 5.3). Figure 5.3 shows the stretches of coastline where the different additional measures are possibly needed for Strategies 2a, b, and c.

Total costs storm surge barrier Strategies 2a, b, and c

Table 5.4 Shows the total construction and maintenance costs for the storm surge barrier strategies 2a, b, and c. Strategy 2c, NJ-NY Connect, is the least expensive strategy with about $11–14.7 bn. The most expensive barrier Strategies are 2a and 2b, with estimates between $15.9 and $21.8 bn. Although Strategy 2b comprises four barriers as compared to three barriers in Strategy 2a, the cost of additional protection measures required in Strategy 2a are considerably higher compared with those in Strategy 2b. Maintenance costs for all strategies vary roughly between $98.5 and $126 mln/yr.

These numbers must be treated with care and are very rough estimates with a lot of uncertainty. It appears that the cost estimates by engineering companies are close to the lower ranges of cost estimates made on the basis of empirical unit cost prices. However, cost estimates are likely to be higher, since contingencies were not always included in preliminary estimates. Furthermore, surcharges on labor costs, which are generally higher in the NYC compared to other locations in the US, can add an additional 10–30% to labor cost (see also Section 2 on building code measures). Finally, there is still significant uncertainty in the designs themselves, for example on the required tons of steel needed in the East River barrier and on the length of movable parts

Table 5.3. **Overview of additional costs for the different storm surge barrier Strategies 2a, b, and c. (all in $ 2012 values)**

		Length [Km]	*Unit costs* [$/km)	*Total costs* [$ bn]	*Unit Maintenance Costs* [$ mln /km//yr]	*Total Maintenance Costs* [$ mln/yr]
Strategy 2a: *'Environmental dynamics'*						
1	Floodwalls	19	30–50	0.6–0.94	*0.1*	*4*
2	Earth Filled dike	87	27	2.3	*0.1*	*3*
3	Retrofit low bulkheads inside	50	41	0.09	*0.1*	*4*
5	Mix Levee/landfill	71	50	3.5	*0.1*	*5*
6	Dike in low urban density	3	10	0.03	*0.05*	*0.5*
7	Beach Nourishment /levee	56	30–45	1.6–2.5	*0.1*	*4*
8	Nature restoration			0.9		*0.5*
10	Flood proofing	16				
Total		**389 km**		**$9.4 – 10.6 bn**[a]		**$21 mln/yr**[a]
Strategy 2b: *'Bay Closed'*						
5	Mix Levee/landfill	54	50	3.5	*0.1*	*5*
6	Dike in low urban density	3	10	0.03	*0.05*	*0.5*
7	Beach Nourishment /levee	56	30–45	1.6–2.5	*0.1*	*4*
10	Flood proofing	16				
Total		**129 km**		**$4.3 – 5.2 bn**[a]		**$9.5 mln/yr**[a]
		Length [Km]	*Unit costs* [US$ mln/km)	*Total costs* [US$ bn]	*Maintenance Costs* [US$ mln /km/yr]	*Total Maintenance* Costs [US$ mln/yr
Strategy 2c: *'NY-NJ Connect'*						
6	Dike in low urban density	3	10	0.03	*0.05*	*0.5*
5	Mix Levee/landfill Bronx	20	50	1	*0.1*	*5*
3	Retrofit low bulkheads inside	50	41	0.09	*0.1*	*4*
7	Beach Nourishment/ levee Rockaways & Sandy H.	45	30–45	0.8–1.2	*0.1*	*4*
Total		**67 km**		**$1.9 – 2.3 bn**[a]		**$13.5 mln/yr**[a]

[a]All summary cost tables are in US$ 2012 values. Indexing was applied using the Construction Cost Index and the Skilled Labor Index from ENR (Engineering News-Record, http://enr.construction.com/economics).

Figure 5.3. Location of flood management measures in Strategy 2a, *Environmental Dynamics.*

in the Outer Harbor Barrier. For example, the total length of movable parts in the Outer Harbor barrier in Strategy 2c is 2 km. However, in the conceptual design, as well as in a recent expert meeting, the required length of sluices was suggested to be longer to reduce flow disturbances of tide.

5.5 Additional issues for storm surge barriers

Permitting and legislation

The U.S. Army Corps of Engineers (USACE) is the agency that evaluates projects in navigable waterways or in wetlands that eventually drain into navigable waters (Scarano, 2009). In order to manage the program, USACE applies administrative processes listed in the Code of Federal Regulations (CFR). The proposed surge barrier projects would need to address major regulatory issues, including construction in navigable waterways and the effects on water quality, aquatic habitat, and endangered species. These regulatory issues are summarized in three main statutory instruments—Section 10 of the Rivers and Harbors Act of 1899, which deals primarily with construction and dredging; Section 404 of the Clean Water Act, which deals with the discharge of dredged and fill materials; and Section 103 of the Ocean Dumping Act, which deals with the transport and discharge of dredged material. In the New York metropolitan area, the regulatory program administration is handled by the Regulatory Branch of USACE's New York District. Its jurisdiction includes Northern New Jersey, Long Island, and the eastern portions of New York State. In New Jersey, however, most regulation under Section 404 is administered by the State of New Jersey.

There are two basic types of permits issued by USACE—individual permits and general permits. Individual permits are required for the more

Table 5.4. Total cost estimates of barrier Strategies 2a, 2b, and 2c (all in $2012 values)

	Construction		Maintenance	
	Construction costs Barriers [US$ bn]	Construction costs Additional measures [US$ bn]	Main. Costs Additional measures [US$ mln/yr]	Main. Costs Additional measures [US$ mln/yr]
Strategy 2a: '*Environmental dynamics*'				
	7.5–10.5	9.4–10.6	**77.5**	21
Total	**$16.9–$21.1 bn**[a]		**$98.5 mln/yr**[a]	
Strategy 2b: '*Bay Closed*'				
	11.6–16.6	4.3–5.2	116.5	9.5
Total	**$15.9–$21.8b**[a]		**$126 mln/yr**[a]	
Strategy 2c: '*NY-NJ Connect*'				
	9.1–12.4	1.9–2.3	104	**13.5**
Total	**$11.0–$14.7 bn**[a]		**$117.5 mln/yr**[a]	

[a]All summary cost tables are in US$ 2012 values. Indexing was applied using the Construction Cost Index and the Skilled Labor Index from ENR (Engineering News-Record, http://enr.construction.com/economics).

complex projects and require the most coordination with other agencies as well as public notification. General permits are less complex. The regulation of permitting is covered through the USACE District Offices. Each District Office administers the program in accordance with the above mentioned Code of Federal Regulations. However, there are local variations across regional USACE offices, which stress the need for a permit seeker to consult with these offices. When permitting activities take place within the State of New York, a joint application has been developed for both a USACE permit and a New York State Department of Environmental Conservation (DEC) permit. This does not result in a joint permit and separate permits will be issued by USACE and DEC.

For the proposed barrier designs and their locations, the permit application will involve a complex review by partner federal agencies, state and local governments, and other local stakeholders. The public notification process will certainly allow for public concerns to be addressed. In addition, the project would be subject to a rigorous environmental, wildlife, and historic properties review, according to the above-mentioned regulations.

Maintenance and institutional issues

In addition to maintenance costs, the daily operational costs of the storm surge barriers are important. Also, forecast and warning systems are required when implementing a movable storm surge barrier, which may require significant institutional capacity. Operational costs include the joint operation of 2–4 barriers according to different operational protocols that will be designed during the planning phase. The choice for a specific operational system depends on the direction and track of a storm surge that approaches NYC. In such a system, the order of closing the barriers will be an important aspect. However, these operational costs (expressed in man-hours) are very small compared with the construction and maintenance costs, and are, therefore, not taken into account in the total costs.

An important question, however, concerns who is responsible for bearing the operation and maintenance costs. For example, the City of Providence is expected to save as much as $500,000 annually after transferring the Fox Point Hurricane Barrier to the US Army Corps of Engineers in 2010. After over 50 years during which the City was responsible for maintenance costs, the Army Corps took over operations and maintenance costs of the barrier. An open question is, therefore, who will bear the O&M costs for the NYC barrier system?

Environmental issues

Apart from the potential negative impacts of a storm surge barrier on the marshlands of Jamaica Bay area, positive environmental effects are also described in several studies (e.g. Hill, 1994; Padron and Forsyth, 2009). With the proper opening and closure regime of barriers, the flushing of the NYC harbor can be increased, thereby alleviating costly dredging activities and improving water quality.

