Feasibility Analysis and Design of a Flood Barrier Concept for The City of New York

by

Demetres Ingilis

Bachelor of Engineering in Civil Engineering
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Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

Flooding has always been a major concern for coastal communities. However, many parts of New York City never had to worry about flooding until Hurricane Sandy hit in October 2012. The hurricane brought a record level storm surge, which destroyed homes, cut power to millions of people and caused a total of $19 billion in damage. The storm surge exposed the City's critical lack of infrastructure and gave the City a major reason to address this problem. Based on projected sea level rise, floods will become more frequent and will cause regular damage to New York City. There are various ways to protect against storm surge, ranging from local barriers in each community to citywide barriers. This study addresses the feasibility and design of a two-barrier system to protect most of the City. A design is proposed where the barriers are walls with a single gate to allow ships to navigate in and out. One barrier, located under the Bronx-Whitestone Bridge, seals the City off from the Long Island Sound, which utilizes a vertical flap gate. The other barrier spans between Sandy Hook and Breezy Point utilizes a horizontally rotating arch gate. A life-cycle benefit analysis was performed to determine the time for a barrier of each height to start providing a return on investment considering upper and lower bounds on the initial construction cost. The quickest benefit occurred in just 36.66 years for a wall height of 15 feet and in just 17.32 years for a wall height of 15.5 feet for the upper and lower bounds, respectively. The chosen height for the barriers was 20 feet which required a maximum of only 1.83 additional years to provide a return on investment while protecting the City against 99.5% of all future storm surges.

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1. INTRODUCTION

1.1 FLOODING EVENTS

Flooding, otherwise known as inundation, is the most common form of damage to the built environment in the United States. Floods vary in size and type and can be caused by a variety of different sources. Common causes of inundation are failed dams or levees, heavy rains, fires (which damage the water retention capacity of soil), snowmelt, and storms. These can be confined to local neighborhoods or they can affect multiple states simultaneously. Additionally, floods can occur over the course of a few minutes (i.e. flash floods) or over a few hours.

There are various types of storms that can cause flooding. They range from the typical heavy downpour to the occasionally occurring hurricane, tropical storm, monsoon, etc. The winds from these storms can create destructive wave damage and any objects picked up by the waves can be used to batter anything in their way. Furthermore, these winds raise the mean water level, making it easier for water to overtop coastal barriers and flood the area. This combination of increased mean water level and stronger wave action is called storm surge.

1.2 STORM SURGE

Before different possibilities of storm surge barriers can be examined, an understanding of storm surges and their causes is necessary. A storm surge is an abnormal rise of water generated by a storm. This rise in water level is unrelated to astronomical tide. Figure 1 shows a typical storm surge due to a hurricane.

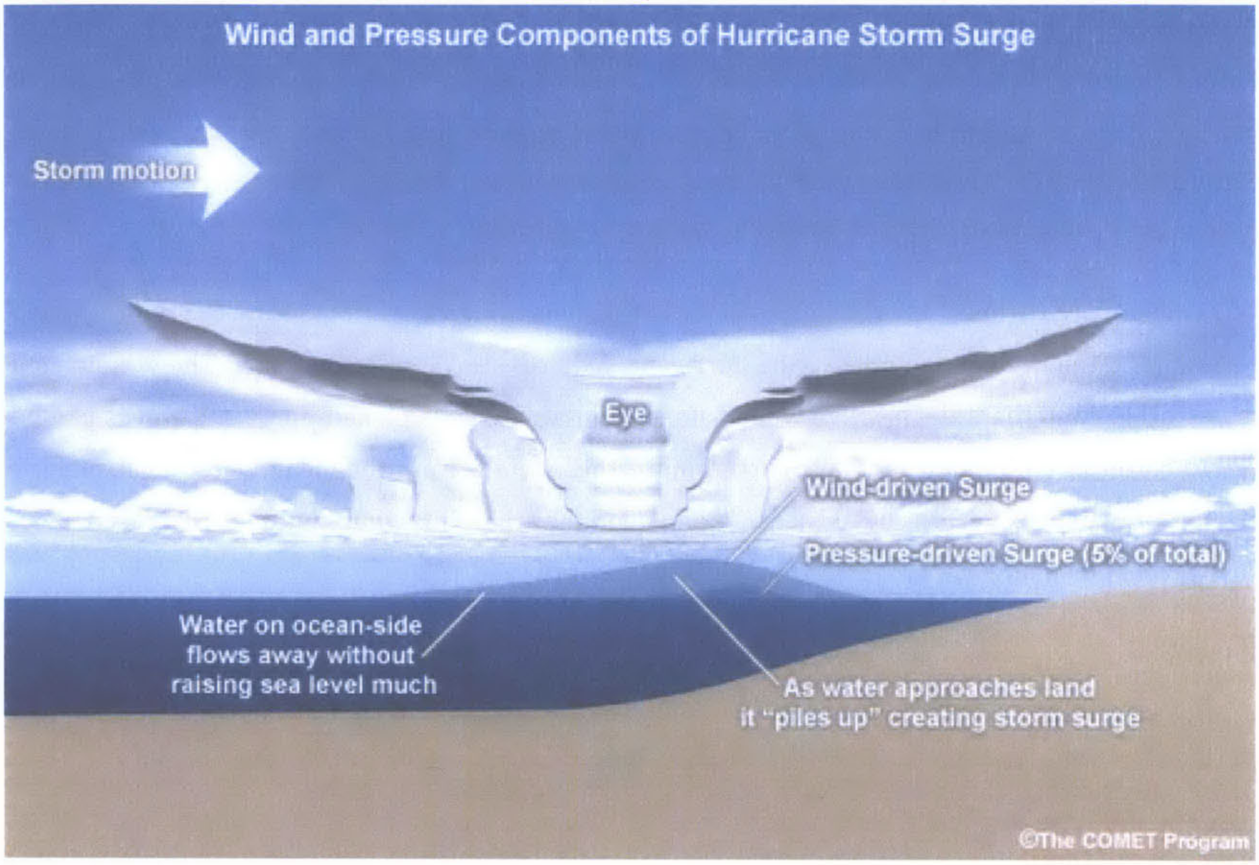


FIGURE 1: TYPICAL STORM SURGE (NOAA, N.D.)

As shown in Figure 1, storm surge is produced by water being pushed toward the shore by the force of the winds moving cyclonically around the storm. In addition, a storm surge is also produced due to the low pressure associated with these types of storms. However, the surge created by the air pressure makes up only about 5% of the total surge, where the remaining 95% is due to the wind.

The maximum potential storm surge for a particular location depends on a number of different factors, such as storm intensity (i.e. tropical storm, Category 1-5), forward speed of hurricane (the speed at which the eye displaces), size (radius of extreme winds), angle of approach to the coast, central pressure and various coastal features including bays, estuaries and slope of the shoreline. Since storm surge is a very complex phenomenon, a slight change in any of the above factors can significantly affect the height of the storm surge. For example, a steep sloping continental shelf will potentially produce a smaller storm surge than a shallow slope. A Category 4 storm hitting the Louisiana coastline, which has a very wide and shallow continental shelf, may produce a 20 foot storm surge, while the same hurricane in a place such as Miami Beach, Florida, where the continental shelf drops off very quickly, might see an 8 or 9 foot surge (NOAA/ National Weather Service, 2013). It is difficult to predict the time of arrival, and that makes it impossible to know if high tide or low tide will be contributing to the height of the surge or detracting from it. It is also difficult to know the wind speed at the time of landfall, how much water will be contributed by rainfall, the exact location of landfall and how topography will influence the movement of water.

One cause of the destructive power of waves is the weight density of the water. Since water weighs approximately 1682 pounds per cubic yard, excessive battering by waves will destroy any structure in their path that is not built to withstand this force. This combination of storm surge and battering waves work to increase the impact on land because the storm surge provides the waves with the opportunity to extend inland. Additionally, currents created by tides combine with the waves to severely erode beaches, coastal highways and foundations of buildings.

Storm surge can make landfall up to five hours before a hurricane makes landfall. It can also take place after a hurricane has moved away from the area. For example, as Hurricane Sandy made landfall and continued west, the high seas in the Atlantic Ocean slumped back into confined spaces like the Long Island Sound.

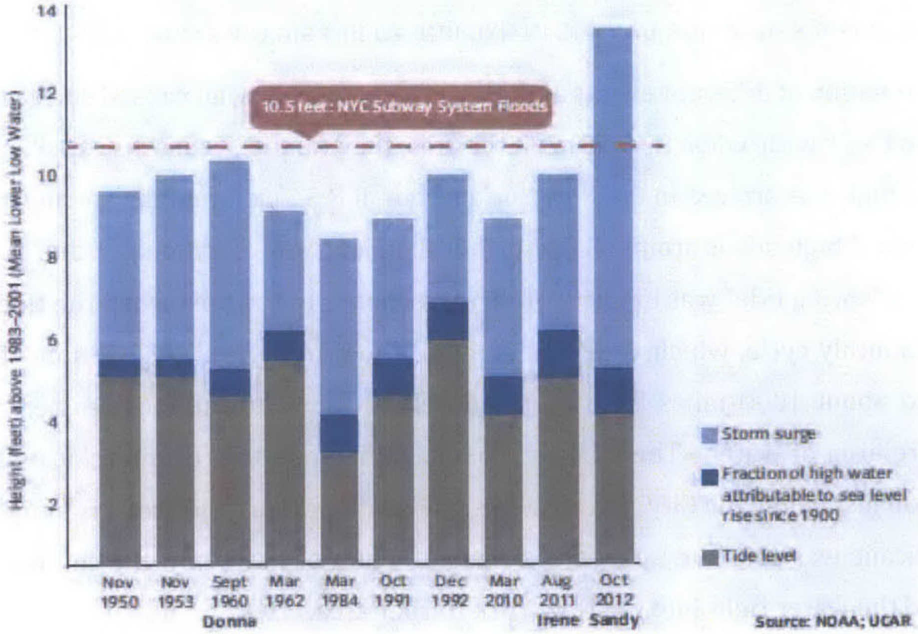
Storm surge may have an ecological impact on an area as well. In estuaries and bayous, the influx of salt water from the ocean due to storm surge can endanger public health, destroy vegetation and can destroy animal habitats.

To get an idea of how devastating a major storm surge could be, the United States Department of Transportation released a study on the effect of a sea level rise of 2-4ft due to climate change (Savonis, et al., 2008). The data provided certainly applies to a possible storm surge as well, because this additional water height, although a permanent rise in water level, can be the difference between staying dry or flooding, if barriers are built in accordance with present day water levels. The report stated that the population density has increased by 32% in counties along the Gulf Coast, 17% in counties along the Atlantic coast and 16% in Hawaii. Much of the United States' densely populated Atlantic and Gulf Coast coastlines lie less than 10 feet above the mean sea level. Over half of the nation's economic productivity is located within coastal zones. 72% of ports, 27% of major roads and 9% of all rail lines within the Gulf Coast region are at or below 4ft elevation. A storm surge of 23ft has the ability to inundate 67% of interstates, 57% of arterials, almost half of the rail track, 29 airports and almost all ports in the Gulf Coast Area.

1.3 FLOODING OF NEW YORK CITY

In light of a recent tragedy that struck New York City and New Jersey on October 29, 2012, a realization came about that measures need to be taken to prevent this kind of disaster from ever striking the area again. Hurricane Sandy was the second costliest hurricane to strike the Eastern Seaboard following Hurricane Katrina, causing $50 billion worth of damage. Its storm surge struck the City and as a result, flooded streets, tunnels, subway lines and cut power to 1.3 million customers for almost a week. New York City public schools were closed for the entire week and the New York Stock Exchange was closed for two consecutive days for weather related purposes for the first time since the Great Blizzard of 1888. Additionally, even six days after the hurricane, the US Energy Information Administration reported that approximately 67% of gas stations in metropolitan New York still did not have gas for sale.

The East River over-flooded its banks causing flooding in Lower Manhattan. Battery Park experienced a record storm surge of 13.88 feet. Other high water events can be found in Figure 2. Large parts of Brooklyn were also flooded such as Brighton Beach, Coney Island, and Sheepshead Bay. The Far Rockaways experienced large amounts of flooding and a severe fire that burned at least 110 houses to the ground (CNN, 2013). However, none of these areas were impacted as greatly as Staten Island. Parts of South Beach and Tottenville were completed destroyed, with many houses deemed unlivable by the Department of Buildings. These locations are shown in Figure 3.



Source: NOAA; UCAR

FIGURE 2: HIGH-WATER EVENTS IN LOWER MANHATTAN (PLANYC, 2013)

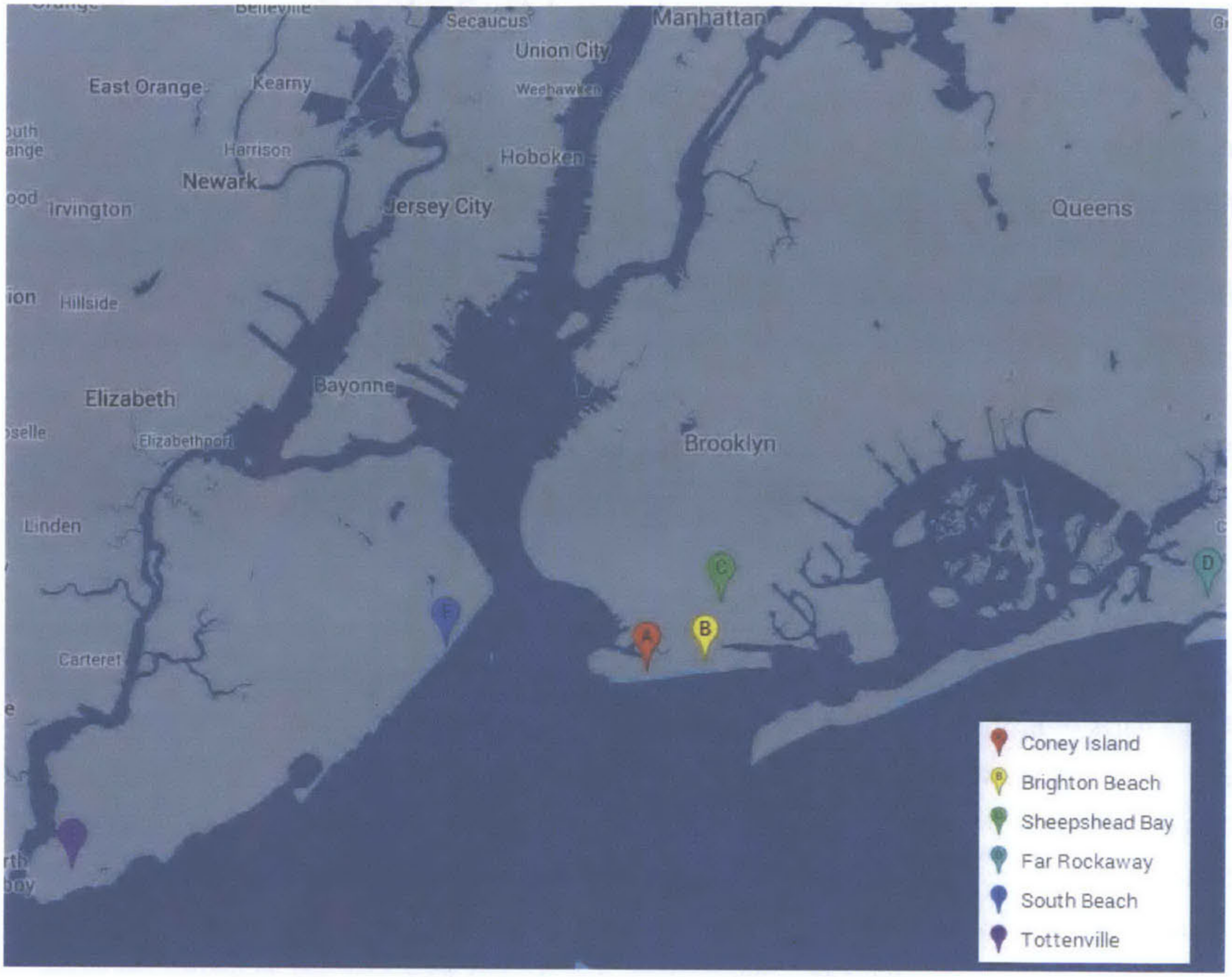


FIGURE 3: LOCATIONS OF MAJOR DAMAGE IN NYC DUE TO HURRICANE SANDY (GOOGLE MAPS, 2014)

A combination of different events at the exact same time is what caused such a massive effect on the area. To begin with, when the storm hit the area, the Atlantic Ocean was experiencing its usual high tide. This high tide arrived in the New York harbor at 8:54 p.m., and the storm surge peaked at 9:24 p.m. A typical high tide is around 5 feet higher than low tide. Additionally, due to the full moon out that night, a "spring tide" was in effect. This corresponds to the time when the tide is at its peak for a typical monthly cycle, which added an extra half foot to the water elevation. The hurricane winds covered about 1000 miles from its most western point to the most eastern point, which displaced more area of water. The damage was magnified due to a counterclockwise spin and a landfall location just below the City. Because this is a location where the ocean is situated east of the land, the hurricane was able to do its worst damage. Figure 4 shows how the combination of these factors pushed the water right into the New York Harbor area.