Barrier failure or partial closure

When evaluating the effectiveness of barriers for reducing flood risk, (partial) closure or construction failure of the structures should be addressed. Bowman *et al.* (2005) simulated the effects of partially closed barriers assuming synthetically boosted Hurricane Floyd (year 1999) conditions (Table 5.5). Such a theoretical operational scheme can be seen as a closure failure. The effects were inconsistent. For example, when ¼ of the span of each of the individual barriers was closed, the water levels in some areas were 0.6–0.8 m higher than in the case without barriers. In the case of ¾ closure, water levels at some location increased, but dropped at the East River.

Table 5.5. **Peak water levels inside the 3- barrier system (Narrows, East River, Arthur Kill) at various locations, with full closure and partial closure regimes**

Location	No barriers	¼ closed	½ closed	¾ closed	Fully closed (outside level)
Perth Amboy	1.2	2	1.5	1.7	1.2
East River	1.7	1.6	0.9	1.2	2
Narrows	1.05	1.6	1.1	1.4	1
Battery	1	1.6	1.1	1.3	

In addition to closure failure, construction failure due to unexpected loadings may lead to the collapse of the protection system. Gaslikova *et al.* (2011) described several failure probability curves which can be used to simulate these circumstances in a risk analysis. The available barrier designs were not provided with any failure probabilities.

Optimum design heights

Furthermore, note there are several studies that show how to calculate the economic optimal protection level for an area (e.g. Jonkman *et al.*, 2009). This optimal protection level can be found by performing an optimization analysis of the relation between the level of investments in flood protection and the level of protection obtained. From this analysis, a point can be determined where the sum of the investment costs and the reduced flood risk are minimal. The protection level that corresponds to this point is the optimal safety level for an area. It has not been investigated whether the assumed future 1/100 design level of 25–30 ft for storm surge barriers or 20 ft for levees is the economic optimum for NYC.

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6. Economic and direct losses from Hurricane Sandy

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6.1 Overview Sandy

Hurricane Sandy is the worst natural hazard to hit the NYC region in its history. Due to her sheer size (Blake *et al.*, 2013) and rare angle of approach (Hall and Sobel, 2013), Sandy caused record high water levels in NYC. The evolution of Sandy from the Caribbean up to the northeast coast of the US was far from straightforward. Sandy hit Jamaica as a category 1 hurricane, strengthened to category 3 hurricane in Cuba, and then weakened quickly to category 1 over the Bahamas. Moving northeastwards, Sandy merged with another weather system (giving it her size), but retained hurricane force winds for most of the time (NASA, 2012). Her path towards the northeast then got blocked by a high-pressure system over the North Atlantic (Blake *et al.*, 2013), forcing her to make a turn to the left, straight towards New Jersey and New York. Despite this complex evolution, the path and size of Sandy were forecasted exceptionally well. Already five days before landfall, the National Hurricane Center (NHC) projected Sandy's track to within a couple of tens of miles (The Washington Post, 2012).

This accurate forecast enabled authorities to take proper actions in preparation of the storm. Schools were closed and evacuations orders (both voluntary as well as mandatory, depending on the city) were issued for low-lying areas. Also the Metropolitan Transportation Authority, which had learned from events in 2007 (extreme rainfall) and 2011 (hurricane Irene), took many precautions; informing the public three days in advance that the system could possibly be shut down. Buses and trains were then moved to higher ground, subway entrances and ventilation grates were covered, staffing the incident command center, deploying emergency crews, and preparing pump trains, portable pumps and response vehicles. Because of these preparations, the recovery went relatively fast, with the first bus lines already back in service the day after the storm, the first subway service three days after the storm and within 5 days 80% of the subway system was back in operation (Kaufman *et al.*, 2012). Generally, the actions of the MTA before and after the storm have been widely applauded (NY1, 2013).

Despite all these efforts, the impact of Sandy on the Eastern seaboard of the US, and in particular the NYC–NJ area, was huge, a testimony to the extreme nature of this storm. Preliminary analyses show Sandy can be ranked as the second costliest storm in terms of damage in the US, after Hurricane Katrina of 2005 (Blake *et al.*, 2013), and could be the sixth-costliest storm, after normalizing (see e.g. Pielke *et al.*, 2008) its damages for inflation, population, and wealth (Blake *et al.*, 2013).

6.2 Damage caused by Sandy

There are various estimates for the losses associated with hurricane Sandy. These vary in terms of area considered (i.e. New York City, New York State, New Jersey), types of damage considered (i.e. different sectors, direct losses, insured losses, indirect losses), and the moment of assessment. Quickly after the storm, Zandi (2012) made a preliminary damage estimate for the US East coast, arriving at a total of $50 bn, including indirect damages. Using storm surge and damage models, RMS estimated the insured losses of Sandy in February 2013 (RMS, 2013), arriving at $20–$25 bn. By April 2013, the Insurance Information Institute estimated the total insured losses of Sandy at $18.8 bn, after 93% of the claims were settled (I.I.I., 2013); making Sandy the third costliest storm in the US in terms of insured losses (after Katrina in 2005 with $48.7 bn and Andrew in 1992 with $25.6 bn).

Post-storm assessments have been made by various companies in the wake of Sandy, illustrating how they have been hit. The states of New York and New Jersey have made comprehensive damage assessments to substantiate claims for the federal relief fund (Table 6.1). NYS requested the federal government for $42 bn, from

Table 6.1. **Overview of the damage assessments by the states of New Jersey and New York (NJ, 2012 and NY, 2012a)**

	New Jersey (million $)	New York (million $)
Government Response and Repair	$529.4	
Individual Assistance	$702.7	$913.3
Housing	$4,921.2	$9,672.0
Business	$8,319.1	$6,000.0
Health	$291.8	$3,081.0
Labor	$760.1	
Schools	$2.6	$342.7
Transit, Roads and Bridges	$1,351.0	$7,348.1
Parks and Environment	$5,526.5	$793.9
Water, Waste and Sewer	$3,012.7	$1,060.3
Government Operating Revenue	$95.0	$461.5
Other Local Government Revenue & Road	$737.5	
Other Local Education	$125.0	
Atlantic City/CRDA	$312.7	
Port Authority	$1,000.0	
Utilities – Gas & Electric	$1,797.3	$1504.0
Total repair and response costs	***$29,484.6***	***$32,804.1***
Additional mitigation and prevention costs	*$7,422.7*	*$9,080.80*
Overall total	***$36,907.3***	***$41,884.9***

which $9.1 bn was for new flood adaptation measures (NYS, 2012). New Jersey claims $37 bn in total damage (HP, 2013), of which $7.4 bn is allocated for additional adaptation measures (NJ, 2012). Federal aid came with the Hurricane Sandy relief bill, which requested 60.4 bn for aid in response, recovery and mitigation (EOP, 2012). This bill passed the senate on January 4, and was signed into law on January 6 by the president. This is lower than the added funds requested by the states of NY and NJ though.

Housing

The impact of Hurricane Sandy on residential property was huge; at least 650,000 houses were damage or destroyed, mostly because of the storm surge and waves (Blake *et al.*, 2013). It is estimated that in the state of New Jersey 346,000 homes were damaged or destroyed, and in the state of New York 305,000 homes (Blake *et al.*, 2013). Even six months after the storms, several tens of thousands of people remain homeless, living in hotel rooms with relatives or in temporary homes (AP, 2013a). In New Jersey especially, the communities along the Jersey Shore (counties of Monmouth, Ocean and Atlantic) were hit hard, with some of the most devastating images of the storm coming from areas like Mantoloking. In addition, the interior of New Jersey was hit, including Jersey City and Hoboken. In New York state Nassau and the counties of NYC suffered badly (NY, 2012b). Several communities in Long Island, such as Fire Island and Long Beach, were particularly severely hit. Striking are the events in Breezy Point, at the tip of the Rockaways (Queens), where a blazing fire sparked by contact between electrical wires and seawater destroyed over a 100 homes (Table 6.2).

Power utilities

Hurricane Sandy has had a huge impact on the power and gas utilities of the NYC–NJ region. Overall, it is estimated that over 8.7 million customers were without power due to the devastating effects of Sandy (WRN, 2012). Many were still affected by power outages more than a week after the storm: about 150,000 in New Jersey, 174,000 in Nassau/Suffolk/Westchester, and 28,000 in NYC (WRN, 2012). For each of the main power utility services in NY and NJ, PSE&G, Jersey Central Power & Light, Long Island Power Authority and Consolidated Edison, approximately a million customers were affected at the height of the blackouts (The New York Times, 2012; see also Table 6.3). Direct damage to the grid power and related utilities included the inundation of 58 substations (NJSpotlight, 2013), flooding of underground equipment, transformers, and downing of thousands of poles and hundreds of miles of wires. Several repair and flood protection projects were rapidly initiated.

In New Jersey, for example, the projected costs for restoring the impacted utilities of PSE&G are estimated to be $250–300 mln (NJ Spotlight, 2013). Large problems arose when switching- and substations flooded near Newark Bay. Because of Sandy, PSE&G is planning a $3.6 bn infrastructure overhaul over the next 10 years, including $1.7 bn to raise switch- and substations (NJ.com, 2013). The

Table 6.2. Overview of properties hit by Sandy in the states of New York and New Jersey

	# properties hit	# properties destroyed	Property damage ($)	# businesses impacted	Description
New York State	305,000[a,c]		9,7 bn[a]	265,300[a]	
NYC			4,7 bn[a]		
Breezy point (Rockaways)		∼500[e]			Over 100 homes destroyed due to fire [c,d,e,g]
Long Island	∼100,000[c,f]	2000	>0.5 bn[c]		80% of homes on fire Island damaged. Also Long Beach severely damaged[f]
Staten Island	14,000[f]	>87[f]			Particularly communities of Midland, New Dorp, and Oakland Beach[c]
Manhattan	Hundreds[c]				
New Jersey	346,000[c]	22,000[c]	4.9 bn[b]	19,000 with severe dam[c]	Severe damage relates to $250,000 or more
Hoboken	>1,700[c]		0.1 bn[c]		∼ 20,000 residents affected[c]
	1000–5000[f]		0.8 bn[f]		1 bn damage in Hoboken, 80% by residential buildings[f]
Jersey Shore			1 bn[f]		Especially Seabright, Mantoloking, Lake Como, Seaside Heigths, Belmar, and Long Beach Island[f]

[a]NY, 2012a; 2012b.
[b]NJ, 2012.
[c]Blake *et al.*, 2013.
[d]Huffington Post, 2012.
[e]UPI, 2013.
[f]The Real Deal, 2012.
[g]Gothamist, 2012a.

estimated flood damage to Jersey Central Power & Light is $630 to $680 mln (NJ.com, 2012; FirstEnergy, 2013). In the whole of New Jersey, power and gas line repairs are expected to cost roughly $1 bn (Blake *et al.*, 2013).

In New York, the damage to Con Edison is estimated at $350–450 mln (Reuters, 2012), and the company is planning a 1 bn dollar investment over the next four years to create flood protection works, make some equipment submersible, and bury some wires of the grid (AP, 2013b). The damage costs for the Long Island Power Authority (LIPA) are estimated of between $900 and 950 mln, roughly a quarter of their annual revenue (WNYC, 2012a). In both New Jersey and New York the damage by Sandy has a sparked a lively discussion on the height of electricity bills (FirstEnergy, 2013; WNYC, 2012a), which are expected to increase to pay for some of the storm damage, as governmental bodies (like LIPA) typically receive a maximum of 75% reimbursement from the Federal Emergency Management Agency (FEMA) to cover the costs of repair (WNYC, 2012a).

Transportation systems

The transport system of the NY Metropolitan Area was hit hard by Hurricane Sandy (see Table 6.4 for an overview). Seven subway tunnels under the East River flooded and Metro-North lost power on multiple lines. The Metropolitan Transportation Authority (MTA) has assessed the infrastructure damage from Hurricane Sandy will cost $4.8 bn to repair. Additionally, $265 mln is needed to cover overtime

Table 6.3. **Overview of damage to some of the main power and utility companies in NJ and NY**

Name of Utility company	State	Max customers affected	Damage [$ bn 2012]	Damage description, repair
PSE&G	NJ	∼1,400,000[a]	0.25–0.3[b]	Excluding costs of electric-generating facilities and shortened life-span of equipment
Jersey Central Power & Light	NJ	∼925,000[a]	0.63[c]–0.68[f]	Repairing substations, replacing 6700 poles, 3600 transformers, 400 miles of wire
Consolidated Edison	NY	∼800,000[a]	0.35–0.45[d]	Flooded underground equipment, 100,000 downed wires
Long Island Power Authority	NY	∼900,000[a]	0.9–0.95[e]	2100 transformers, 4500 poles, repair of 400 miles of wire

[a]The New York Times, 2012.
[b]NJ Spotlight, 2012.
[c]FirstEnergy, 2013.
[d]Reuters, 2012.
[e]WNYC, 2012a.
[f]NJ.com, 2012.

and lost revenue (NY1.com, 2013; MTA, 2012). The most costly items on the repair list of the MTA include (MTA, 2012) $600 mln to restore the South Ferry/Whitehall subway stations in lower Manhattan; $650 million to repair the train service to the Rockaways; and $770 mln to repair flood-damaged signals in Brooklyn, Queens, and Manhattan. Also the repairs of the Hugh L. Cary and Queens Midtown tunnels are expected to cost $350 mln and $400 mln, respectively. The MTA estimated that it lost 49.7 million trips because of Hurricane Sandy (43.8 million in NYC Transit, 2.4 million on the LIRR, 1.8 million on Metro-North Railroad, 1.6 million on the MTA Bus Co., and 100,000 on the Staten Island Railway (MTA, 2013). The MTA expects FEMA and insurance will cover most of the costs, but anticipates it will have to raise around $950 mln (MTA, 2012), likely by cutting back on internal costs (Gothamist, 2012b). The MTA states it will not only repair broken systems but will also improve flood resilience while repairing them.

The total damage to roads and infrastructure in New Jersey is estimated at $2.9 bn (Blake *et al.*, 2013). The PATH tubes between New Jersey and New York were entirely filled with seawater, and the Hoboken PATH station was entirely inundated. Damages to the PATH system are approximately $0.3 bn (HobokenPatch, 2012). The damage to NJ Transit Rail is estimated at $400 mln (Blake *et al.*, 2013; WNYC, 2012b). Of the $400 mln, around $100 mln is from damage to trains and equipment and $300 mln is due to repair tracks, wires, signaling, electrical substations and equipment, for emergency services, and lost revenues (Rail News, 2012). Overall, nearly a quarter of their locomotives (62) and a quarter of their train cars (261) were damaged in yards in the Meadows complex and Hoboken (CBS New York, 2012). On top of this damage, NJ Transit Rail believes around $800 mln is necessary to make the transit system more resistant to future storms (Rail News, 2012). By comparison, the damage to Amtrak was relatively low, $30 mln in repairs and $60 mln in lost revenues. Amtrak is also looking to improve the resilience of its system, especially related to Penn station and the tunnels (Rail News, 2012).

Besides PATH other units of the Port Authority of New Jersey and New York suffered badly. Overall, the damage to the Authoritiy is estimated at $2 bn. This includes the damage to PATH, as well as damage to airports (LaGuardia), the WTC site, tunnels, and electrical equipment damaged or corroded by salt water (App.com, 2013). BoatUS estimates that 65,000 boats were destroyed by Sandy, with a total damage of roughly $650 mln (Blake *et al.* 2013). Also, about a quarter of a million cars were damaged, of which 150,000 were in NYC (Autoblog, 2013).

Other infrastructure

Besides energy systems and transportation, other infrastructure was hit hard by Sandy. Preliminary estimates show that Hurricane Sandy will cost broadband, telephone, and cable companies, such as Verizon and AT&T, around $600 million in repair and cleanup expenses (about.com, 2012). Medical infrastructure was also hit hard. Various hospitals were affected, including the NYU Langone Medical Center, which had to be evacuated because of power outage, the Bellevue Hospital (FierceHealthcare, 2012), and Coney Island Hospital (The Hill, 2013). Costs for hospitals in NYC after Sandy total to about $800 mln (The Hill, 2013). A large portion of this relates to permanent reconstruction works to the hospitals more resilient in future situations. This includes, for instance, the relocation of Coney Island Hospital's emergency department to the first floor, the relocation of mechanical gas systems out of basements, retrofitting elevators, and creating floodwalls (The Hill, 2013). Also $207 mln of the federal relief funds have been allocated for the renovation and repair of key departments and systems at the VA Manhattan Medical Center (EOP, 2012).