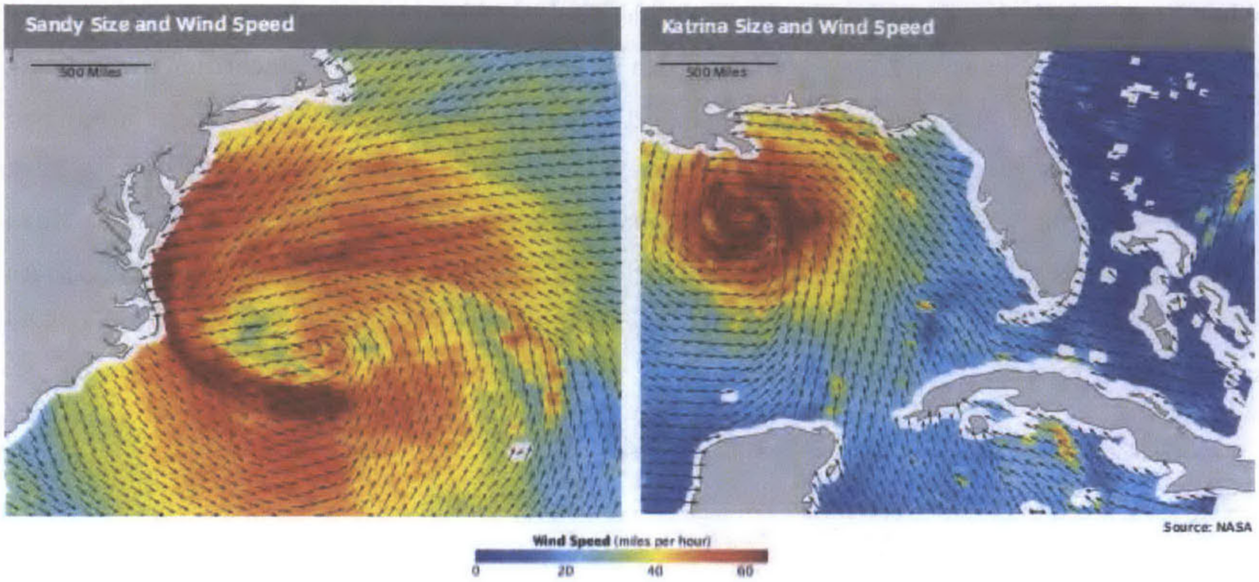


FIGURE 4: COMPARISON OF HURRICANES SANDY AND KATRINA ON SIZE AND WIND SPEED (PLANYC, 2013)

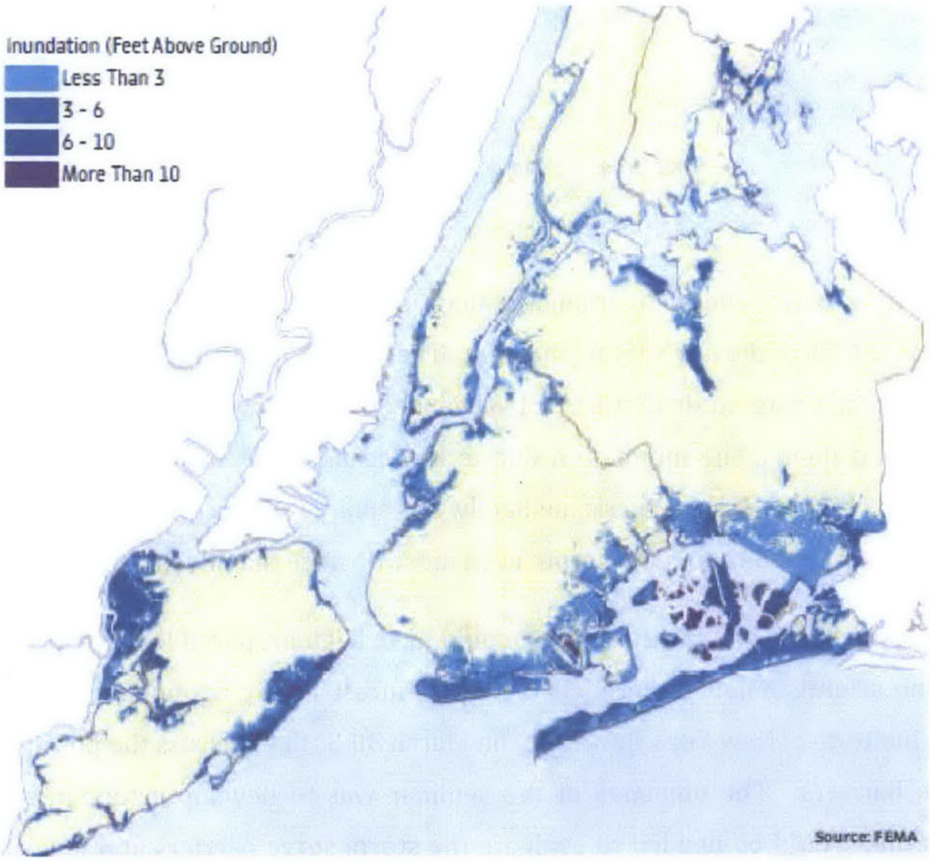


FIGURE 5: INUNDATION DUE TO HURRICANE SANDY (PLANYC, 2013)

While this combination wreaked havoc in the southern areas of New York City, the northern areas did not flood as badly as they could have. This is again attributed to the tidal level of the ocean.

When New York Harbor was experiencing high tide, the Long Island Sound was experiencing its low tide. Therefore, the peak water level did not reach its largest possible value. According to modeling undertaken by the storm surge research team at the Stevens Institute of Technology, if Sandy had arrived earlier— when it was high tide in western Long Island Sound rather than in New York Harbor—the peak water level in the western Sound could have reached almost 18 feet above Mean Lower Low Water, or MLLW. The observed height was 14 feet above MLLW (PlaNYC, 2013). An actual versus hypothetical tidal timing graph of the western portion of the Long Island Sound can be seen in Figure 6.

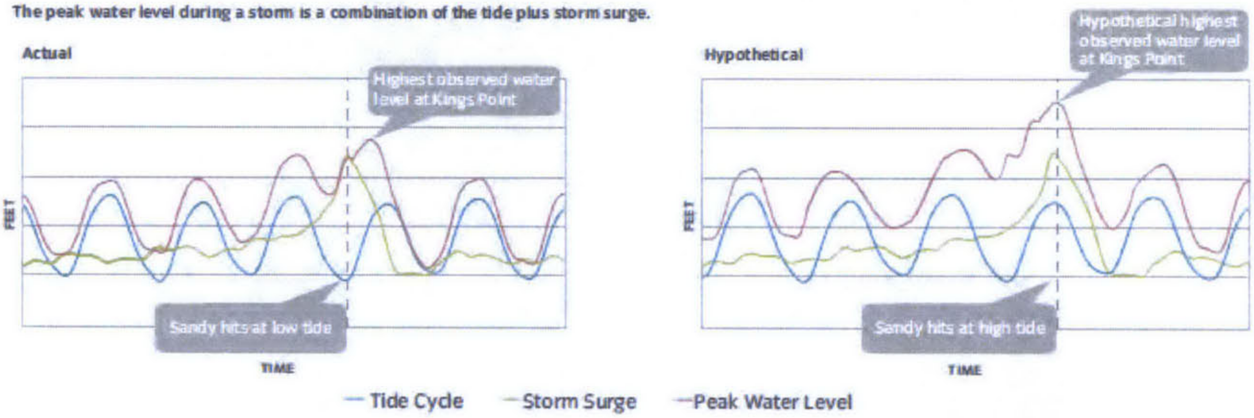

The peak water level during a storm is a combination of the tide plus storm surge.

FIGURE 6: WESTERN LONG ISLAND SOUND TIDAL LEVELS DURING HURRICANE SANDY (PLANYC, 2013)

According to the Federal Emergency Management Agency (FEMA), 51 square miles of the City flooded. That is 17% of the city's total land area. The agency also stated that if a 100 year storm hit the city, a storm of a magnitude that has a 1% chance of occurring every year, only 33 square miles of the city would flood. The inundation due to Hurricane Sandy can be seen in Figure 5, on the previous page. This shows that Hurricane Sandy was a very rare occurrence, which under the right conditions and circumstances, could create even more damage than it was originally intended to.

Hurricane Sandy was a disaster that could have been prepared for. For instance, a group of engineers and scientists had gathered at the 2009 Infrastructure Group Seminar that was held at Polytechnic Institute of New York University on March 30-31th to discuss the possible installment of storm surge barriers. The objective of the seminar was to develop a fundamental base of the information that would be needed to evaluate the storm surge barriers and lead the way to their future development (ASCE, 2009).

2. LITERATURE REVIEW

2.1 STORM SURGE BARRIERS

Storm surge barriers have many functions other than the literal translation of the name. Although the primary function is storm surge protection, many of these barriers must also contain passageways for ships and may need to manage discharge of water and tidal flow. The barriers have an extensive amount of requirements and functional demands. They are required to possess a wet cross section to aid in regulating tidal flow and river discharge. They must prevent water from overtopping or leaking past the barrier. The risk of failure, both structurally and for closure, must be minimized and they must be designed and constructed to have a minimum impact on the environment. During construction, sufficient flow and navigation must be maintained so existing conditions are not greatly affected. The barriers are designed to withstand a certain flow rate and wave conditions. They must be suitable for the required water depth and reverse head and must be able to withstand wind, flow or wave induced vibrations or oscillations. The vulnerability to impact of heavy objects such as barges must be minimized as well as the vulnerability to vandalism. In the case where the water is used for passageway of ships, clearance height and width of span for ships must be adequate. All systems and materials must be readily accessible for inspections and maintenance and the choice of such materials must provide minimal maintenance. Overall, the relevant aspects that are kept in mind when designing these systems are maintainability, reliability, environmental impact, aesthetic landscape, impact on water systems and ease of construction. In order for these systems to succeed, these aspects must be incorporated into every feature in the design (Hill, et al., 2012).

2.1.1 TYPES OF FLOOD BARRIERS

There are various types of navigable storm surge gates that exist around the world such as the mitre gate, also known as the double-leaf gate, the vertical lifting gates, flap gates, etc. Figure 7 shows a schematic drawing of each gate and its basic functional mechanism.

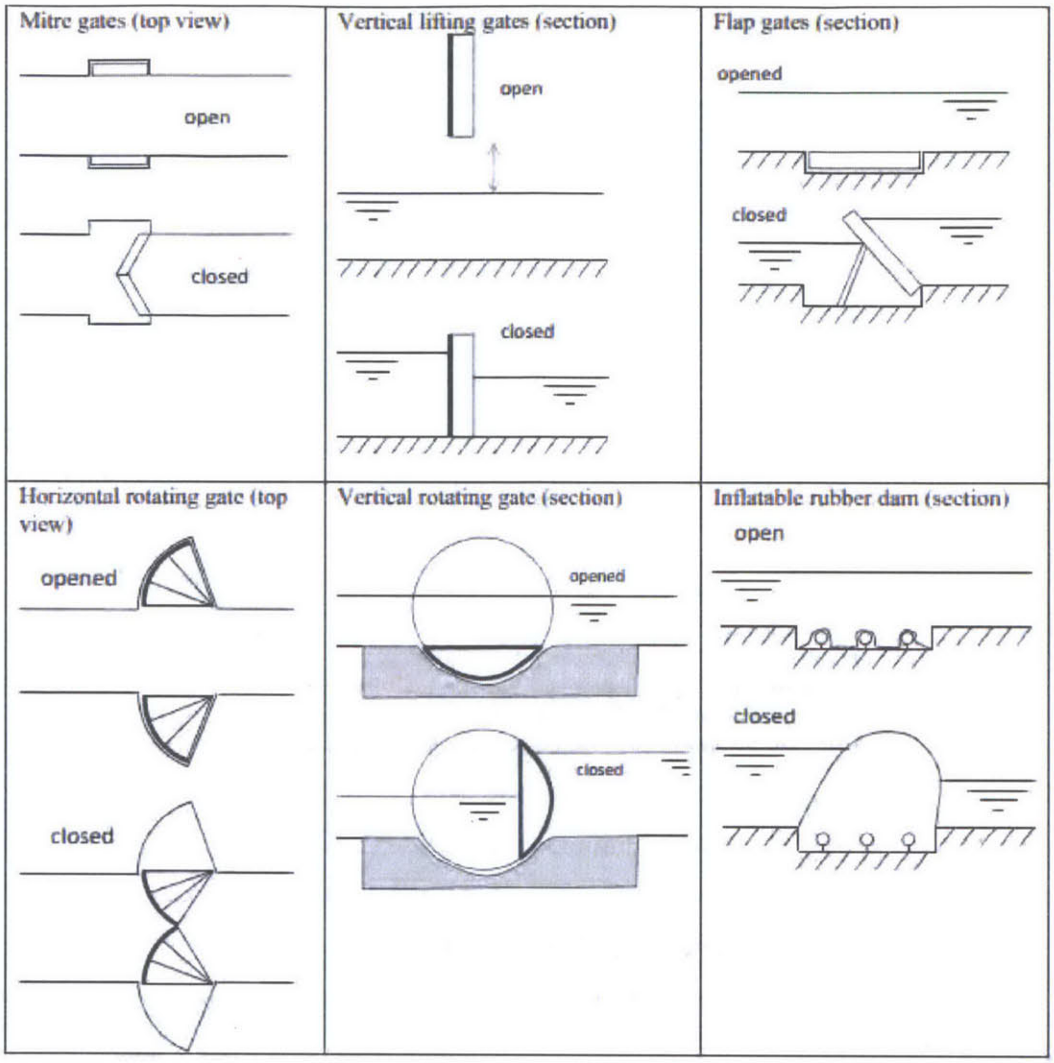


FIGURE 7: VARIOUS TYPES OF FLOODGATES (DIRCKE, ET AL., 2012)

The mitre gate barriers are often used in locks or canals. Although these gates are typically used for navigation locks rather than flood control, they are used in Goole, England to prevent the harbor draining if the canal walls collapse. These gates are only used when the water is equal on both sides of the gate. The gate has two hinged structures that are hinged like doors on either side of the channel. The two leaves meet at a 30 degree angle and rely on the mitreing action to span the opening (International Navigation Association, 2006). The favorable structural aspects of such a barrier are that there is an unlimited clearance height for ships, little space is required for the installation, it has already been proven to work, and it is very resistant to wind, which can be a major contributing factor during hurricanes. On the other side, it has a limited gate span of only up to 100 feet which might not suffice for some of the ships trying to pass through and there is little or no use for this structure in bodies of water where flow or waves are present, because of its sensitivity to vibrations (Hill, et al., 2012). A hydraulic advantage to this barrier is the ability of horizontal closure and the ability to discharge any excess water travelling through the gate.

Another type of storm surge barrier is the vertical lifting gate storm surge barrier. This type of gate is widely used and has reported satisfactory results. Since it is so widespread, there is an abundance of readily accessible knowledge on the construction techniques and the functionality and behavior under flow and wave conditions. Lifting gates are not the most aesthetic choice for storm barriers, however. The towers that raise and lower the gates, along with their foundations, are constructed within cofferdams, while concrete ridges are floated in and immersed on a gravel base or pile foundation that is located underwater. The bed adjacent to the sills, or ridges, and the towers should be riprap protected. The structural advantages are that there is a large gate span (up to 300 feet) allowing large ships to pass through while requiring little space to install. The raised gate is accessible for maintenance. Structural disadvantages include limited height clearance for ships. Since this is a vertical raising gate, when the barrier is in use, the gate is lowered into the water which prevents any ships from passing through and when the barrier is not in use, the gate is raised, providing limited clearance height. When the gate is raised, it is susceptible to wind load and therefore must be sufficiently designed to withstand wind and wave loads. When the gate is lowered, the underside needs to be free of silt. Designers must also consider water depth versus gate height because the water level may vary. The gate must have a tall enough height to protect from storm surges when the water rises, while making contact with the seafloor. Some hydraulic advantages include vertical closure, which is preferred because of the little space it requires, the ability to discharge excess water and the ability to overflow and reverse flow. When using this system, there is limited vertical flow forces and wave loads that need to be accounted for. However, the vertical gates are sensitive to vibrations and there is little stiffness during operation. The way the vertical lifting barrier works is that there are sliding gates that are driven by hydraulic cylinders with a long piston, which are hinged to the side towers. The gates are arc shaped and the retaining plate, located at the high water side, is connected to the truss girders. When not in use, the clearance height between the mean water level and the gate underside should be at least 50 feet, which requires very tall towers. A floating beam across the canal protects the barrier from ship collisions. During extreme storm conditions, the water level on the high side may rise above the top of the gates which will result in overflow of water through the gates. However, even if the gates overflow, they will still reduce the storm surge, assuming the surge dies down quickly after overtopping the gate, not giving the water behind the gate enough time to rise to the surge height (Dircke, et al., 2012).

Flap gates are another alternative for storm surge barriers. Flap gates are not visible when the barrier is in not in use. When the barriers are not being used, they are stored in a bottom recess with one end hinged to the sill. The gate rotates about the hinge, the barrier is put in operation, and the free end emerges above the water surface. There are two types of flap gates: gates driven by hydraulic cylinders and pneumatic gates operated by air injection into floatation tanks. Flap gates are not typically used in flood protection schemes mainly because inspection, maintenance and replacement can be very difficult in addition to silting at the gate recess, which can create technical issues. However, this alternative has advantages: the invisibility of the barrier (when it is not in use), the distribution of the load on the foundation (because this system is continuous along its length), and the unlimited extent of the flow opening. Other advantages include the lack of limitation in the span. Therefore, boats of any size can sail through without clearance height restrictions. Since there are separate flaps there is a reduction in the risk of total failure. However, the failure of one section can compromise the entire purpose of this barrier by allowing water to pass through to the other side at this point of failure. Although this is true for any barrier design, the many mechanisms in this flap gate design provide a larger chance of failure. To combat this, larger span flaps will reduce the number of flaps, which will, in turn, reduce the chance of failure. Other disadvantages include the large mass of the barrier and the small stiffness. Since the barrier is submerged in water, it is susceptible to corrosion; sand may wear out the hinges. Additionally, this system is also sensitive to vibrations. This type of storm barrier is suitable for deep waters and it is controlled by flow and wave loads. It is not subjected to wind loads since it is mostly immersed in the water.

Horizontally moving or rotating gates are generally not preferred due to their significant disadvantages. This type of storm surge barrier requires deep waters to store the gates when they are not in use and there is a large risk of malfunction when silting occurs on the sill. In order to limit the force on the joints and the hinges, floatation tanks must be installed in the gates. The barriers consist of two side chambers and abutments with gate supports that are built within cofferdams. The sills may be floated to the site and submerged onto a gravel base of pile foundation that has been constructed underwater. Structural advantages include large span and no clearance height limitations. The tanks would not induce wave or flow forces on the gate in the vertical direction. The barrier is not subject to wind load, is suitable for deep waters, is immediately ready for use after installation, reduces the load on sill and is a stable structure that consists of dry docks that require little maintenance. Some disadvantages include the need for large space and deep excavation which would result in an increase in the cost (International Navigation Association, 2006).

There are two types of vertically rotating gates: segment gates with circular side disks and conventional radial gates that are rotated above the water level. The closed gate bodies enable the construction of gates with long spans and supporting gate arms at two sides. The abutments with necessary driving systems can be built within the cofferdams and the sill can be built within the cofferdam or shipped over to the site and installed thereafter. Some advantages include large gate span, immediate use after installation, controlled flow and wave loads, minimal space requirement, no wind loads, no clearance limitation, and are easy to inspect and maintain. Some disadvantages include a large load transfer, high sill tolerance demands, vulnerability to corrosion and the sensitivity to oscillation in case of overflow. The way this storm barrier works is the hollow gate body is filled with water once the gate is immersed. When the gate body is lifted, the internal water flows out through check valves while air flows in at the same time through openings in the side disks. On the other hand, when the gate body is lowered, water flows into the hollow gate through openings in the side disks, and air is blown out through the air vents in the side disks. This system is used to minimize the amount of silt that enters into the gate interior. The segment gates can be rotated 180° so that the gate body is fully lifted above the water and is accessible for inspection and maintenance (Dircke, et al., 2012).

Inflatable rubber dams are widely used in the world but for purposes other than storm surge protection. They are used in river engineering, water control applications and for the creation of other water reservoirs. Since the fabrication of large reinforced rubber sheets is extremely difficult, rubber dams have not yet been constructed for deep water applications. The advantages of this barrier are that there is no limitation for the span, no clearance height required and no susceptibility to wind loads. Additionally, there is a direct transfer of hydraulic load, there is no need for hinges and it is not sensitive to the silting of sill. However, the disadvantages include the large mass and small stiffness of the barrier, the determination of stability from internal pressure, storage of the rubber sheet and difficulty to inspect and maintain (Hill, et al., 2012).

Table 1 contains a summary that can be used in order to aid in the comparison of the various storm surge barriers available. Mitre gates are primarily used in shipping locks because waves and currents are limited. In such cases, they prove to be very cost effective. However, if strong tidal currents and high waves are present, mitre gates are not possible. Vertical lifting gates are reliable and cost effective if no height requirement is necessary. Up to a required clearance of 30 meters, lifting gates are very appealing. However, many find lifting gate aesthetically unpleasing due to their high visibility. When an aesthetically pleasing barrier is sought after, either the flap gate or the inflatable rubber dams are possibilities. Flap gates enable an unlimited barrier width; however, are difficult to maintain since they are stored underwater. Rubber dams are still an advancing technology and many of these barriers that are in place today are not used for storm surge protection in deep waters; therefore, at this point in time, they are not a viable option. Horizontally rotating gates are a possibility when a big span is required. These gates allow a span of up to 350 meters and provide unlimited vertical clearance. This barrier is one of the more expensive ones and will usually be selected for the protection of big port areas. Vertically rotating plates have a limited span as well as a limited vertical clearance. However, inspection and maintenance is easy because the gate can fully rotate above the water surface.

TABLE 1: COMPARISON OF GATE TYPE CHARACTERISTICS

	Mitre	Vertical lift	Flap	Horizontal	Vertical rotate	Rubber
Span > 30m	–	+	+	+	+	+
Span > 100m	–	–	+	+	–	–
Water depth > 10m	+	+	+	+	+	–
Impact upon landscape	+	–	+	+	–/+	+
Maintenance	+	+	–	0	+	0
Currents and waves	–	+	0	0/+	0/+	0
Closure time	+	+	+	+	+	0/–
Space required	+	+	+	–	+	+
Colliding ships	0/–	+	+	0/–	+	0
Reliability	–/+	+	0/+	–/+	+	0
Clearance height	+	–	+	+	–/+	+

Legend: - Not favorable up to not feasible; 0/-: Below average / vulnerable; 0: Average / possible; 0/+: Above average; +: Favorable / proven technology; -/+: Score depends on design choices and conditions.

2.2 IMPLEMENTED SOLUTIONS IN OTHER CITIES

2.2.1 VENICE FLOODGATES

The MOSE project, short for Modulo Sperimentale Elettromeccanico, is the floodgate system that is currently being implemented in the Venetian Lagoon, in Venice, Italy. The reason for this is the ever increasing sea level, which has led to the flooding of streets in Venice on a regular basis during certain parts of the year. Scientists predict that the sea level will rise even more in the next century, between 18 and 59 cm, which puts Venice in dire need of a solution.

The project began just over ten years ago, in 2003, and is scheduled to be completed in 2016. It consists of providing three barriers at the Lido, Malamocco and Chioggia inlets to the Venetian Lagoon that will rise to seal off the lagoon from the Adriatic Sea during high tides. The location of the three inlets with respect to Venice can be seen in Figure 8, below. More extreme weather events are very unlikely in this part of the world.

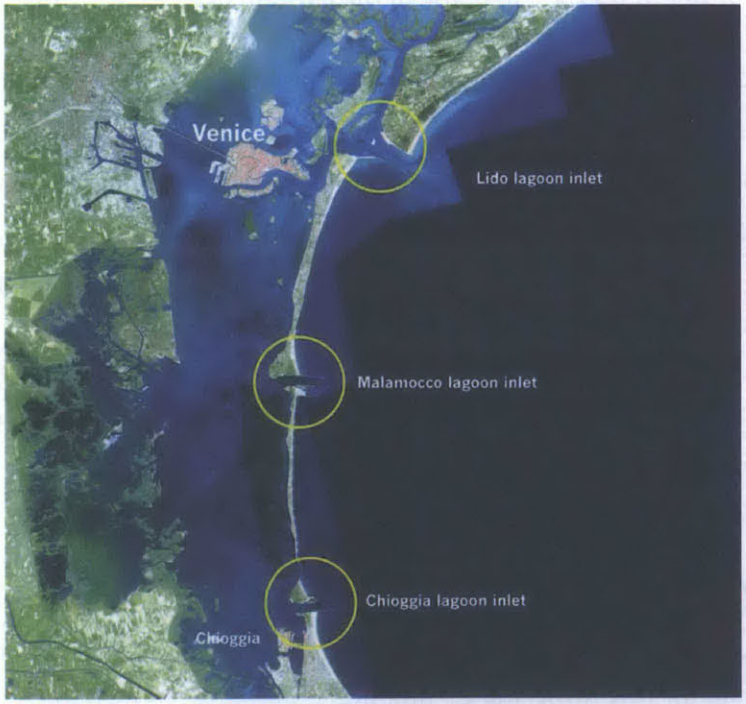


FIGURE 8: LOCATION OF VENICE FLOODGATES (REINA, 2008)

Although the project officially started in 2003, it had been studied for almost 30 years before that. During the flood on November 4, 1966, many of Venice's built up areas experienced a tide of 6.36 feet (194 cm). That led the government to call for ideas from all over the world to help solve this problem. However, no proposal completely satisfied all the requisites and the project was abandoned. In 1984, the government created a committee, Consorzio Venezia Nuova (CVN), which was entrusted with the design and implementation of a solution to the flooding and the ecological degradation that the flooding caused (Reina, 2008). CVN is owned by roughly 50 Italian contracting companies. Rather than working together, each of these 50 companies individually takes on smaller tasks that lead to the final goal. Design work officially started in 2003 and construction, a year after.

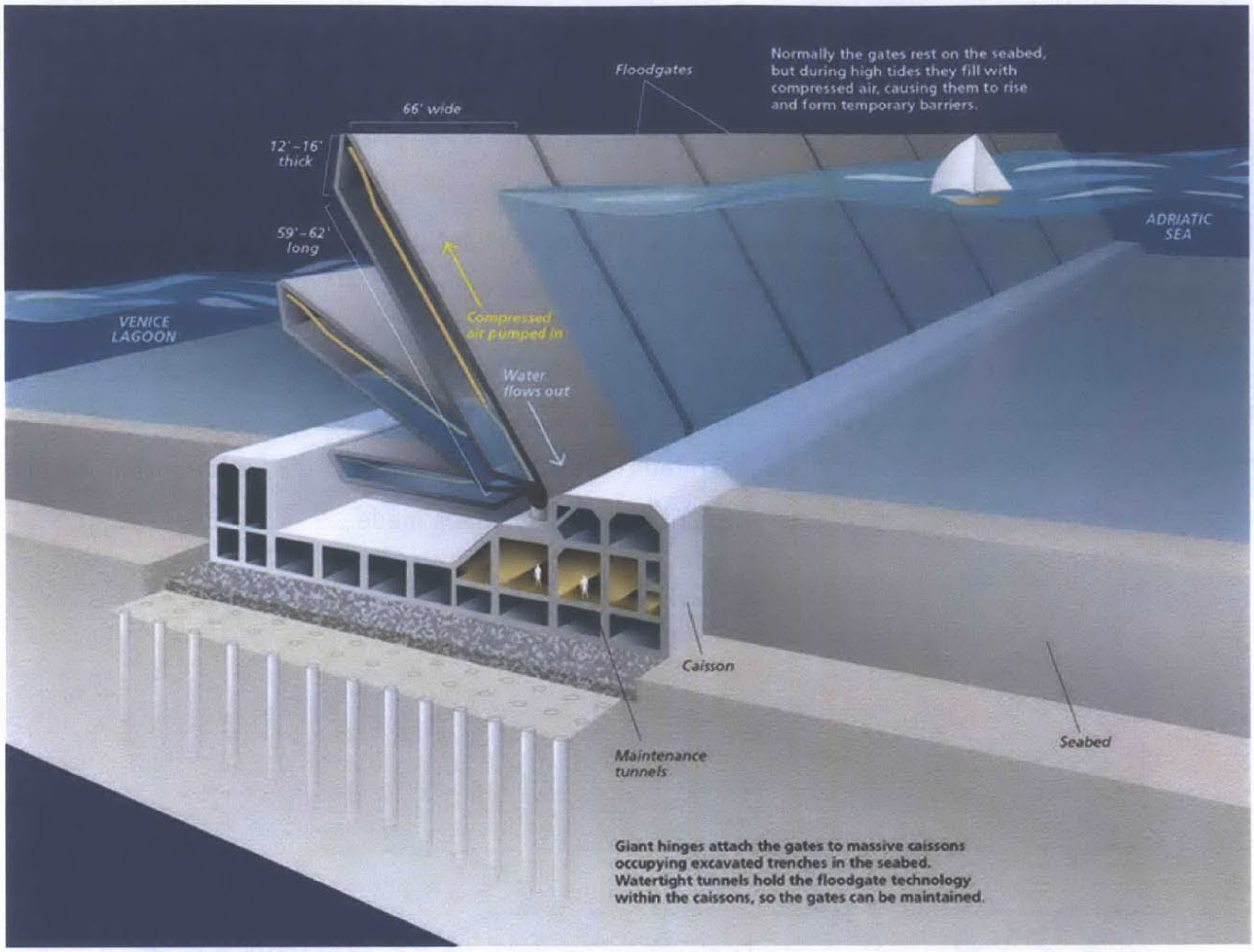
The design consists of 78 individually working gates that span a total of 1.6km over the three inlets. The Lido inlet is the widest, and consists of a small artificial island at its center. This makes each inlet opening roughly 400 meters wide. Each gate is hinged and rises out of the water when tides rise to 3.61 feet (110 cm). It rises as air is injected into each gate. This addition of air forces out the water inside and causes the gate to rise to the surface. The gate itself is free to oscillate about its hinges as major tides hit its surface to reduce the forces on the hinges.

Each gate varies in size between 18.5 x 20 x 3.6 meters and 29.5 x 20 x 4.5 meters in length, width and thickness (Taylor, 2014). When not in operation, the gates will lie flat on the sea floor, in concrete caissons. Figure 9 shows a schematic of the gates in use.

When activated, the gates are planned to be in use for increments ranging from four to five hours. This includes the time it takes to raise and lower the gates, which is 30 and 15 minutes, respectively. Additionally, each inlet contains a lock to let ships enter and leave when the floodgates are up. The lock at Malamocco will allow large ships and cruise liners to enter and leave. The locks at the other two inlets are smaller and will allow pleasure craft and smaller vessels to enter and leave.

CVN came up with this idea from a possible 30 that were initially proposed. The reason this was chosen was because it satisfied some major criteria, such as, being the cheapest solution, the solution that required little maintenance and in the case of aesthetics, being out of sight when not in use.

As of January 2014, the system is about 80% completed and is on schedule to be finished in 2016. The barriers across the Lido inlet have been completed, in addition to the giant lock at Malamocco. The budget for this project is €7 billion.



Normally the gates rest on the seabed, but during high tides they fill with compressed air, causing them to rise and form temporary barriers.

Giant hinges attach the gates to massive caissons occupying excavated trenches in the seabed. Watertight tunnels hold the floodgate technology within the caissons, so the gates can be maintained.

FIGURE 9: SCHEMATIC OF THE VENICE FLOOD GATES (ULAM, 2013)

Due to this large price tag and the length of the project so far, people have been wondering if the flooding is serious enough to justify the cost. The answer is yes because a survey of tidal heights has shown that tides over 110 cm have become more frequent lately than they had been in the past. For example, in 1920, there were just two events that surpassed the 110 cm mark. Between 2001 and 2010, there have been a total of 64 (Taylor, 2014). According to calculations for the flood gates, the gates have been designed to handle an increase of 60 cm in water level rise without failing. This can account for the worst case hypothesis that scientists have predicted of 59 cm sea level rise in the next century. Additionally, the gates can be raised to an angle greater than the default angle of 45 degrees to prevent even more water from entering the lagoon.

2.2.2 NETHERLANDS: THE DELTA PROJECT

The Delta Project is depicted as one of the most astounding hydraulic engineering feats ever to be erected. This monumental advancement in storm water surge protection expands throughout The Netherlands' western coast. Planning for this project began in 1953 and it became operational in 1986. The project was fully completed in 1997 (Deltawerken Online, 2004). This project would prove to be vital for the survival of the cities located by the coastline.

Topographically, The Netherlands is susceptible to storm water overflow because it is located below sea level. There were approximately 111 serious floods between the year 1000 and 1953. These storms claimed many lives and devastated the surrounding lands. It was evident that for the area to develop, defenses against water overflow would have to be made.

FIGURE 10: DIKES LOCATED IN THE NETHERLANDS (RADIO FRANCE INTERNATIONALE, 2008)

The fight against storm water surges dates back to the Roman times, where they constructed dams in the Rhine Valley as a means of protection from overflow. However, due to the lack of efficiency, these dams were utilized more as a safe ground than for overflow prevention. In their early construction period, the Romans built mounds on which they took refuge during periods of high water (Deltawerken Online, 2004). It was not until the tenth century that the inhabitants began to build flood defenses. The first type of flood water prevention system was rudimentary; it consisted of low walls and dikes made up of spades and baskets. An example of these dikes can be seen in Figure 10. However, these walls would prove to be inefficient during more significant storms.

As years passed construction techniques improved and it was not until the 19th century that concrete and pitching techniques were used in the construction of the dikes. However, a storm on January 1, 1953, would prove these structures to be an inadequate defense against storm water surges. The storm claimed over 5000 lives and engulfed 200,000 hectares of fertile land along with countless villages (Deltawerken Online, 2004). As a result of the devastation caused by the storm, the Delta Commission committee was founded.

The committee first met on February 21st, 1953. Mr. Maris was appointed as the direct - General Minister of Waterways and Public Works. The purpose for this union was to decide on methods to drain the areas that flooded regularly during high water levels and protect them from the water (Deltawerken Online, 2004). Two options were considered: either raising the existing dikes or closing down some tidal inlets. These two options were part of a proposed Delta Act. However, closing down inlets was viewed as a less viable solution because the surrounding rivers were vital to shipping traffic. Therefore, the committee compromised and agreed upon redirecting ship traffic, solely, through two water ways, The New Waterway and the Western Scheldt. This compromise proved to be difficult to implement because of the economic impact on its surroundings.

Eventually, Parliament approved the act in 1957, thus, allowing construction to begin. The engineers decided to erect dams to close off four inlets: the Veerse Gat, the Eastern Scheldt, the Brouwershavense Gat and the Haringvliet (Deltawerken Online, 2004). These dams would not only prove to play a vital role in water control, but also helped minimize the project's cost by reducing the lengths of the proposed dikes from 700 kilometers to 25. The engineers were also faced with construction issues. The dams required careful planning with regards to the construction phase of the project due to poor weather conditions.