Wastewater treatment, drinking water, and contaminated sites

In the aftermath of Sandy, the EPA assessed the quality of the drinking water and wastewater facilities, and supported the repair and maintenance of damaged wastewater treatment plants in New Jersey (EPA, 2012a). Problems of contamination may arise when the wastewater plants get filled by seawater water, which may cause sewage water to mix with the hydrological system, bypassing the treatment facilities of the plant. Initial reports from the Rockaways show leakage of the Bay Park sewage treatment plant, leading to only partial treatment of waste (MSNBC, 2012). However, additional drinking water analyses at water wells located on Shinnecock Nation showed water quality from the wells met New York State drinking water and groundwater standards (EPA, 2012b). The EPA also assessed possible pollution in the Gowanus Canal and Newtown Creek in Brooklyn. Although the Gowanus Canal did overflow, there were no significant health risks (DN, 2012).

Furthermore, The EPA assessed 40 drinking water facilities and 23 wastewater treatment plants in New Jersey (EPA, 2012a). Of these 23 facilities in NJ, two wastewater treatment plants requested further assistance from the EPA (the Passaic Valley Sewerage Commission in Newark, New Jersey, and the Middlesex County Utility Authority in Sayreville, New Jersey). The Passaic Valley Sewerage Commission was flooded and lost electricity during the storm, and the EPA removed wastewater from the plant until the plant was back in operation. The Middlesex County Utility Authority lost power during the storm to its water utility intake pumps and the EPA assisted in fixing damaged equipment. Furthermore, in preparation for Hurricane Sandy, the EPA secured contaminated sites in the federal Superfund program in New Jersey and New York to protect against potential damage. Since the storm, the EPA has been assessing these 105 sites and it appears they do not pose an immediate threat to public health or the environment. In the whole of New Jersey, repairs to the wastewater and sewer services are estimated to cost about $3 bn (Blake *et al.*, 2013).

6.3 Damage and risk of NYC and surrounding region

In order to evaluate flood risk management strategies for New York City, it is important to have insights in both the costs and benefits of such strategies. The costs have been described in detail in previous chapters of this report. In order to gain insights into the benefits, the risk reduced by installing storm surge barriers and/or levees need to be understood. In order to do so, detailed risk estimates for buildings and vehicles in NYC (De Moel *et al.*, 2013) are used. De Moel *et al.* (2013) use data from over 500 synthetic hurricanes (from Lin *et al.*, 2012) and a damage model based on the HAZUS MH model (FEMA, 2009) to calculate the flood risk of buildings and vehicles in NYC. This risk estimate is used as a base and scaled up to include also other sectors at risk (i.e. infrastructure, public space, etc.), indirect effects (after the flood event), and risk in parts of NJ that are protected by the barrier strategies. Scaling up this risk is done by using damage assessments of Hurricane Sandy.

Damage NYC

The state administration of New York estimated the total damage in the state at $32.8 bn; it also disclosed a more detailed summary of the damage assessment (NY, 2012b). This detailed summary shows that damages to NYC are estimated at roughly $15 bn.

Table 6.4. **Overview of damage to some of the main transportation companies in NJ and NY**

Transport				
Name of Transportation company	**State**	**Lost rips [mln]**	**Damage [$ bn 2012]**	**Damage description, repair**
MTA	NY	49.7[a]	5.0[b]	7 East River tunnels flooded, Stations of South Ferry and Whitehall, damaged signals, etc.
PATH	NY–NJ		0.3–0.8[e,h]	Hoboken station, pumps, electrical equipment
NJ Transit Rail	NJ		0.4[c]	Damage to all 12 rail lines; flooded cars and locomotives [d]
Amtrak	NJ	0.18	0.09[f]	Reparing signals, pumps, tunnels, stations (30 mln)[f]; operating losses (60 mln)[g]

[a]MTA, 2013; [b]MTA, 2012; [c]WNYC, 2012b; [d]CBS New York, 2012; [e]HobokenPatch, 2012; [f]AP, 2013c; [g]Rail News, 2012; [h]App.com, 2013.

However, this estimate excludes any damage to infrastructure, of which most in NYS can be attributed to NYC. For instance, of the damage sustained by the MTA, totaling $5.0 bn, 89% can directly be attributed to NYC, 2% to counties outside NYC, and 9% to the system as a whole (MTA, 2012). Including parts of the state-wide damage to infrastructure in the NYC estimate brings the total up to roughly $21.3 bn (Table 6.5).

The above estimate of $21.3 bn of damage to NYC by Sandy only includes direct damages. Besides direct damages, large disasters like Sandy also affect the regional economy and result in indirect damages due to loss of production after the event, both in the area struck by the disaster and outside. Such indirect costs can be calculated as the reduction in production of goods and services, quantified in terms of value added (Hallegatte, 2008). There have been several economic studies trying to quantify this effect (e.g. Jonkman *et al.*, 2008; Hallegatte, 2008; Li *et al.*, 2013). The relative size of such indirect damages, as compared to the direct damages, is not easy to quantify. It is sometimes stated, without proper argumentation, that such indirect losses can be roughly the same size as the direct losses (Toyoda, 2008). Few empirical evidence exists though. Toyoda (2008) estimated the indirect losses after the great Hanshin-Awaji (Kobe) earthquake in 1995 using questionnaires and statistical analyses of macro-economic data. Toyoda (2008) arrived at indirect losses that were indeed roughly the same as the direct losses, more than 10 years after the event. Hallegatte (2008) created a input-output modeling framework to assess the indirect losses of Hurricane Katrina, and explore the effect of different sized events. Hallegatte concludes that for very large disasters (direct damage roughly $200 bn), the indirect costs can be just as large as the

Table 6.5. **Overview of state-wide and NYC damage of Hurricane Sandy, including estimates for infrastructure damage in NYC**

	NYS (in M$)	**NYC (in M$)**
Gov't response and repair	1627.3	486
Indiviudal assistance	913.3	530
Housing	9672	4738
Business	6000	4512.1
Health	3081	2799
Schools	342.7	300
Transit, roads and bridges	1484.40	1013
Parks and environment	793.9	300
water, waste and sewer	1060.3	117
Gov't operational revenue	461.5	250
MTA	5022.6	4800[a]
Utilities	1504	1000[b]
Port Authority	841.1	500[c]
Total	**32804.1**	**21345**

[a]Close approximation 96% of total MTA damage.
[b]Assumed, roughly two-thirds of state-wide damage.

Table 6.6. Aggregated FEMA housing assistance data for owners and renters at various spatial levels.

	NY	NYC	NJ	NJ – barrier 2c*	NJ – barrier 2ab**
Owners					
Valid Registrations	150582	66516	146294	57257	40596
Registratrions × avg. damage	1.82×10^9	0.83×10^9	1.22×10^9	0.26×10^9	0.13×10^9
Renters					
Valid Registrations	113748	84221	108202	72003	62129
Moderate damage	44%	44%	47%	47%	53%
Major damage	24%	26%	14%	18%	17%
Substantial damage	32%	30%	39%	35%	30%

*Includes the counties of: Passaic, Bergen, Hudson, Essex, Union, Middlesex and (northern) parts of Monmouth.
**Includes the counties of: Passaic, Bergen, Hudson, Essex, Union, and parts of (northern) Middlesex.

direct losses. For smaller events, this ration is smaller, however. For Katrina, direct damage estimated at $107 bn by Hallegatte (2008), the indirect losses are estimated at roughly 40% of the direct losses ($42 bn). Given that hurricane Sandy was a smaller event in direct losses as compared to hurricane Katrina, we assume here indirect losses to be about one-third of the direct losses. This would result a total damage of about $28.5 bn for NYC; 17% of this damage can be attributed to damage to housing (4.7/28.5).

Damage NYC vs. NJ

The barrier strategies described in this report do not only prevent flood damage in NYC, but also in parts of New Jersey. In order to get a grip on this spatial dimension, the housing assistance data of Hurricane Sandy collected by FEMA has been used (FEMA, 2013). This database, generated 15th of February 2013, provides the number of valid registrations per zip-code, and the average damage per house as inspected by FEMA inspectors. By multiplying the average damage per house with the amount of valid registrations an indication of the total housing damage can be calculated at the zip-code level. These data have been aggregated to NYC and the parts of NJ that are protected by the various barrier strategies (Table 6.6).

From Table 6.6, the fraction of housing damage caused in parts of New Jersey as compared to NYC can be calculated. For the area protected by the barrier 2c strategy, this is roughly one-third of the damage in NYC, whereas for the area protected by the barrier 2ab strategy this is roughly one-sixth of the housing damage in NYC.