It was decided upon that the contractors would take a "minor to major" approach during the construction phase. The relatively easy construction was completed first and then they worked up to the more complex phases. Contractors had to develop new construction technologies to implement these structures. Since a project of such magnitude was never undertaken before, the technologies to implement such structures were yet to be invented; therefore, contractors had to develop new techniques as the building process went along. One main technological innovation, which is widely used today, was prefabrication.

Other advances were sluice caissons and a cableway with gondolas, which were devised to carry out the work on the wider inlets. The huge concrete caissons were improved and in the 1970s, man-made fibers came into use for dike construction and for sea and river bed protection (Deltawerken Online, 2004). Advancements in computers, more efficient laboratory testing and measuring techniques aided in the development of these methods.

The first step of the construction process required laying down an adequate foundation for the piers. The foundation design was critical because the bed of the Eastern Scheldt is constantly moving. Polypropylene mats, with concrete blocks were used to protect the bed on which the barrier would stand on. After the seabed was properly compacted, a prevention system was implemented so that the sand would not flush away when the barrier closed. The piers made up the structures which supported the barriers. These piers can be seen in Figure 11, below.

FIGURE 11: REMOVABLE BARRIERS (SLATER, N.D.)

The pier system, which can be seen in Figures 12 and 13, is made up of 65 "colossal" piers, which stand 30 to 40 feet high, depending on location, and weigh 18,000 tons each. The piers weigh this much because they need the ability to transfer the water pressures from the gate to the foundations. Each pier took about a year and a half to be completed.

FIGURE 12: PIER SYSTEM UNDER CONSTRUCTION (DELTAWERKEN ONLINE, 2004)

FIGURE 13: CONSTRUCTION OF PIER (DELTAWERKEN ONLINE, 2004)

2.3 PROPOSED SOLUTIONS SPECIFIC TO NYC

The City of New York has come up with various solutions to combat water level rise on its shores. Each solution is recommended for a specific location of the City based on the resources or lack of resources available in that location alone. The solutions are grouped into one of the following sections: increasing edge elevations, decreasing wave damage and protection against storm surge. All solutions that New York City developed are based on an in depth analysis that considered factors such as the type of hazard and the frequency of occurrence of that hazard in the specified location and the impact on the existing environment. Once this analysis was complete, each solution's cost effectiveness was determined. These costs included both initial construction and future maintenance costs. Finally, the city took into account aesthetics, ecosystem preservation and accessibility for the public for each solution. For example beachfront properties with large seawalls between them and the beach will hinder people from moving to that area.

The City argues that it does not want to use only one type of technology for multiple reasons (PlaNYC, 2013). It believes that incorporating multiple technologies keeps the City informed of a various portfolio of solutions and does not risk catastrophic damage if the only implemented defense fails. This method also allows the City to begin some projects and keep others tabled as money becomes available instead of using one massive project that required all expenses to be accounted for at the beginning of the project. This leads to the final reason which is that having a variety of little solutions enables their construction to start far earlier than one massive project. However, there is a chance that the total cost of these little solutions may be more expensive than a single, massive project.

2.3.1 INCREASING EDGE ELEVATIONS

The City believes that increasing coastal edge elevations is necessary to prevent future inundation. This feat will be accomplished through the incorporation of beach nourishment, revetments, bulkheads and tidal gates/drainage devices. Each of these solutions is believed to help in the monitoring of future sea level rise which will help provide better solutions as better data is made available.

Beach nourishment consists of adding large amounts of sand to widen and elevate beaches. This is not a one-time solution due to the fact that beach erosion is a constantly occurring phenomenon. As water washes up on shore, it takes away some sand, leaving beaches thinner and shorter. Thinner beaches allow water to get closer to homes and shorter elevated beaches may not provide the necessary amount of water absorption as well as not providing water an uphill battle to reach homes. Unfortunately, the sand used for beach nourishment erodes faster than the natural sand on the beach, can also bury or crush marine life that is exists on the beach before the new sand is added and can also make the water muddy. Furthermore, during nourishment, the beach becomes a construction zone; thus, making it unusable by the public (Barber, n.d.). Typical examples where this system can be used are on the Rockaway Peninsula, Coney Island and Staten Island.

Stone revetments, also known as rip-rap, are used on shores to protect against erosion by absorbing the energy of incoming waves. They allow the area behind them to be raised to a higher elevation, are one of the most economical solutions and require minimal maintenance. Conversely, if not installed correctly, revetments can have no effect on the protection of a shoreline. Proposed locations of revetments are on Coney Island Creek and Staten Island. A revetment can be seen in Figure 14.

FIGURE 14: STONE REVETMENTS (IXIGO.COM, N.D.)

The third solution that creates an elevated coastal edge are bulkheads. Bulkheads are concrete or stone walls that are placed at the edge of the water to absorb the impacts from waves. They allow buildings, roadways and parks to be built closer to the edge of the water. Including raised bulkheads in various locations can also combat the effects of future sea level rise. Bulkheads are as effective as revetments; however, some bulkheads are treated with chemicals to prevent the growth of marine life on them. This may cause problems when chemicals seep into the water. Proposed locations of bulkheads are on the south shore of Brooklyn, the Rockaway Peninsula, western Manhattan and the north shore of Staten Island. An example of a bulkhead can be seen in Figure 15.

FIGURE 15: BULKHEAD (BIG ISLAND VENTURES, N.D.)

Tidal gates/ drainage devices are used to prevent water from flowing in the opposite direction. These can be implemented in flood prone areas to improve the performance of the drainage network and reduce flood risk. They typically work like dams, which hold back water on one side and have openings that allow it to controllably pass through at an acceptable flow rate. These must be properly controlled so that the accumulation of water on the upland side of the gate does not flood that area. Similarly, they must be maintained so that they perform to the level required of them. Proposed locations of these tidal gates and drainage devices are on Staten Island, northern Queens and the Rockaway Peninsula.

2.3.2 DECREASING WAVE DAMAGE

The City believes that decreasing wave damage is necessary to prevent future inundation. This feat will be accomplished through the incorporation of dunes, breakwaters, wetlands and reefs and the use of groins. Each of these solutions is believed to reduce the strength of waves so that they do less damage to buildings and the environment.

Dunes are just mounds of sand that are typically placed along the back end of a beach. As waves hit these dunes, some of energy is absorbed by the sand. If the wave has enough energy to make it over the dune, it will have significantly less energy to do much damage. However, these dunes may wash away as they are constantly bombarded. Therefore, some beaches have primary and secondary dunes. If waves make it over the first dune or if that first dune is washed away, the waves still have to get over the next dune. A problem with this system is that dunes need to be replenished, as does beach nourishment. Dunes that contain roots from plants or large rocks are the most effective, because the roots and rocks stabilize the sand in place. Proposed locations for this type of solution include the Rockaways and Coney Island. Figure 16 shows a dune after a storm.

FIGURE 16: BEACH DUNE (THE GREEN EDITION, 2012)

Breakwaters perform just as their name implies. They absorb the energy of the incoming water. This system is typically used offshore and can be composed of large rocks or other strong materials. These breakwaters can provide erosion free beaches behind them, and also create calmer waters, which can provide habitats for new ocean organisms. Problems with this design include massive objects in the water that may create problems for ships and a reduced connection between the shore and the ocean for many underwater organisms. Proposed locations include The Rockaways, south shore of Staten Island, and Upper Bay. An example of a breakwater can be seen in Figure 17.

FIGURE 17: BREAKWATER (ALAMEDA POINT ENVIRONMENTAL REPORT, 2012)

Wetlands and reefs can provide a decrease in wave energy, although how this is accomplished is still not entirely understood. It is believed that these and other living shorelines (i.e. coastal forests) provide obstacles that reduce the strength of passing waves. Even though history and analytical models have shown that these environments reduce wave energy, they are still susceptible to a major storm which may wipe out life in an entire wetland. Proposed locations include Jamaica Bay, southwest Brooklyn, and northern Queens.

Groins, also known as jetties, are a group of large rocks or timber pieces that are placed in a line on the water perpendicular to the shore. Groins can be used to slow the erosion from beach nourishment projects and reduce the energy of waves that hit the shoreline at an angle. A problem with them is that they can disrupt the natural transfer of sediment, which can hurt ecosystems. Proposed locations include southwest Brooklyn and The Rockaway Peninsula. Figure 18 shows groins in action.

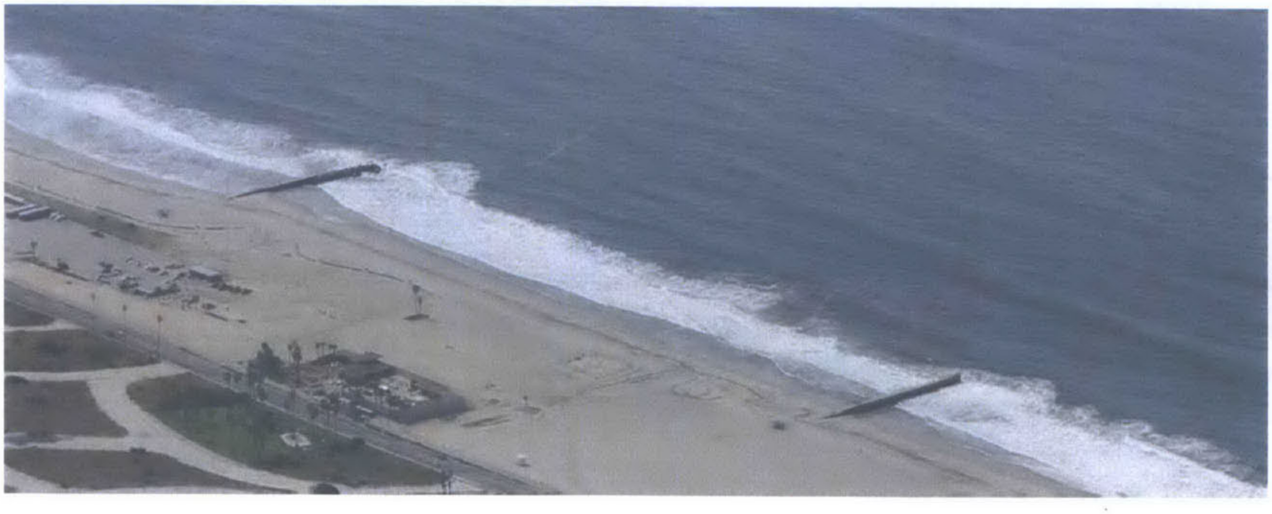


FIGURE 18: GROINS (CALIFORNIA STATE UNIVERSITY LONG BEACH, N.D.)

2.3.3 PROTECTING AGAINST STORM SURGE

The City believes that protecting against storm surge is necessary to prevent future inundation. This feat will be accomplished through the incorporation of floodwalls/levees and local storm surge barriers. Each of these solutions is believed to prevent a sudden rise in water level from ever reaching the shore.

Floodwalls are walls of a certain height that are placed in zones that are at risk of elevated water levels. These walls can either be permanent or temporary. Permanent walls may not be aesthetically pleasing for coastal communities but they do not require the amount of maintenance that temporary walls need because they do not have to be put up every time there is a rise in sea level. Levees are more natural barriers which are integrated into the environment that are made of rocks or other materials. In other words, they are the vertical portion of earth between two areas of land of differing elevation. Like floodwalls, levees can be aesthetically unpleasing if not done correctly. Proposed locations of both floodwalls and levees are mostly along the east coast of Staten Island.

Local storm surge barriers are barriers located in the water that contain movable gates that open and close. The City wants these barriers to be solutions for local communities, instead of for the City as a whole. Proposed locations include the entrances to Newtown Creek, Rockaway Inlet and the Gowanus Canal.

Two ideas for creating global storm surge barriers that can protect the city as a whole have also been proposed. Both designs call for massive walls that will seal the City's waters off from the ocean's. One idea uses a three-gate design while the other uses only a two-gate. The three gate system will contain three walls, each with a gate that can open or close that allows ships access to navigate. The walls would be placed at the Narrows, the Arthur Kill and the connection between the East River and the Long Island Sound. The two gate system would contain the same wall at the connection between the East River and the Long Island sound but would also contain a massive wall that spans between Sandy Hook, NJ and the Rockaway Peninsula. But just like all the previous proposals, these systems also have their advantages and disadvantages. Proposed locations of the barriers are shown in Figures 19 and 20.

Global storm surge barriers offer simplicity; one design would protect the whole city without the need for tens of little projects throughout the city. Furthermore, they can guarantee that strong waves and massive water surge will never be an issue. However, in "A Stronger, More Resilient New York", the City states that the disadvantages are what make global barriers not a feasible solution.

The report states that such a system would cost between \$20 and \$25 billion, an amount of funding that is very difficult to secure at once. The project would also take decades to complete. This leaves the City vulnerable to more storm surge attacks in that timeframe. Massive walls would create hydrodynamic and environmental impacts. Fish migration, river flows and water quality issues may arise. Levees must also be created in areas located at the edges of these walls in order to prevent the water from flowing around the walls. This leads to major aesthetic changes to the beaches and shores and a supplementary cost to the project. The construction of the walls could create rifts between communities and the government, where some communities along the north and south shores of Long Island being located outside of the protection zone of the barriers. The barriers would not address the rise in sea level because the gates would be open most of the time, requiring additional measures to be taken at the shores. Finally, a failure in one gate will leave the whole city at risk of flooding.

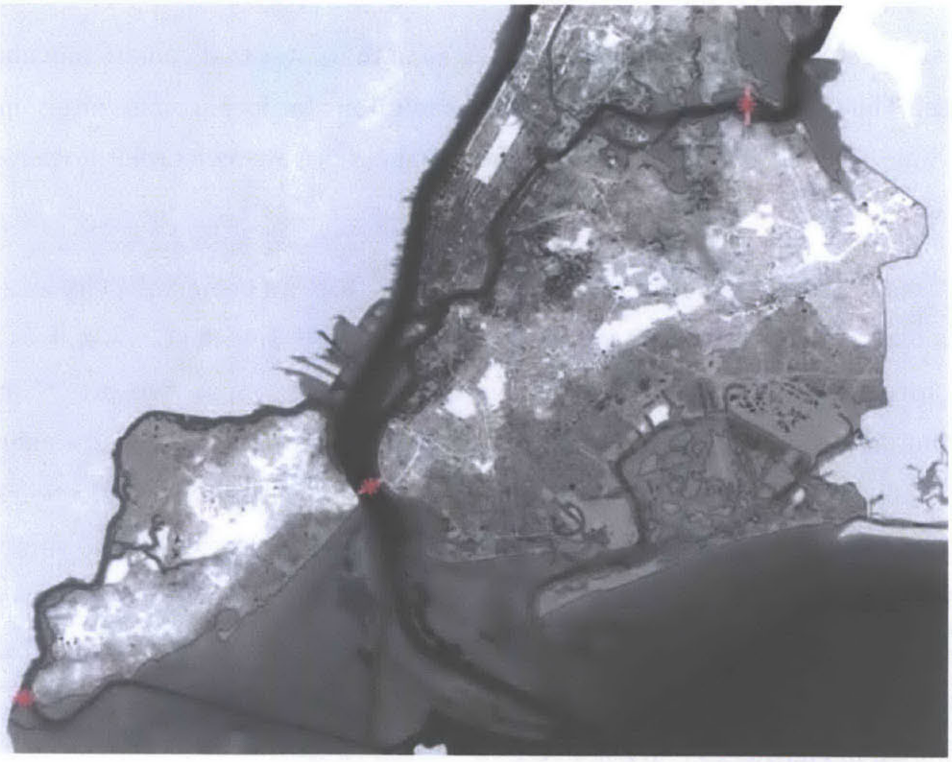


FIGURE 19: 3-GATE GLOBAL BARRIER SYSTEM (PLANYC, 2013)

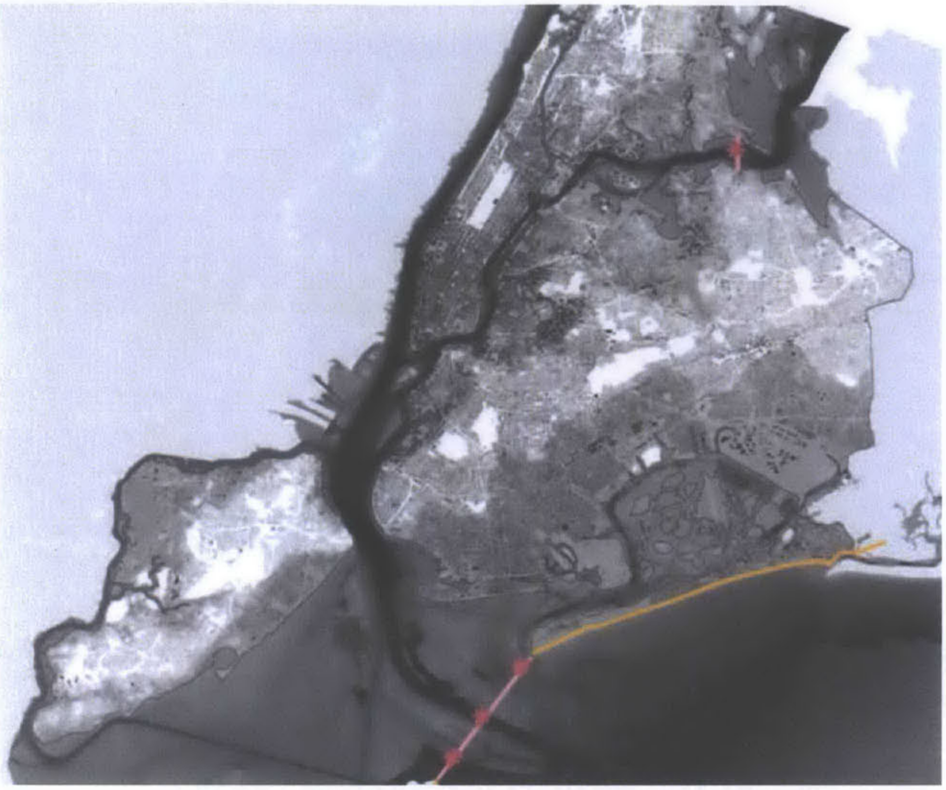


FIGURE 20: 2-GATE GLOBAL BARRIER SYSTEM (PLANYC, 2013)

3. SELECTION OF BARRIER LOCATION AND GATE

The information contained in this section contains original work that supplements the information presented in the Literature Review. It contains an analysis that ultimately determines the ideal location of the barrier and the optimal type of gate that will be operated.

3.1 GEOGRAPHICAL REQUIREMENTS

In order to determine the optimal location that the offshore barriers will be placed, it is necessary to understand the factors involved in choosing the right location. The possible choices include creating a wall that is the shortest distance across or creating a wall in shallower waters. Unfortunately, these two options are opposites when it comes to New York City's geography and harbor water depths. For that reason, an optimal middle ground needs to be determined. Using The National Oceanic and Atmospheric Administration's (NOAA) nautical charts, water depths and spans were calculated.

3.1.1 EAST RIVER BARRIER LOCATION

The first proposed barrier is that which will be located in the East River/ Long Island Sound to protect the City against storm surge from the northeast. The location with the shortest spandrel distance is below the Bronx- Whitestone Bridge at about 3100 feet. This location, labelled as "1" in Figure 21, contains very shallow water, a water depth up to 18 feet, for about 50% of its span, with most of this 50% being under 10 feet. The deepest elevation is around 70 feet, a depth which spans about 1500 feet across.

The next possible barrier location is under the Throgs Neck Bridge with a spandrel length of about 3550 feet. This location was proposed because it is the easternmost location with a spandrel length under 7000 feet. This barrier is meant to include a few more communities behind the barrier. Only 10% of the length has a water depth below 18 feet. The peak depth is about 78 feet, while over 70% of the span is at a depth greater than 60 feet. This location is labelled as "2" in Figure 21.

The third possible barrier location is that between the south tip of Throgs Neck and the US Merchant Marine Academy at Kings Point. Although this span is over 7200 feet long, it passes through much shallower waters. The largest depth along this span is 45 feet. Furthermore, this barrier will include all communities protected by the second proposed barrier while also protecting ones located in Little Neck Bay. This is labelled as "3" in Figure 22.

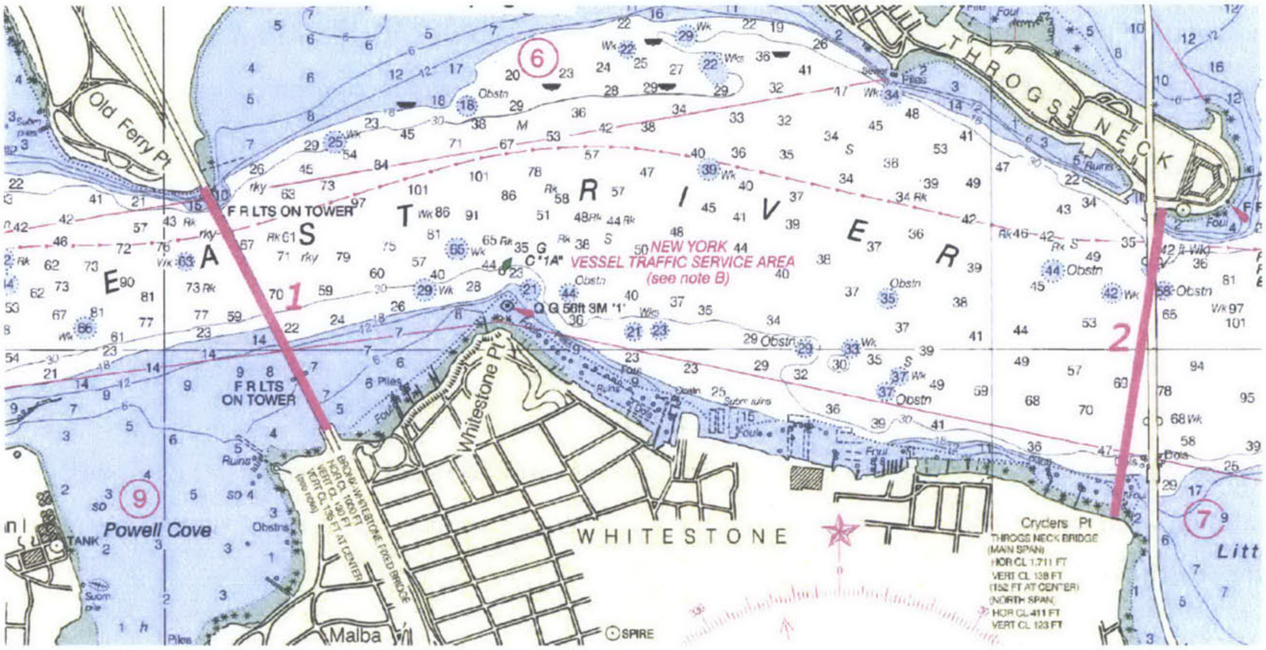


FIGURE 21: EAST RIVER PROPOSED BARRIER LOCATIONS 1 AND 2

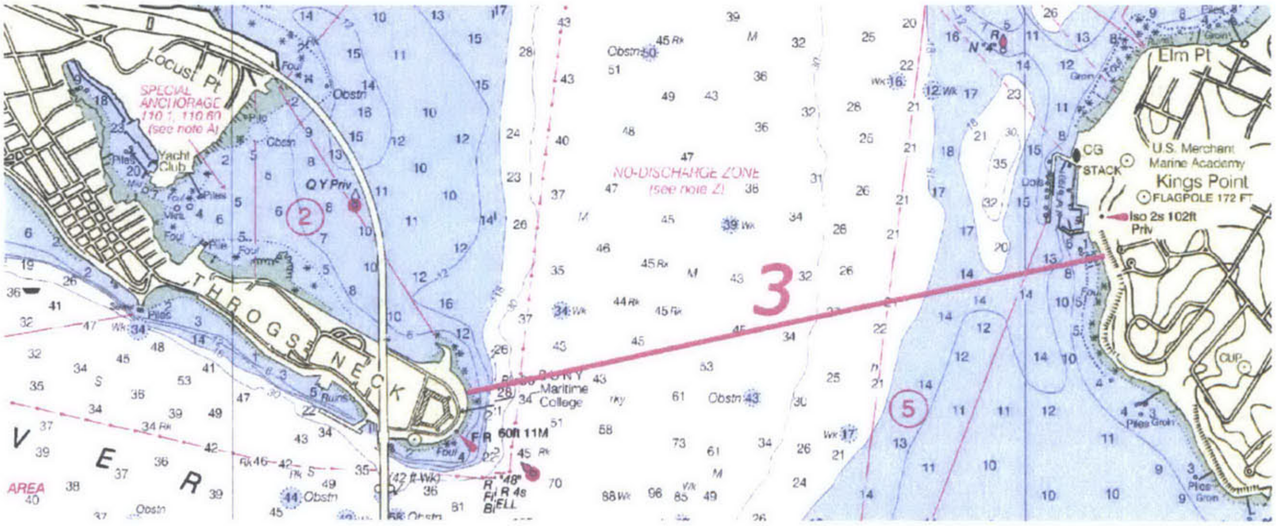


FIGURE 22: EAST RIVER PROPOSED BARRIER LOCATION 3

The final proposed location is creating a barrier between the south point of City Island and Kings Point. This location will protect all communities in Eastchester Bay, in addition to all regions already protected by the third proposal. The length is 9500 feet where 60% of the span has a depth below 18 feet. The deepest point is about 68 feet. The problem with this solution is that a second barrier is needed to stop water from going around the north end of City Island. The span at that location is 600 feet. This last barrier system is shown as "4" in Figure 23. To see the location of all proposed East River/ Long Island Sound barriers in relation to one another, please see Figure 35 in Appendix A.

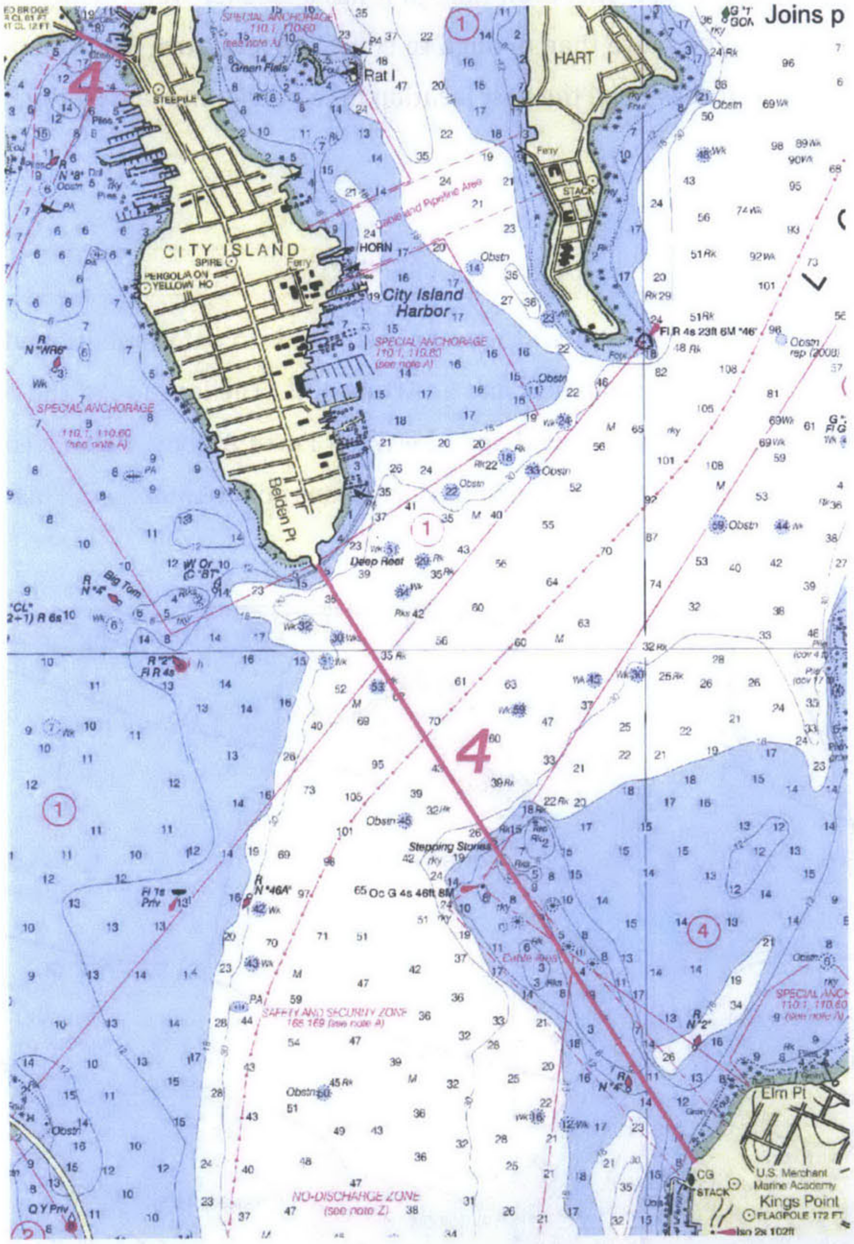


FIGURE 23: EAST RIVER PROPOSED BARRIER LOCATION 4

To narrow the choices down, water depth is considered. Locations 1, 2 and 4 have peak depths of 70 feet or greater. This peak depth covers about 1200 feet of barrier in location 1, 1650 feet in location 2 and about 1200 feet in location 4. This and the fact that not much additional protection is gained with location 2 rules it out. A second gate will need to be placed for location 4.

This increases maintenance costs and is the longest span. Additionally, the communities along Eastchester Bay are not at a great risk of flooding, even for a 500 year storm, according to FEMA's new 2013 flood maps. This can now be ruled out. The length of the barrier at location 3 is almost more than double that of location one, even though it has a smaller water depth. The cost savings from the shorter span will be more than enough to cover the few extra feet of depth at location 1. Consequently, location 1 proves to be the best location for a barrier in the East River.

3.1.2 3-GATE SYSTEM

The two or three gate system will now be evaluated. As aforementioned, the three gate system incorporates a gate at the Narrows and at Arthur Kill. The location of the barrier at Arthur Kill does not need to be evaluated. It will span between Perth Amboy, NJ and Tottenville, Staten Island. This is the narrowest part of Arthur Kill, which spans about 1650 feet. This is labelled "5" in Figure 24.

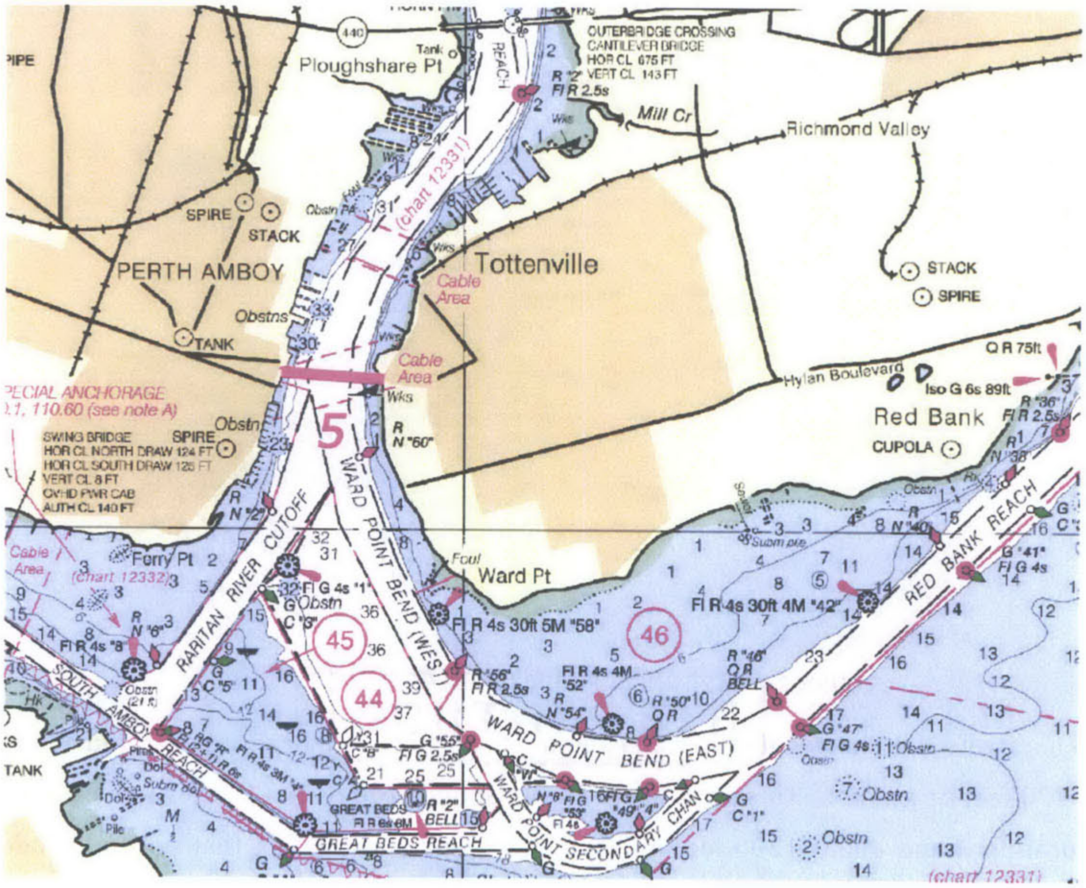


FIGURE 24: LOCATION OF ARTHUR KILL BARRIER

There are two proposed barrier locations at The Narrows. The shorter span of the two, labelled "6" in Figure 25, spans 5000 feet and reaches a maximum depth of 78 feet. The other proposed location is labelled "7" in the same figure and spans 7500 feet and reaches a max depth of about 60 feet. The extra area protected by barrier location 6 is almost negligible. Almost the entire span of barrier 6 is at a depth of greater than 50 feet. About 3000 feet are at a depth of greater than 50 feet at barrier 7. In this situation, the cost savings of shorter depth outweigh the shorter span and barrier location 7 is chosen. The full three gate system is shown in Figure 36 in Appendix A.