Risk NYC and parts of NJ

To allow for a comparison of costs and benefits, estimates of the flood risk of NYC and the surrounding area are needed in terms of expected annual damage (EAD). De Moel *et al.* (2013) have estimated expected annual damage related to buildings and vehicles in detail for NYC. They arrive at risk of almost $71 M/yr for NYC. Of this risk, about 41%, or $29 M/yr, is risk resulting from residential buildings. This risk estimate excludes several important factors that also constitute to the total flood risk, like the risk to infrastructure, public areas, and indirect losses. While building code strategies only reduce the flood risk to buildings (as also estimated by De Moel *et al.*, 2013), protective strategies including surge barriers and/or levees would also reduce the risk to these other factors. We've seen with the damage of Hurricane Sandy in NYC that approximately 17% of the total damage could be attributed housing. Applying this fraction of the total damage of Sandy to the residential risk estimated by De Moel *et al.* (2013), we arrive at a total risk of $174 M/yr. To include also parts of New Jersey that would be protected by barrier Strategies 2a/b and 2c, this risk can then be increased by 1/6 and 1/3, respectively, arriving at $203 and $232 M/yr.

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Appendix A. Locations of the barriers

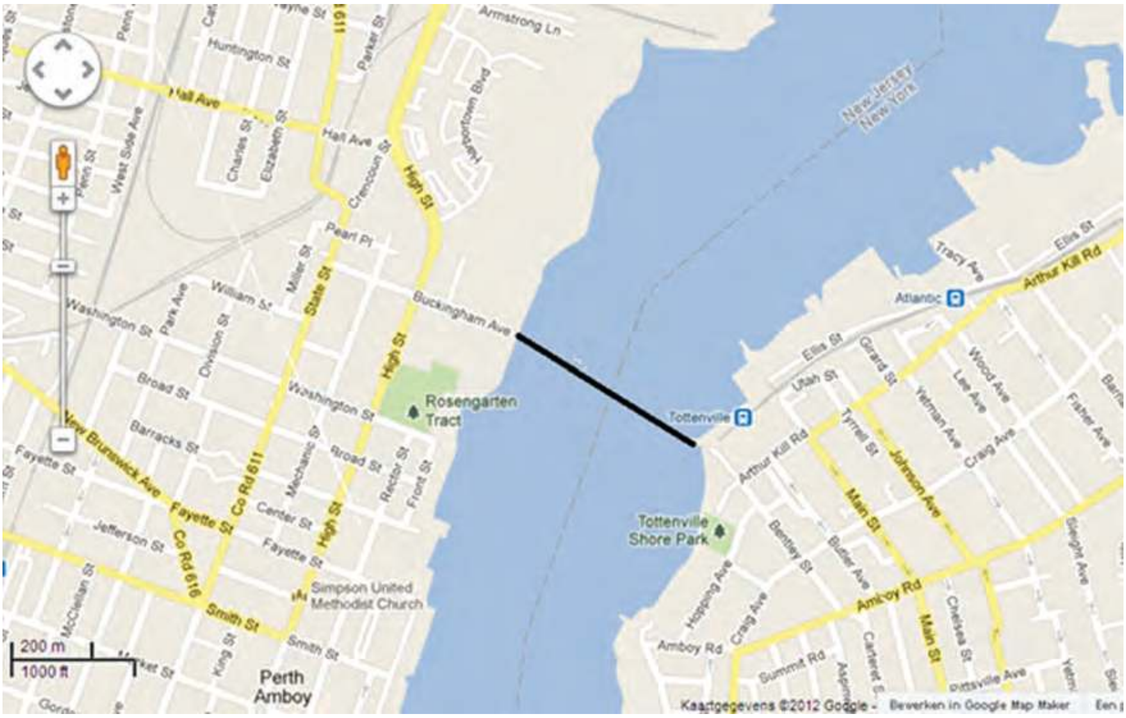

Figure A1. Possible location of the Arthur Kill barrier.

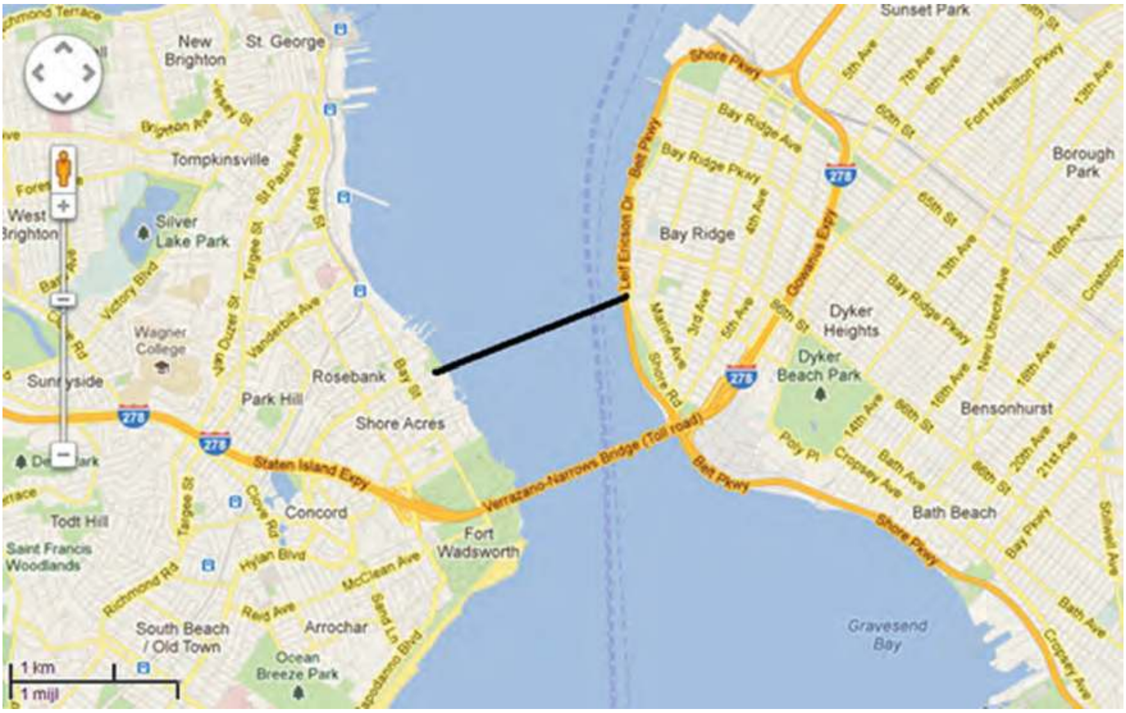

Figure A2. Possible location of the Verrazano Narrows barrier.

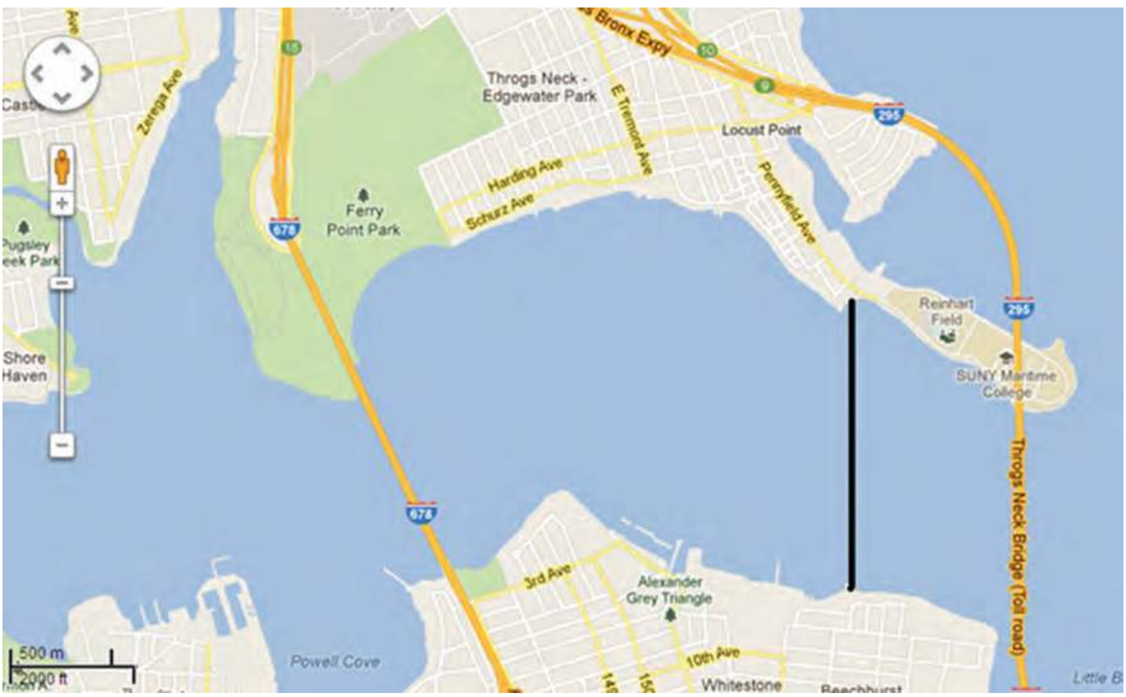

Figure A3. Possible location of the Long Island Sound Barrier.