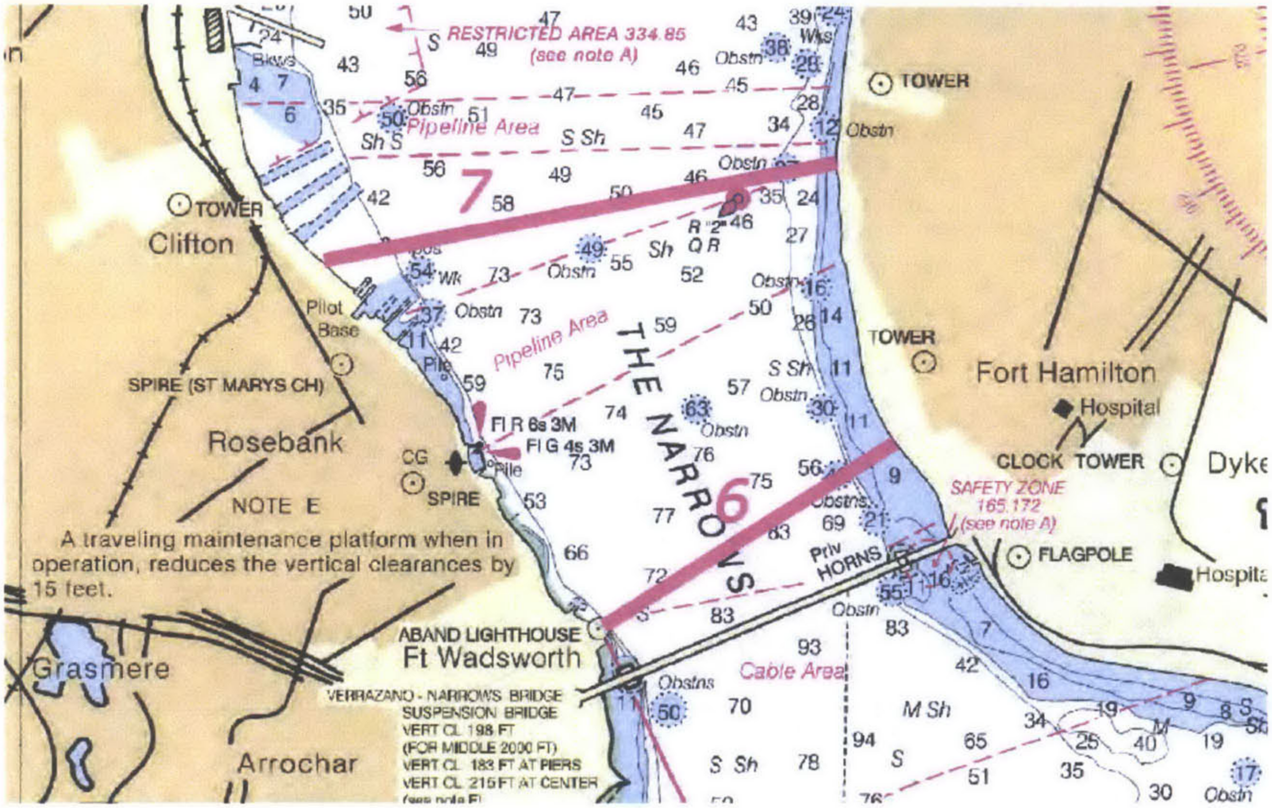


FIGURE 25: THE NARROWS PROPOSED BARRIER LOCATIONS 6 AND 7

3.1.3 2-GATE SYSTEM

The two gate system will create a barrier between Sandy Hook, NJ and Breezy Point, Queens. This barrier is shown in Figure 26. This massive proposed barrier will span 31,000 feet and will be able to protect all of Brooklyn, Jamaica Bay, Staten Island and also all parts of New Jersey north of Sandy Hook. Furthermore, the largest depth along this span, not including the dredged and navigable Ambrose Channel is 26 feet. The channel itself is about 2000 feet wide and 40 feet deep. Taking into account the amount of area protected by the two gate system and the shallow waters it crosses, the two gate system will be more cost effective in the long run. The entire two gate system is shown in Figure 37 in Appendix A.

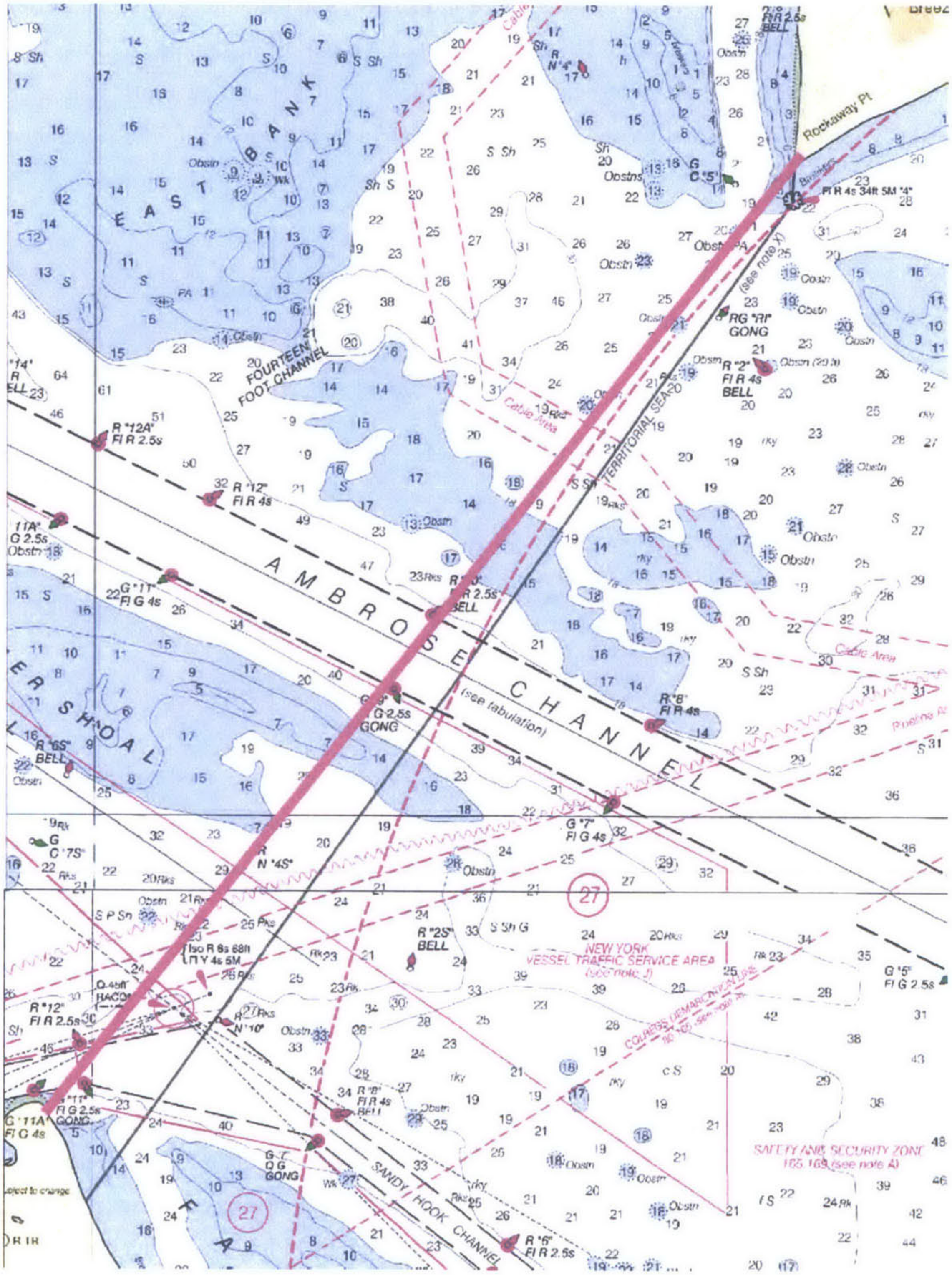


FIGURE 26: PROPOSED BARRIER BETWEEN SANDY HOOK AND BREEZY POINT

3.2 OPTIMAL BARRIER TYPE

Now that the best locations have been chosen, it is necessary to choose the best type of barrier. Both locations of the two gate system are not similar in any respect. Therefore, in order to choose the best barrier, each location will be evaluated separately. Now looking back at Section 2.1.1 with a better idea of the geographical constraints of the proposed locations, the best decision can be made regarding the type of barrier. As will be seen in the next section, initial cost of each barrier gate will not be factored in because the difference in price of one gate to another is an insignificant amount of money when compared to the amount of money that will be spent on the wall itself.

Since water depth is greater than 30 feet for the ship passageways, rubber dams are not an option for either location. When evaluating the East River gate, a 500 foot opening can be considered adequate and 1000 feet in the Ambrose Channel can be considered an adequate opening for the other gate. This eliminates the mitre gate for both locations because two rotating gates cannot cover such a large width. Additionally, due to the use of these waterways by cruise ships and cargo ships, a vertical lifting gate will be inadequate because of its height restriction. The vertical lifting flap gate is not suitable for the Ambrose Channel because it is very sensitive to vibrations and silting. Because this channel is located between the Atlantic Ocean and the mouth of the Hudson River, it will be subject to both wave action and silt depositing. The East River has significantly less waves and a slower moving current, which does not pick up as much silt as the Hudson River. A horizontally rotating arch requires a bit of space to store and support the arches. Moreover, this support needs to be dug securely into the ground. Although it is possible to place these supports 70 feet into the East River, it is rather difficult. Additionally, horizontally rotating arches can be severely damaged if hit. This is especially an issue with large ships because the opening will only be 500 feet wide. Finally, vertical rotating gates are not feasible for either location for the same reason as the mitre gates; they cannot span large distances.

Thus, the best gate choice for the East River barrier is the vertical lifting flap gate (like in Venice). For the Ambrose Channel, the best gate is the horizontally rotating arch. Table 2 shows the cost of maintenance for both gates. These costs were acquired from similar projects throughout the world (PBS, 2002) (Seacity2100, 2011). The rotating arch yearly maintenance cost is an approximation of 1% of the total cost of construction of the project. These maintenance costs per year per foot were then adapted to the lengths of the gate openings in New York City. The total maintenance cost for the City will then be $4.692 million/yr.

TABLE 2: MAINTENANCE COST OF PROPOSED GATES

Type of Gate	**Existing Example**	**Annual Cost of Example**	**Equivalent Cost/yr./ft.**	**Cost to New York City/yr.**
Vertical Flap	MOSE Floodgates (Venice)	$9.2 million	$1,764	**$882,000**
Horizontally Rotating Arch	Maeslantkering Barrier (Rotterdam)	$4.5 million	$3,810	**$3.81 million**

4. RISK/ PROBABILITY OF OCCURRENCE

The information in this section details how flood risk was determined for New York City in the past and how new data and rising sea levels are altering this risk. Based on the future risk, a barrier height is chosen.

4.1 DETERMINATION OF PROBABILITY

Before determining what barrier height design is most feasible, it is necessary to understand where the probability of flood occurrence originates. FEMA has been developing and maintaining flood maps for New York City since 1983. These maps, known as Flood Insurance Rate Maps (FIRM), describe the federal government's assessment of flood risk for certain areas. These maps are commonly used, as their name suggests, as a basis for home insurance calculations. For example, if a family is looking to build a house on a certain property, it can use the FIRM to identify the base flood elevation (BFE), or minimum height to place the first floor so that flooding does not occur, in turn, lowering the insurance on the home. Many homes in the floodplain are constructed on stilts, so that water can pass through under the house with no damage.

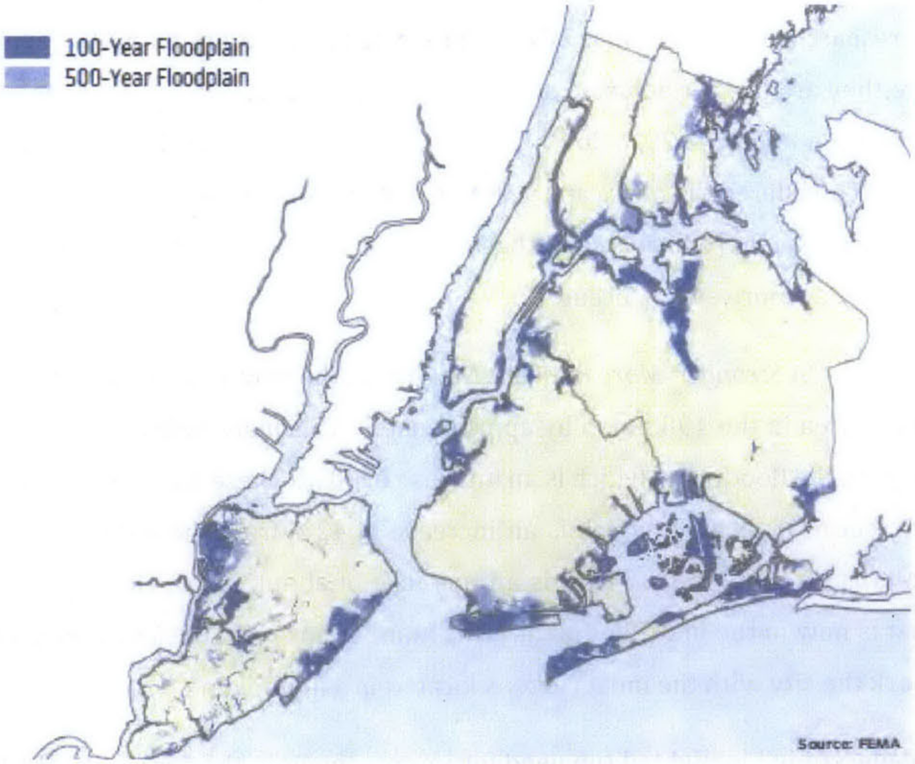


FIGURE 27: 1983 FEMA FLOOD INSURANCE RATE MAP FOR NYC (PLANYC, 2013)

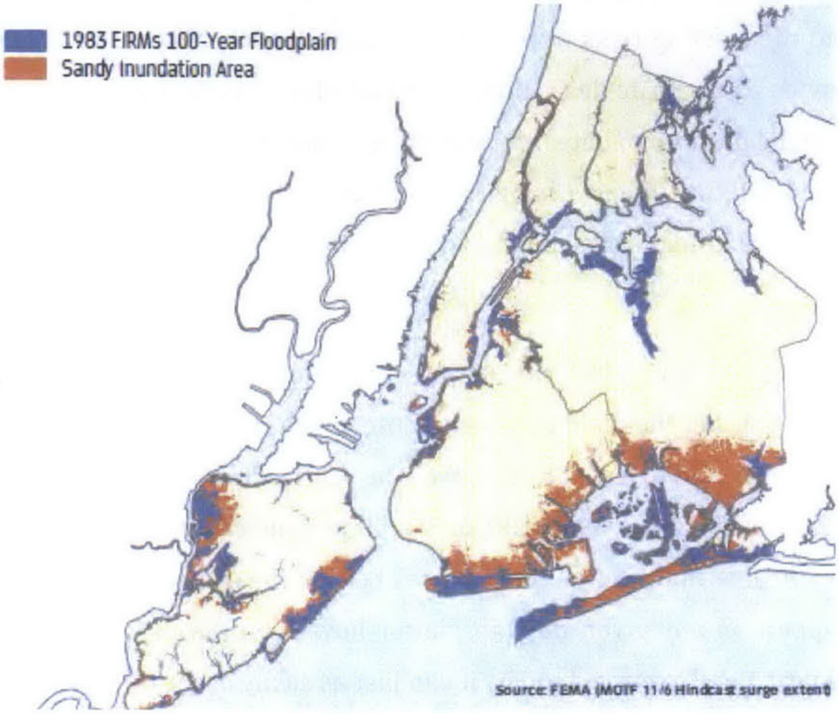
Areas that fall within the 100 year floodplain are labeled as special flood hazard areas (SFHAs), and are further divided into insurance risk zones. Figure 27 shows the 1983 FIRM for New York City.

The 1983 FIRM map shows the 33 square miles that FEMA believed would flood when a 100 year storm hit the City. This same 1983 map was used for 30 years. It should be noted that the City realized that the FIRMs were outdated due to increasing shoreline development and the rise in sea level and mapped out the most accurate elevation maps for all of New York City in 2010. When Hurricane Sandy hit the city, the inundation area it covered was more than 1.5 times the 1983 100 year floodplain. This caused severe damage to many buildings lying outside of the floodplain because they had not been constructed using flood prevention techniques. Figure 28 shows the flooding effect of Hurricane Sandy compared to the 1983 FIRM.

After the hurricane hit, FEMA released temporary maps, which would help people start the rebuilding process. These maps were known as Preliminary Work Maps (PWM). These PWMs are considered the best available information until the real FIRM maps are released. However, the new FIRM maps for NYC will not become available until around 2015, due to the long process the maps undergo before being released. Initially, FEMA releases the Preliminary FIRMs, which contain all the new elevation research performed since 2010. These maps then undergo a public review and appeals process, where they are further adjusted and finally released as official FIRM maps. A PWM of New York City can be seen in Figure 29, below. Comparing the PWM to the Hurricane Sandy Flood area shows that FEMA considered the hurricane a 500-year storm and updated the PWM accordingly. This tells us that risk assessment (which is solely based on past events) can never be fully understood, but can only get clearer as more events occur.

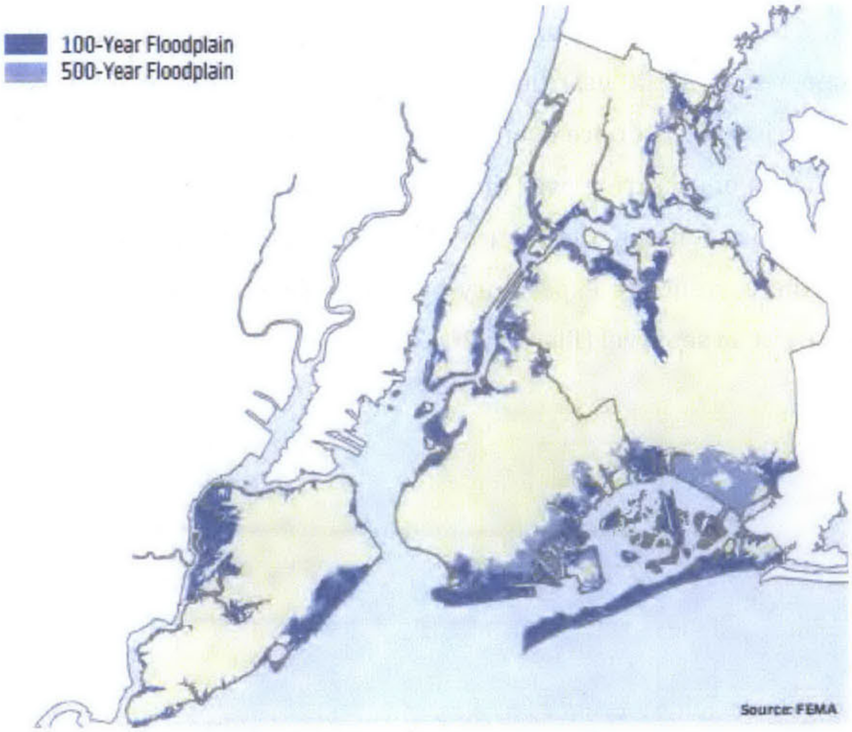
According to *"A Stronger, More Resilient New York"*, the new 100 year floodplain in the PWMs is larger than the area in the 1983 map by approximately 15 square miles, or 45%. There are now 67,700 buildings in the floodplain, which is an increase of 90%. These buildings encompass over 534 million square feet of floor area, which is an increase of 42% from the old maps. The number of residential units is up to 196,700. That is an increase of about 61%. The largest statistic is the population that is now in the new floodplain. This number has risen 83% to almost 400,000, which makes New York the city with the most citizens located in a floodplain.

Hurricane Sandy highlighted the need for improvement in the current FEMA flood-mapping process. FEMA's whole process- the lack of regular updates, along with the time involved in performing these updates and the communication to people has made it difficult for residents, business owners, infrastructure operators and governments to address their own flood risks.



Source: FEMA (MOTF 11/6 Hindcast surge extent)

FIGURE 28: HURRICANE SANDY FLOOD AREA VS. 1983 FIRM (PLANYC, 2013)



Source: FEMA

FIGURE 29: 2013 PRELIMINARY WORK MAP OF NYC (PLANYC, 2013)

New York City has taken action to combat one form of flooding. It now requires new waterfront development to design for future sea level rise and other various coastal events. As stated earlier, the City pushed FEMA to update their maps so that residents and business owners could better understand the existing risks from flooding. However, the City also realized that new maps may not even provide an accurate description of the flood risks in the future. To ensure that the City would always have the most up to date information, it formed the Nonprofit Coordinating Committee of New York (NPCC) and the Climate Change Adaptation Task Force by writing them into law. Their job was to update local climate projections and identify and implement strategies to address the projected risks.

Before getting into actual risk calculation, it is necessary to understand the 100 year flood. As previously stated, it is not the flood that is guaranteed to happen once every 100 years, but rather, it is the flood that is expected to happen once over the course of many 100 year periods. It identifies the probability of a storm that has a 1 in 100, or 1%, chance of occurring over the course of any given year. Similarly, a 500 year flood has a 0.2% chance of occurring in any one year period. Additionally, this flood can happen on any given day, no matter how soon the previous occurrence was. For example, if a 100 year flood occurred today, it can just as easily occur tomorrow, as well. However, this 1% chance of occurrence can be misleading because as the statistics add up, so does the probability, therefore decreasing the name of the flood to, say, a 50 year flood (2% chance of occurring yearly). This 1% chance of occurrence might seem small but it makes a difference for a business or a homeowner. A 100 year flood today, without considering future sea level rise, has a 26% chance of occurring at least once over the life of a 30 year mortgage. Additionally, a 100 year flood has a 45% chance of occurring over the 60 year life of a power substation. However, even if these values do not cause concern, the chance of witnessing a 100 year flood over the lifetime of a child born today (the current life expectancy of a New Yorker is 80.9 years) is 56 percent, not including the future rise in sea level (PlaNYC, 2013).

4.2 CALCULATION OF RISK AND BENEFIT

As previously stated, many different designs can be created for the proposed barrier system in New York Harbor. If multiple designs cover all the required criteria, standard property that determines the most feasible design is almost always cost. This cost includes the initial cost to build the structure, standard maintenance of the structure and the cost to replace parts of the structure when damaged. The structure is damaged when it undergoes an impact. These multiple impacts can weaken a structure which brings up the following question- Is it cheaper to use better materials and a stronger design initially or constantly replace the damaged parts in the future. This process is called risk based design optimization. An example of an impact may be a tsunami or a ship that hits a barrier.

For the purposes of this analysis, impacts will not be considered. Moreover, the barriers will not be composed entirely of gates along their span, but rather one gate for every barrier. This will minimize the maintenance costs because the rest of the barrier will be a wall. The height of the barrier will also change the initial cost but can prevent costs from damage to the City when a less probabilistic flood occurs.

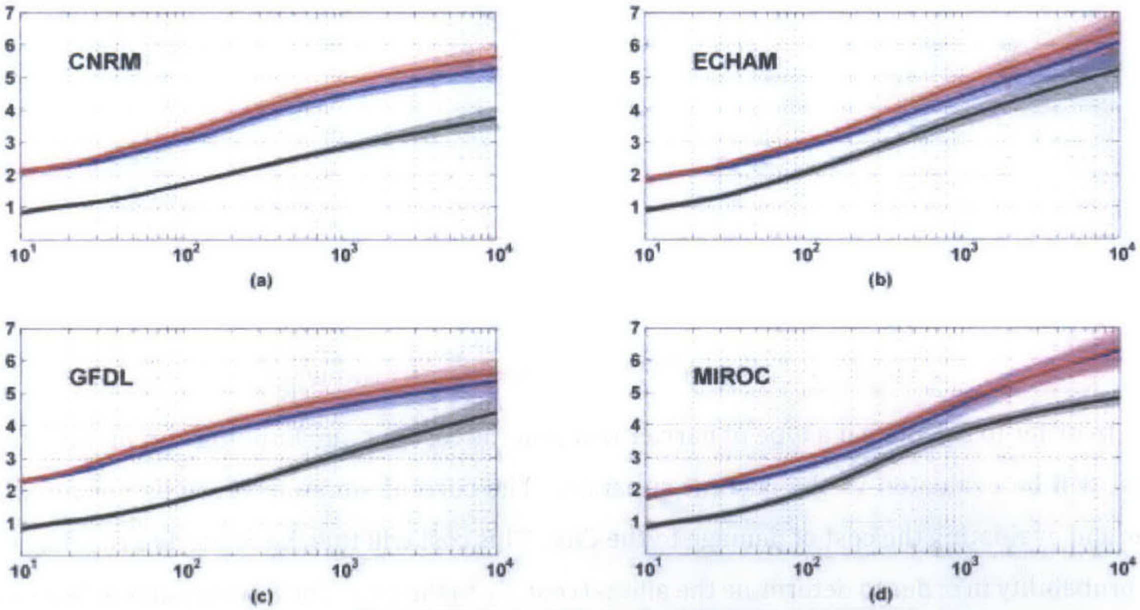


FIGURE 30: FUTURE STORM SURGE HEIGHTS FOR NEW YORK CITY (LIN, ET AL., 2012)

According to computer models specifically applied to New York City (Lin, et al., 2012), over the next century, water levels will rise, making the 100 year floods and 500 year floods into 50 and 240 year floods, respectively. The models predicted a water level rise of 1.6 to 4.9 feet. Figure 30, which is taken from the same research report, shows four different models computing current and future flood return levels, assuming sea level rise is 3.28 feet (1 meter).

In the figure above, the black line corresponds to the current estimated flood return levels. The blue line corresponds to IPCC-AR4 A1B climate scenario. This is a scenario published by the Intergovernmental Panel on Climate Change where the climate is affected by all energy sources equally. The red line corresponds to a storm that has a 10% increased radius (the distance from the eye of the storm to the edge) and a 21% increased radius of maximum wind, which creates a larger storm surge. The shade shows the 90% confidence level. The x-axis is the return period (years) and the y-axis is the flood height (meters). The predicted 500 year flood height is about 4.1 meters (13.45 feet). The predicted 1000 year flood height is about 4.9 meters (16.1 feet).

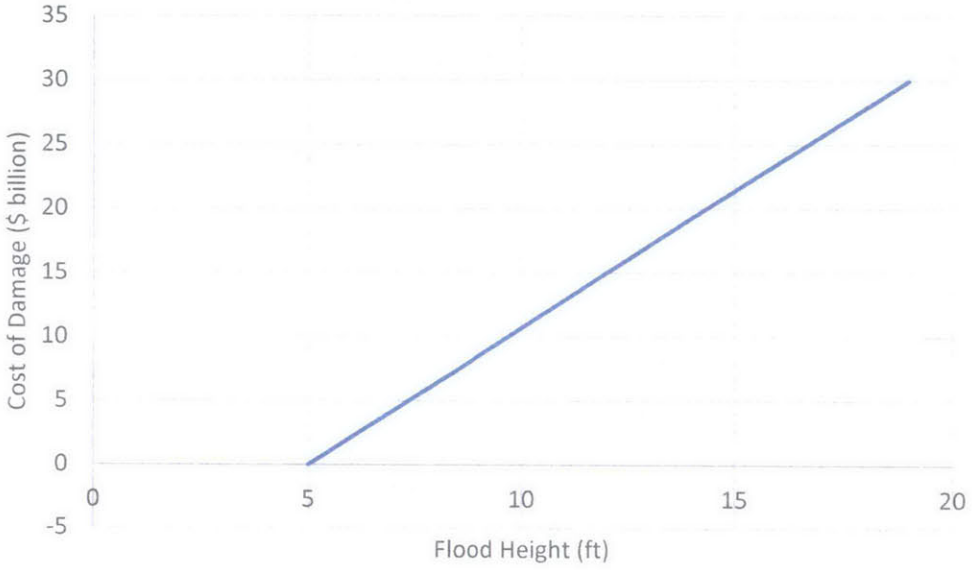


FIGURE 31: DAMAGE COST VS FLOOD HEIGHT (NO WALL)

In order to calculate if a type of barrier is worth the cost put into building and maintaining it, the cost will be evaluated vs the current situation. The current situation involves not building a barrier and evaluating the cost of damage to the City. This cost will then be related to the derivative of the probability in order to determine the annual cost, C_A, to the City. The lowest parts of Manhattan are only 5 feet above mean water level. Therefore, the calculations will assume that no damage occurs from surges up to 5 feet. Anything higher than that will be linearly related to the damage that Hurricane Sandy cost NYC. As aforementioned, the hurricane reached a peak height of 13.88 feet and cost the City $19 billion. Figure 31 shows this relationship. For the purposes of this calculation, the variable *x* will correspond to the water height above sea level. The cost equation is calculated as

$$C(d) = 0 \; for \; x < 5$$

$$C(d) = 2.14x - 10.7 \; for \; x \geq 5. \tag{1}$$

Taking the average depth that the four models predicted, the probability of occurrence for every future flood depth was determined. The annual exceedance frequency, N, is the inverse of the return period, T. This result is shown in Figure 32.

$$N = \frac{1}{T} \tag{2}$$

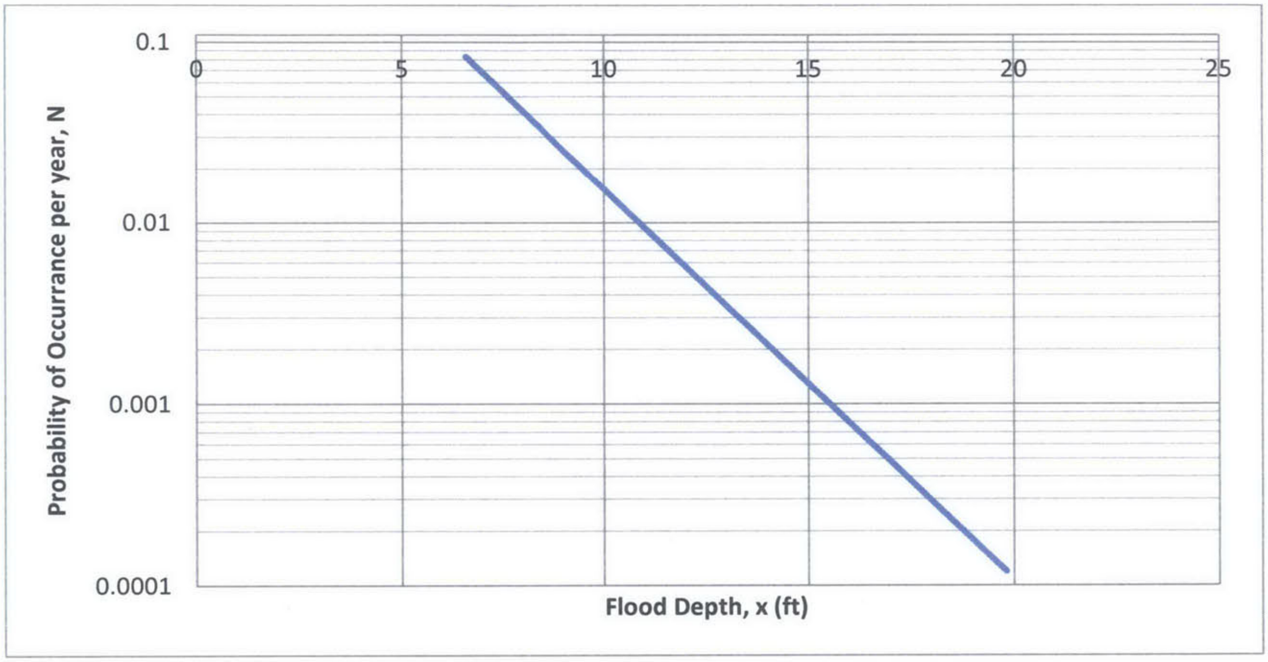


FIGURE 32: DEPTH VS PROBABILITY OF OCCURRENCE

The curve that fit this data has an equation,

$$N = 2.1656e^{-0.495x}. \tag{3}$$

The annual cost was then calculated using,

$$C_A = \int_5^{\infty} C(d)n(d)dx, \tag{4}$$

where *n(d)* is the probability of flooding between a depth range of *x* and *x + dx*.

$$n(d) = -\frac{dN}{dx}. \tag{5}$$

Assuming a wall of a specific height is built, the same integral can be evaluated between the height of the wall and infinity because any flood less than the height of the wall will not cause damage and if the flood does overtop a wall, it will flood the City with a surge of the same height. The difference between the annual cost of the current situation and the annual cost from any height wall is the cost savings to the city that the wall will provide. The annual damage cost to the City for various wall heights and cost savings per year is shown in Table 3. The full range of data is shown in Figure 33.

TABLE 3: DAMAGE COSTS AND SAVINGS FOR NYC FOR VARIOUS WALL HEIGHTS

Wall Height above mean sea level (ft.)	Annual Cost of Damage ($ million/ year)	Cost Savings of Wall to City ($ million/year)
0	787.967	0
10	230.454	557.513
15	33.21	754.757
20	3.958	784.009

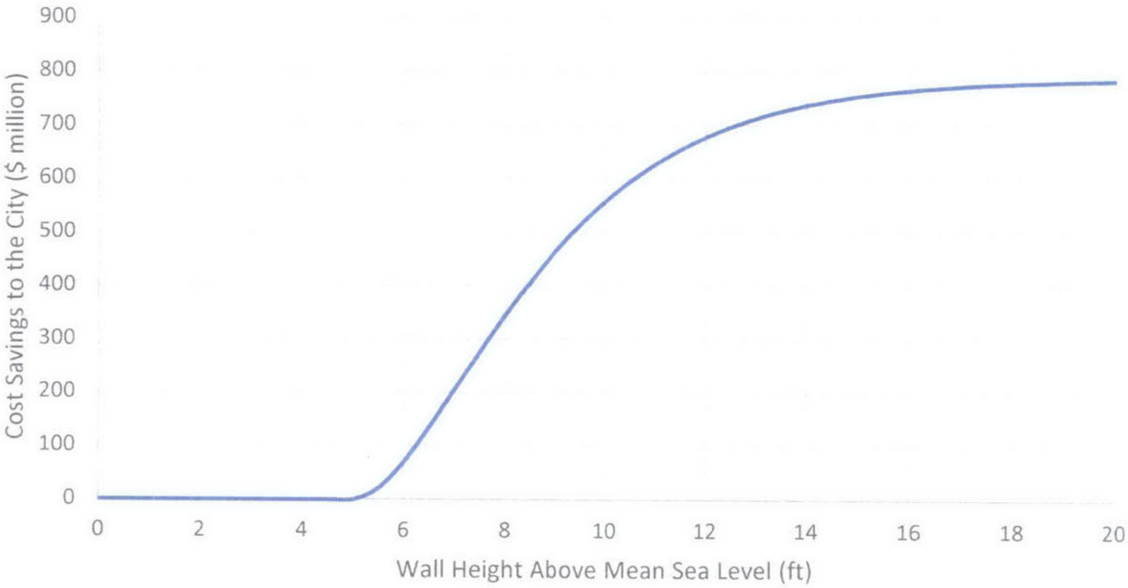


FIGURE 33: WALL HEIGHT VS COST SAVINGS

In order to combine annual costs with the fixed initial costs over time, a lifetime for the structure needs to be determined. This magnitude should be in the range of 10^2 years because design and construction may take about 15-20 years. All barrier heights up to 20 feet above mean sea level will be analyzed to determine the life-cycle benefit for the structure. The equation for life cycle benefit is

$$LCB = LCC(without\ barrier) - LCC(with\ barrier) \tag{6}$$

where the life-cycle costs without a barrier and with a barrier are

$$LCC(without\ barrier) = (ADC\ without\ barrier) \times (number\ of\ years) \tag{7}$$

$$LCC\ (with\ barrier) = ICC + (AMC + ADC\ with\ barrier) \times (number\ of\ years)\,. \tag{8}$$

ICC is the initial construction cost, AMC is the annual maintenance cost, and ADC is the annual damage cost. Setting LCB = 0 and solving for the number of years yields the amount of time required for a barrier of that height to start providing a positive annual benefit.

$$number\ of\ years = \frac{ICC}{(ADC\ without\ barrier - AMC - ADC\ with\ barrier)} \tag{9}$$

Additionally, the number of years could be discounted for the cost-benefit analysis. This analysis was not performed due to the uncertainties in this study.