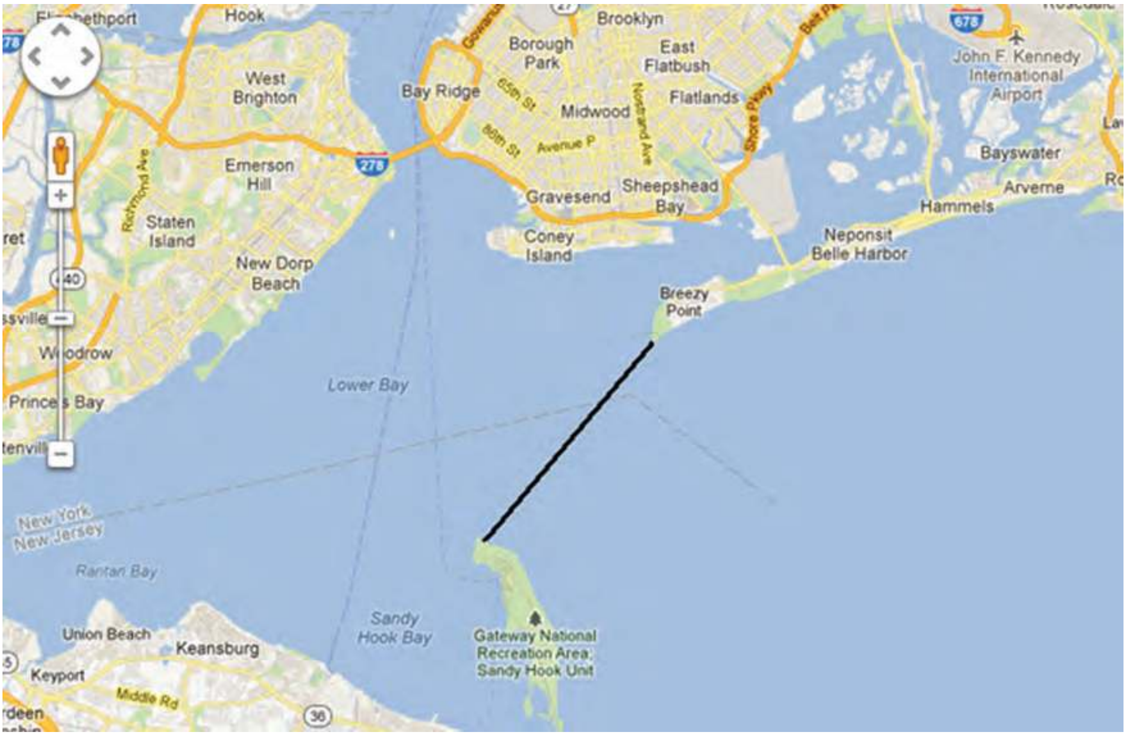

Figure A4. Possible location of the NY-NJ Outer Harbor Barrier.

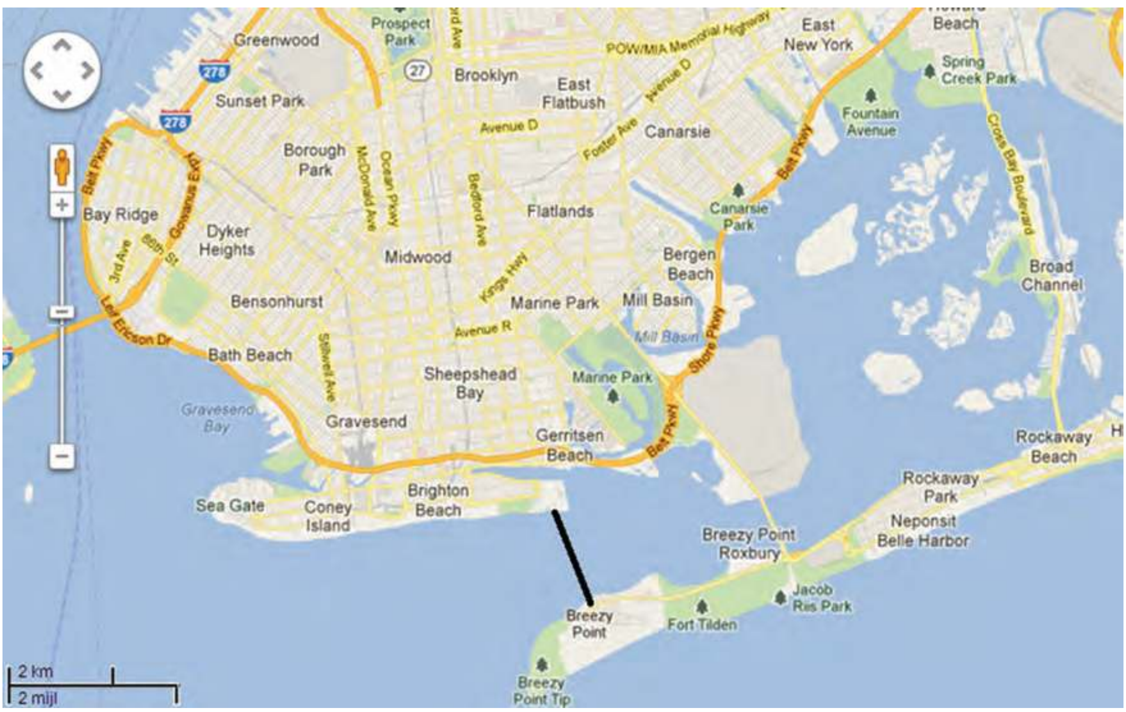

Figure A5. Possible location of the Jamaica Bay barrier.

Appendix B. Detailed cost estimates of East River Barrier

Project: East River Storm Surge Barrier 3/19/2009

Rough Order of Magnitude Cost Estimate

Description	Qty.	Unit	Unit Price	Extended Price	Totals
Dredging & Disposal-4800'x 120' wX 27' deep	576,000	CY	$ 150	$ 86,400,000	
Ground Improvement	1	Allow	$ 50,000,000	$ 50,000,000	
Gravel Base - 4800'x120' wX 5' deep	107,000	CY	$ 75	$ 8,025,000	
Cut Off Wall- 50' Deep	240,000	SF	$ 400	$ 96,000,000	
Assemble Gates Off Site: 4800'/100' w=48 Ea.					
Reinforced Conc. Slab 48 ea X100'X 70' w	336,000	SF	$ 500	$ 168,000,000	
Steel Gates & Gaskets	5,000	Ton	$ 12,000	$ 60,000,000	
Hyd. Cylinders Systems- Allow	48	Ea	$ 1,000,000	$ 48,000,000	
Preparation of Slab & Gates For Floating- Cofferdam	48	Ea	$ 400,000	$ 19,200,000	
Barge Transport & Lower Gates	48	Ea	$ 100,000	$ 4,800,000	
Tie & Secure Gate Slabs	48	Ea	$ 50,000	$ 2,400,000	
Remove Cofferdam	48	Ea	$ 200,000	$ 9,600,000	
Fill Trench/ River Bed Restoration- Gravel	160,000	CY	$ 75	$ 12,000,000	
Shore Line Site Work, Anchorage & Bulkhead	2	Allow	$ 10,000,000	$ 20,000,000	
Hyd. Oil Storage, Control & Monitoring Housing	1	Allow	$ 50,000,000	$ 50,000,000	
Test & Commision	1	Allow	$ 2,000,000	$ 2,000,000	
S/T				$ 636,425,000	
Mobilization & Staging Site	10%			$ 63,643,000	
Contractor indirect Field Cost	15%			$ 95,464,000	
Sub-Total Estimated Construction Cost- Base				$ 795,532,000	
Contingency	40%			$ 318,213,000	
Total Estimated Construction Cost					$ 1,113,745,000
Engineering	15%				$ 167,062,000
Permits	2%				$ 22,275,000
Construction Management	12%				$ 133,649,000
Authorities Admin & Engineering	5%				$ 55,687,000
Totals					$ 1,492,418,000
				say	**$ 1,500,000,000**
				to	**$ 1,700,000,000**

Figure B1. Cost estimates East River barrier (Parsons Brinckerhoff, 2009).