4.3 CALCULATION OF LIFE-CYCLE BENEFIT

Due to the fact that a project of this magnitude and scope has never been done before, costs are highly uncertain. Therefore, in order to determine the feasibility of the barrier, a lower and an upper bound initial cost were assumed. The lower bound assumed a $10 billion cost for all submerged parts of the structure (everything from the seabed to the mean water level) and a $200 million cost for every additional 0.5 foot increase in wall height above sea level. The upper bound assumed a $20 billion cost for all submerged parts of the structure and a $500 million cost for every additional 0.5 foot increase in height. Table 4 shows the lower and upper bound initial construction costs of some barrier heights. The cost may, however, be anywhere between the upper and lower bounds.

TABLE 4: INITIAL COST FOR CERTAIN BARRIER HEIGHTS

Barrier Height Above Sea Level (ft.)	Initial Construction Cost ($ billion)	
	Lower Bound	Upper Bound
5.5	11.1	22.75
10	12	25
15	13	27.5
20	14	30

The life-cycle benefit is the amount of time required for something to become profitable. In this case, it is the number of years required to make the barrier start paying for itself. These results were calculated using Equation 9. Figure 34 shows the results of these calculations.

Based on these results, the global barrier option becomes very feasible. This is because even the upper bounds curve does not require a large timeframe to start saving the City money. In fact, for all wall heights between about 7.4 feet to the maximum 20 foot height, the wall requires less than 100 years of service to start saving the City money. For example, based on the upper bounds curve, a wall of only 10 feet above sea level requires only 45 years of service.

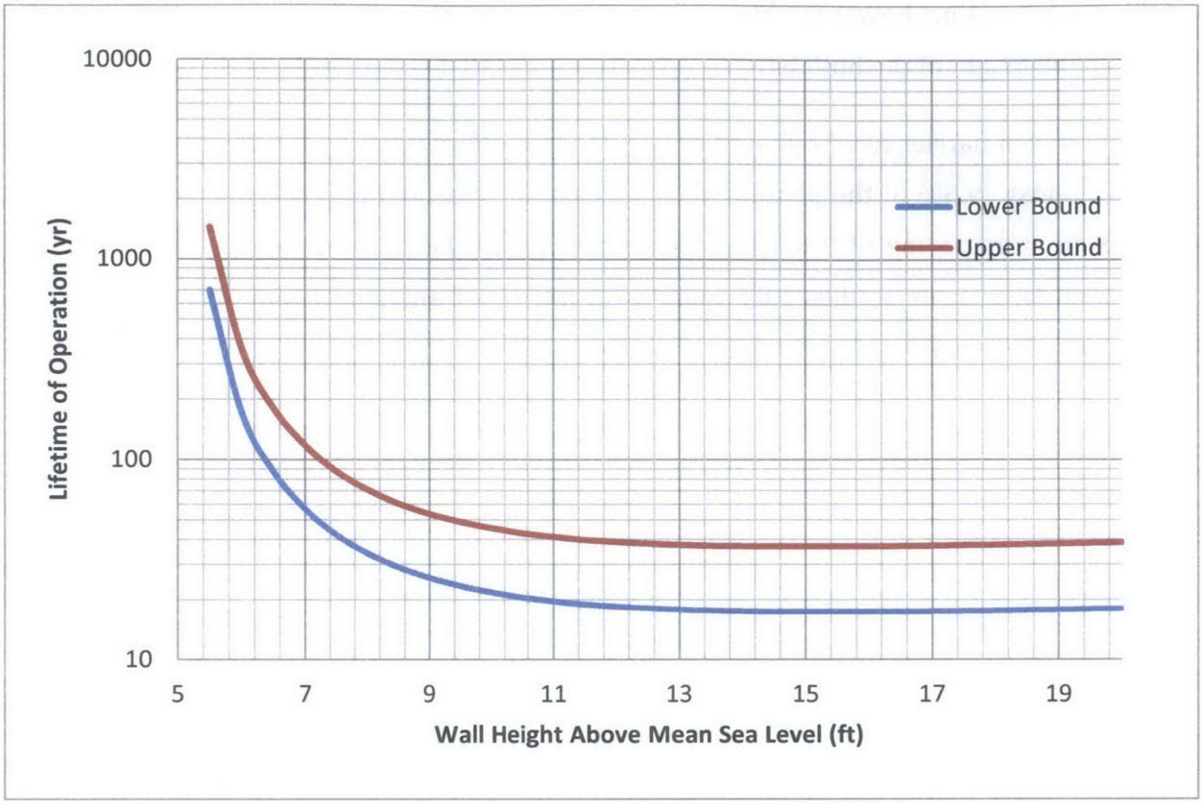


FIGURE 34: YEARS REQUIRED TO ACHIEVE POSITIVE LIFE CYCLE BENEFIT

The curves reach a minimum lifetime of operation before they start to curve back up again. This is because the cost savings from any additional wall height is less than the cost of that additional wall height, and needs a longer amount of time to be paid off. The minimum lifetime for the upper bounds curve is around 36.66 years at a wall height of 15 feet above sea level. The lower bounds minimum is around 17.32 years at a wall height of 15.5 feet above sea level. Moreover, since these minimums for the extreme cases only differ by a 0.5 foot wall height, all values in between will be within this 0.5 foot variation, as well.

Since the time for the life cycle benefit is so low, any height greater than about 6.5 feet above sea level can be feasible (worst case scenario requires 179.1 year life-cycle). This means that the City can construct any size wall it wants. If the City wants the greatest return on its investment, then the City will choose the minimum point from Figure 34.

If the City wants to focus more on preventing damage than getting the quickest return, it will choose a barrier height where the slope is positive. However, what a business chooses to do does not always align with what the consumer wants. The consumers, in this scenario the citizens, want total protection from flooding; however, this is impossible because there is always a possibility of a flood greater than the height of the built barrier, no matter how tall it is initially built to.

The chosen barrier height should be the one that offers the full 20 feet because it provides protection against 99.5% of the possible damage cost per year and only takes a maximum of 1.83 more years to start paying off than the option that offers the quickest return. On a project as important and large scale as this, 1.83 years is an irrelevant amount of time when discussing an increase in people's well-being and safety.

5. CONCLUSION

From the above analyses, the location, type and height of all barriers has been determined. The location was established by analyzing the water depths at different locations around the City, taking into account various parameters such as, additional neighborhoods protected, simplicity, depth of water and barrier length, etc. The type of barrier chosen was determined from water depth of the proposed location, width of gate opening, aesthetics and maintenance, among others. The height of the barrier was selected by running a life-cycle benefit analysis. This analysis used assumptions in the initial construction cost, future frequency of water levels, maintenance costs and flood damage cost to the City.

The final barrier design was chosen to be a two-barrier system. The East River barrier would be located below the Whitestone Bridge and the other barrier would connect Breezy Point, NY, and Sandy Hook, NJ. In order to reduce maintenance and the risk of a system-wide failure, each barrier would contain only one gate that allowed ships to enter and exit. The remainder of each barrier would be just a wall.

For the East River barrier, a vertical flap gate, similar to the ones being built in Venice, would be used. This type of barrier is ideal because this location does not have that great a silting problem, something that is a major concern for vertical flap gates. Additionally, because the East River connects with the Long Island sound, wave and vibration action are minimal. The other barrier gate type was chosen to be a horizontally rotating arch because of the relatively shallow water depths at this location and with its strength in the three aforementioned categories. The rotating arch, however, must cover a gate width of 1000 feet, a first of its kind.

The height of the proposed barrier should be 20 feet. At this height, the City saves 99.5% of the predicted annual damage costs due to flooding. Moreover, based on the life-cycle analysis, it only takes the 20 foot barrier less than two years extra to start providing the City with a return on investment when compared to the wall height that requires the least time to provide a positive life-cycle benefit.

Although this research includes theoretical values in many places, the methodology developed in this thesis will provide a better solution when more accurate values are obtained.

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APPENDIX A: PROPOSED BARRIER LOCATIONS

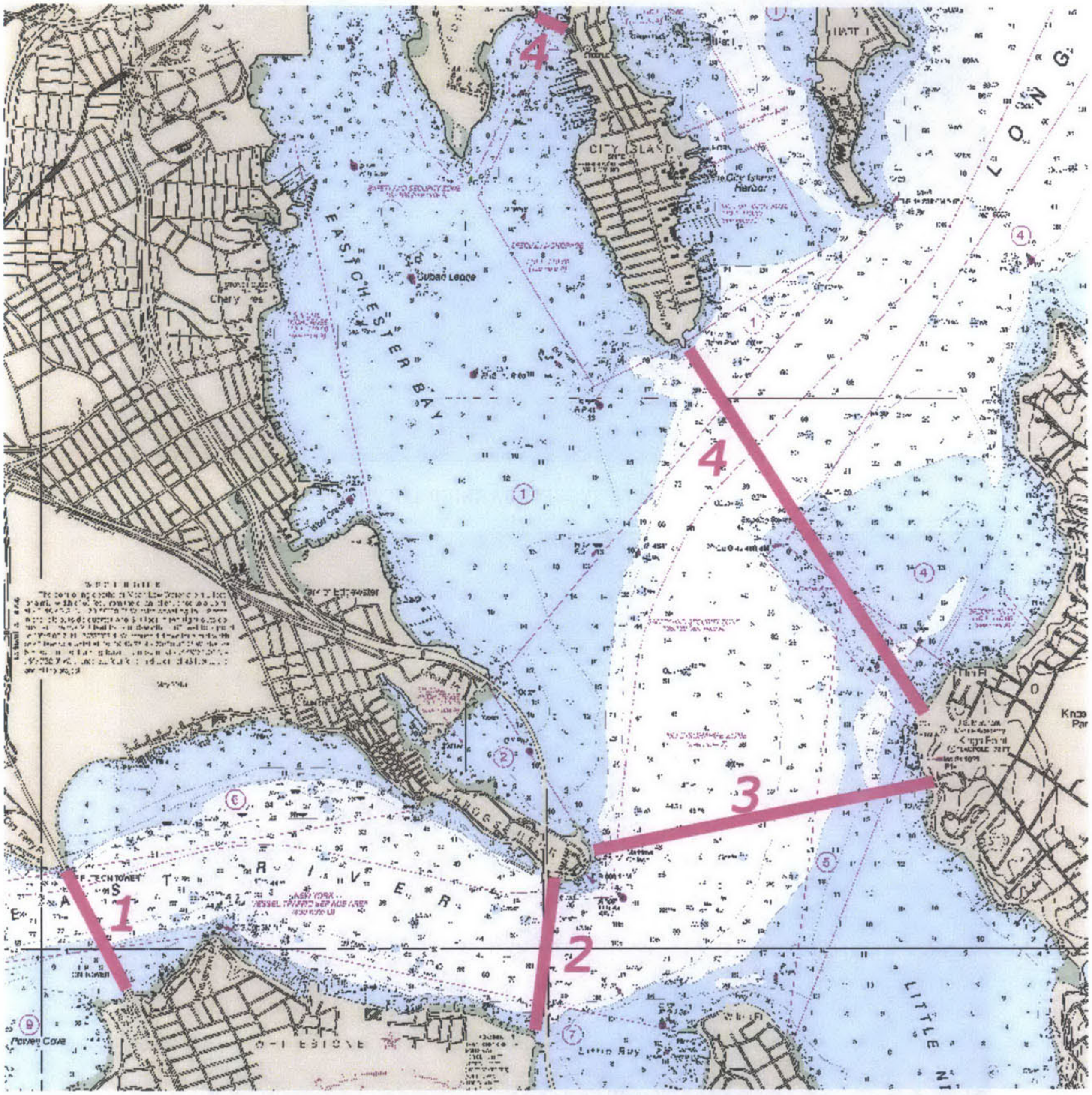

FIGURE 35: EAST RIVER BARRIER PROPOSALS

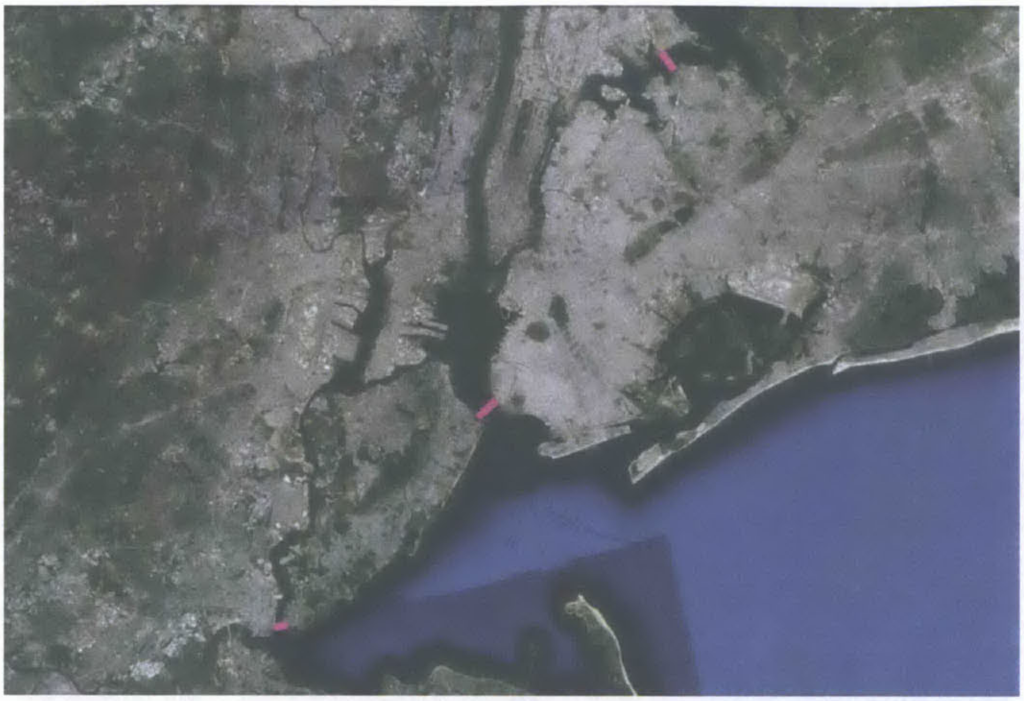

FIGURE 36: 3-GATE SYSTEM BARRIER LOCATIONS

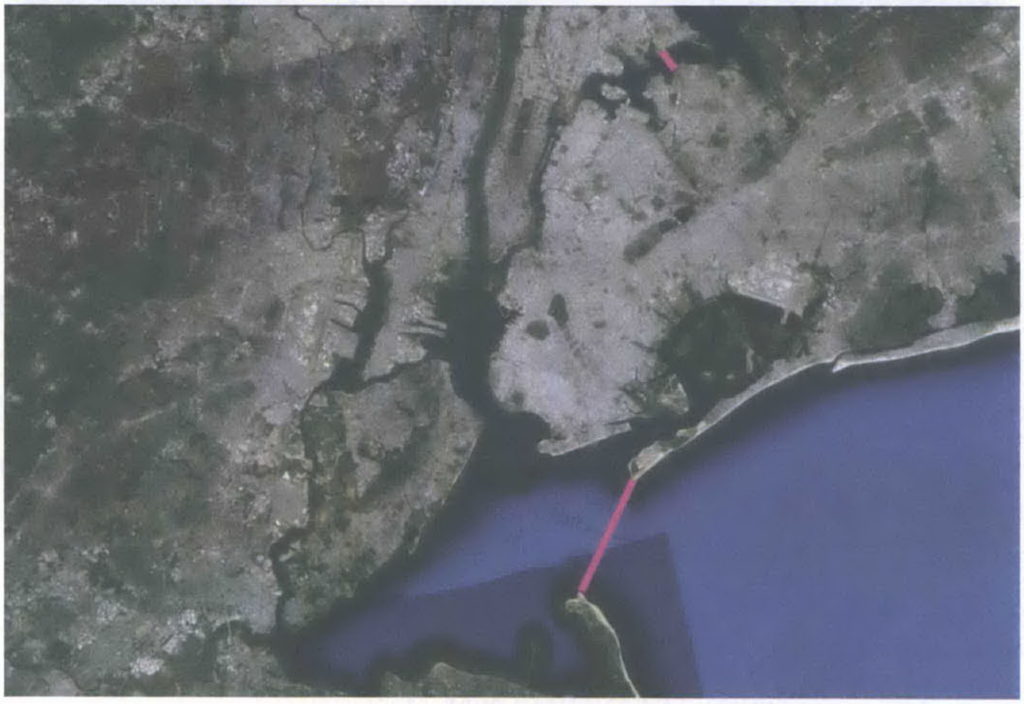

FIGURE 37: 2-GATE SYSTEM BARRIER LOCATIONS