Appendix C. Results of the regression analysis

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-1244,813	938,889		-1,326	,210
	Head_(m)	265,870	184,755	,132	1,439	,176
	Span_movable_part_(m)	2,307	,216	,975	10,664	,000

a. Dependent Variable: cost mov parts

Figure C1. Results of the regression analysis.

Appendix D. Letter Environmental Agency UK, March 2012

Annual operations and maintenance costs are approximately £8 million a year to maintain and operate. In addition we also spend approximately £10 million on capital improvements to the defences (2008/2009 expenditure levels).

Table D1. Maintenance costs Thames Barrier, UK

Year	2006-07	2007-08	2003-09	2009-10	2010-11	5 Year Maintenance Cost
Thames Barrier Maintenance Cost	3,095,336.00	3,875,275.60	3,083,288.40	3,097,816.48	3,071,613.27	16,223,329.95

As of February 2011, the Thames Barrier has now been closed 440 times, 119 of which have been to protect London from flooding since the barrier became operational in 1982. Of the closures, 78 were for tidal surge conditions and 41 were to prevent rainfall/fluvial flooding. In addition to these, one closure was to assist with salvage work on the Marchioness and one for repair works following the Sand Kite incident. The other occasions were monthly closures, for experiments and tests.

With regard to estimates of the value of the barriers, based on the cost of damages prevented or lives saved, the Thames Estuary 2100 Report provides some information on what is at stake in the tidal estuary in its entirety. Information can be found in Chapter 1 on Page 12: http://www.environment-agency.gov.uk/research/library/consultations/106100.aspx

The following link is to the Thames Barrier information pack that can be found in the Thames Barrier website:

http://www.environment-agency.gov.uk/static/documents/Leisure/Thames_Barrier_2010_project_pack.pdf

And answers to your remaining questions can be found at the following website link; http://www.environment-agency.gov.uk/homeandleisure/floods/38353.aspx

If I can be of any further help, please contact me.

Yours sincerely

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Appendix E. Storm surge water levels with and without storm surge barriers

Table E1. Maximum Water Elevations Projected at Different Locations in New York Harbor Under Different Future Sea Level Rise Scenarios (Unit: meters) (Kim *et al.*, 2009)

	Without Storm Surge Barriers				With Storm Surge Barriers			
	Current Sea Level	2020s Sea Level Rise 9.4 cm (3.7 inch)	2050s Sea Level Rise 24.6 cm (9.7 inch)	2080s Sea Level Rise 45.2 cm (17.8 inch)	Current Sea Level	2020s Sea Level Rise 9.4 cm (3.7 inch)	2050s Sea Level Rise 24.6 cm (9.7 inch)	2080s Sea Level Rise 45.2 cm (17.8 inch)
Sandy Hook	2.85	2.94	3.10	3.31	3.06	3.16	3.31	3.53
Willets Point	2.89	3.00	3.15	3.39	3.01	3.11	3.29	3.53
Jamaica Bay	2.65	2.75	2.92	3.16	1.17	1.37	1.63	1.99
Elizabeth, NJ	2.83	2.91	3.07	3.30	1.14	1.37	1.70	2.11
Battery	2.64	2.73	2.90	3.12	1.01	1.21	1.55	1.96
Hunts Point	2.76	2.87	3.02	3.26	1.12	1.24	1.41	1.61

Appendix F. Vertical datum and NYC DEM information

Datum Conversion Chart (Elevations in Feet)			
Datum	MLW	NGVD29	NAVD88
Top of Pier	12.16	10.54	9.44
MHHW	4.88	3.26	2.16
MHW	4.51	2.89	1.79
NAVD88	2.72	1.10	0.00
NGVD29	1.62	0.00	−1.10
MLW	0.00	−1.62	−2.72
MLLW	−0.20	−1.82	−2.92

Figure F1. NYC 2010 DEM. November 2011.

This three-foot bare earth Digital Elevation Model (DEM) for New York City was produced in November 2011 from 2010 NYC LiDAR data to support the production of updated hurricane surge (SLOSH) inundation area and depth data for NYC OEM and NYS OEM. The data are in feet, referenced to NAVD 88. No additional quality assurance or control was performed on the final DEM other than that already performed on the source .las data.

NYC DoITT provided the source 2010 LiDAR (.las) tiled data which was collected from April 14 to May 1, 2010, by Sanborn and reviewed for quality assurance and control by the Center for Advanced Research of Spatial Information (CARSI) lab at CUNY Hunter College. Accuracy of the source LiDAR data: 9.24 cm RMSE vertical accuracy, 33 cm horizontal accuracy, and 8–12 points per square meter point density.

The U.S. Army Corps' CRREL (Cold Regions Research and Engineering Laboratory) in Hanover, New Hampshire, produced this data at the request of the USACE New England District to meet the hurricane SLOSH data production schedule. Only class 2 (bare earth) points from the source .las tiles were used for production. No additional quality assurance or control was performed on the final DEM other than that already performed on the source .las data.

Appendix G. Jamaica Bay surge height simulations

TABLE I - EFFECTS OF BARRIERS ON HURRICANE TIDES

A - DIMENSIONS OF BARRIER OPENINGS FOR SURGE TESTS

	Ungated Opening [a]			Gated Openings [a,b]			Total Opening
Plan No	Width (FT)	Depth at MSL (FT)	Area Below MSL (SQ FT)	No of Gates	Depth at MSL (FT)	Area Below MSL (SQ FT)	Area [a] of Openings Below MSL (SQ FT)
Base	3,700	--	117,750	--	--	--	117,750
6	110	33	3,630	16	26	31,200	34,830
8	150	23	3,450	16	26	31,200	34,650
7	150	26	3,900	16	26	31,200	35,100
9	200	23	4,600	16	26	31,200	35,800
3	300	33	9,900	12	26	23,400	33,300

a - MSL = mean sea level b - all gates 75 feet wide

B - MAXIMUM BAY LEVELS FOR PLANS 3 AND 6 (FT MSL)

	1950 Surge			Standard Project Hurricane(SPH)		
Location	Without Barrier	With Barrier		Without Barrier	With Barrier	
		Plan 3	Plan 6		Plan 3	Plan 6
OUTSIDE BARRIER						
Fort Hamilton	8 2	8 1	8 2	12 3	12 3	12 3
Parkway West	8 2	8 0	8 3	11 7	11 6	11 6
INSIDE BARRIER						
Parkway East	8 3	6 6	4 8	11 0	4 6	2 6
Canarsie	8 3	6 7	5 0	11 3	4 8	2 9
Grassy Bay	8 4	6 7	5 0	11 3	4 8	2 8
Rosie's Boats	8 3	6 6	5 0	11 3	4 9	2 8

Figure G1. Jamaica Bay surge calculations by Panuzio, F. L (1976).

Appendix H. Expert interviews

Name specialist	Company	Subject
Piet Dircke	Arcadis	Verrazano barrier
Hessel Voortman	Arcadis	Verrazano barrier
Graeme Forsyth	Halcrow	Outer Harbor Barrier
Mike Abrahams,	Parsons Brinckerhoff	East River Barrier
Phil Girandola	Parsons Brinckerhoff	East River Barrier
John Taylor	Parsons Brinckerhoff	East River Barrier
John Clifford	Perkins Eastman	Building code & flood proofing
Joseph Ackroyd	NYC-DOB	Building code & flood proofing
James Colgate	NYC-DOB	Building code & flood proofing
Sean Woodroffe	Karl Fischer Architecture	Building code & flood proofing

Appendix I. Shoreline typology and associated flood management measures

Table I1. Based on draft methodology by Mary Kymball, NYC-DCP, 2012

	Land use/density						
	High-density Mixed Use	Mid-density Residential/ Commercial	Mid-density Commercial/ Industrial	Mid-density Residential/ Industrial	Mid-density Residential	Low-density Residential	Low-density Industrial/ Commercial
Geomorphology							
Rocky bluffs on sheltered waters				*North Shore Staten Island*	*Upper Manhattan and the Bronx*		*West Shore Staten Island*
Sandy bluffs on sheltered waters				*Randalls Island*	*Throggs Neck, City Island*	*South Shore Staten Island*	
Oceanfront barrier beaches		*Coney Island*			*Far Rockaway*	*Breezy Point, Sea Gate*	
Marshes on sheltered waters							
Hardened Bays and straits	*Lower Manhattan*	*East Harlem*	*South Bronx, Sunset Park*	*DUMBO, Long Island City*			
Canals and small rivers				*Gowanus, Newtown Creek*	*Bronx River*		
Geomorphology							
Rocky bluffs on sheltered waters				Floodwall	Land fill/floodwall		Floodwall
Sandy bluffs on sheltered waters				Floodwall	Flood proofing	Nourishment/ hidden levee/	
Oceanfront barrier beaches		Nourishment/build up levee/			Nourishment/ hidden levee/	Nourishment/ hidden levee/	
Marshes on sheltered waters							
Hardened Bays and straits	Land fill /Elevate highway	Floodwall/Elevate highway	Floodwall/Elevate highway	Levee/Land fill			
Canals and small rivers				Small barrier	Floodwall/levee		

Appendix J. Preliminary damage estimates by Hurricane Sandy

Adapted from Zandi (http://www.moodys.com/Pages/Hurricane-Sandy.aspx?WT.mc_id=home_banner_sandy).

Table J1. Overview of preliminary damage estimates by Hurricane Sandy for the US East Coast (adapted from Zandi, 2012)

Lost Output	$ bn	Damages	$ bn
Transportation/utilities	0.7	Households	11.0
Retail	0.2	Housing	10.5
Prof./business services	4.6	Vehicles	0.5
Information	1.8	Businesses	10.0
Financial activities	7.0	Infrastructure	9.0
Education/healthcare	1.7		
Leisure/hospitality	0.9		
Other services	0.5		
Government	2.6		
Total net loss	**19.9**	**Total**	**30.0**

Table J2. Overview of economic indicators for the region affected by Sandy

Region	Nominal GDP, bil $	Employment, ths	Households, ths	Value of housing stock, mil $	Average household income, ths	Unemployment rate, %
Bridgeport	65.5	416.7	340.3	86,452.7	211.3	8.1
New York City	1,217.6	8,525.0	6,973.3	1,332,910.3	159.5	9.3
New Jersey ex New York City	53.9	483.9	329.9	228,960.5	483.3	11.4
Philadelphia	325.0	2,711.5	2,280.4	396,970.1	130.9	8.8
Washington	416.6	3,036.3	2,145.9	533,994.3	162.5	5.6
Total of all regions	2,078.6	15,173.4	12,069.8	2,579,287.9	229.5	8.5
US	15,775.7	133,376.7	119,736.4	16,079,067.0	112.3	8.1
% of US	13.2	11.4	10.1	16.0	NA	NA

Appendix K. Land cover hit by Sandy inundation per county in NJ and NYC (in km^2)

	Open Water	Developed Open	Developed low intensity	Developed medium intensity	Developed high intensity	Barren land	Deciduous forest	Evergreen forest	mixed forest	Shrub/ Scrub	Herbaceuous	Hay/ pasture	Cultivated crops	Woody wetlands	Emergent herbaceuous wetlands		
StatenIsland	2.7	4.0	5.5	3.7	2.4	1.5	1.8	0.0	0.0	0.0	0.0	0.3	3.2	6.1	4.6	0.0	0.0
Brookyn	1.7	1.0	1.7	6.1	12.7	0.5	0.4	0.0	0.0	1.1	0.2	0.0	0.0	0.0	1.2	0.0	0.0
Queens	4.3	3.3	6.9	15.5	24.3	2.1	1.0	0.0	0.1	1.8	0.4	0.0	0.0	0.8	5.9	0.0	0.0
Manhattan	20.1	0.7	1.4	3.0	5.4	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0
Bronx	0.6	0.9	1.6	3.1	3.0	0.1	0.3	0.0	0.0	0.5	0.2	0.1	0.0	0.1	1.5	0.0	0.0
Bergen	0.1	0.4	0.5	0.8	0.5	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0
Hudson	37.1	4.9	14.2	25.7	30.0	0.1	0.4	0.0	0.0	0.3	0.0	0.3	0.1	17.2	4.1	0.0	0.0
Essex	0.3	0.4	1.3	6.3	8.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0
Union	0.9	1.6	3.5	5.9	3.7	0.2	0.2	0.0	0.0	0.0	0.0	0.1	0.7	0.7	1.8	0.0	0.0
Middlesex	9.3	4.6	6.3	5.9	2.5	0.6	4.2	0.2	0.1	0.0	0.0	0.3	6.9	11.1	5.6	0.0	0.0
Monmouth	13.6	3.2	6.6	5.2	0.9	3.7	1.1	0.6	0.0	0.0	0.0	0.6	2.3	4.2	4.8	0.0	0.0
NYC	29.5	9.8	17.1	31.4	47.9	4.2	3.6	0.0	0.2	3.5	0.8	0.4	3.2	7.0	14.7	0.0	0.0
NJ	61.2	15.1	32.4	49.9	45.6	4.8	6.0	0.9	0.1	0.3	0.0	1.3	10.1	33.5	16.4	0.0	0.0
NJ/NYC ratio		1.54	1.89	1.59	0.95												
NJ/NYC ratio urban		**1.33**															

Appendix L. Cost estimates for Hybrid Strategy 1c.

The total cost for Strategy 1c are depicted in Table L1. Only free board building code levels (maximum +4 ft) for new buildings are required in the 1/100 A zone ($154 mln). Higher freeboard levels for new buildings (maximum +6 ft) will be applied in the 1/100 V zone ($4.6 mln). These building codes only pertain to new structures the 1/100 flood zone and not the 1/500 flood zone. In addition, we apply wet flood proofing of +2 ft to existing buildings in the 1/100 A zones ($384 mln). The total building code costs for S1c is $542 mln.

For the additional no regret protection measures, we take the low range of unit cost in Table 6.2 of $10-$20 mln/km for a total length of 80 km of coastline (80 * 10–20 = $0.8–$1.6 bn), since the protection measures do not yet have to meet the extreme 25–30 ft design water levels. Only the coastlines of Rockaways and Sandy Hook will be protected to a design water level of 25–30 ft ($0.8–1.2 bn, see Table 7.2), since these areas lie outside the protection of any barrier strategy. Local scale infrastructure enhancement of $0.3 bn will be limited to those locations where levees are too costly (e.g. low urban density areas in the Bronx and Staten Island). As in the barriers strategies, the marshlands in Jamaica Bay, finally, will be strengthened to prevent erosion. Maintenance costs, finally, are estimated on $13.5 mln/yr, the same as the costs for all protection costs in the Strategy 2c

Table L1. Overall costs for Strategy 1c, Resilient Open City: A Hybrid Solution (all in $2012 values)

Measure type	Costs	Description
Building code 1/100 flood zone	$0.4 bn	This is the cost range of upgrading buildings in 1/100 areas. This cost range is lower than Strategy 1a, since (1) buildings in the 1/500 flood zone are not considered and (2) parts of the flood zones are protected by levees
Moderate Protection Manhattan, the Bronx, Brooklyn /Red Hook	$0.8 – $1.6 bn	These measures include: Retrofit low bulkheads, (e.g. Brooklyn, Manhattan); Mix Levee/landfill (e.g. retrofit FDR drive Manhattan,).
Beach strengthening Rockaways	$0.8-$1.2 bn	Beach Nourishment (e.g. Rockaways).
Local scale infrastructure enhancements	$0.3 bn	Only to infrastructure objects in low urban density areas in the Bronx and Staten Island
Env. measurement Jamaica Bay	$0.9 bn	Marshland stabilizing through nourishments
Infrastructure	$3.2 bn	Costs of adaptation measures are estimated at only 50% of the infrastructure costs in Strategy 1b, since additional protection measures in Manhattan, Brooklyn and the Rockaways will protect infrastructure
Total	**$6.4 – $7.6 bn**	
Total adaptation costs NJ	***$4 bn*** [1]	
Grant Total (NJ-NYC) *Strategy 1c A Hybrid Solution*	***$10.4 – 11.6 bn***	

All summary cost tables are in US$ 2012 values. Indexing was applied using the Construction Cost Index from ENR (Engineering News-Record, http://enr.construction.com/economics). The CCI annual escalation rate was set to 2.4%, on May 2nd 2013.