Head of Bay Coastal Resilience

Jamaica Bay, New York



Head of Bay Coastal Resilience Princeton University and City College of New York with funding from the National Science Foundation (NSF) EAR-1520683 and Princeton Environmental Institute's Grand Challenges program. October 2018 **Project Team** Rennie Jones, Paul Lewis, Ning Lin, Reza Marsooli and Guy Nordenson (Princeton University) and Catherine Seavitt (City College of New York) Interns Yolanda Jin and Reuben Zeiset (Princeton University) Collaborators Michael Oppenheimer, James Smith, and Gabriel Vecchi (Princeton University), Kerry Emmanuel (Massachusetts Institute of Technology), Howard Kunreuther (University of Pennsylvania), and Thomas Knutson (NOAA Geophysical Fluid Dynamics Laboratory) **Special Thanks to** American Littoral Society Governor's Office of Storm Recovery Jamaica Bay-Rockaway Parks Conservancy New York Department of State NYC Department of City Planning NYC Department of Parks and Recreation Port Authority of New York and New Jersey Regional Plan Association Tantala Associates, LLC The Nature Conservancy

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executive summary

The Head of Bay Coastal Resilience project aims to strengthen east Jamaica Bay's flood resilience by providing actionable strategies for adaptation. The project is a design and planning element of the National Science Foundation (NSF EAR-1520683) "Hazard SEES: An Integrated Approach to Risk Assessment and Management in Responding to Landfalling Hurricanes in a Changing Climate" led by the principal investigators, Ning Lin, James Smith, Michael Oppenheimer, Gabriel Vecchi, and Guy Nordenson (Princeton University), Kerry Emanuel (Massachusetts Institute of Technology), Howard Kunreuther (University of Pennsylvania), and Tom Knutson (NOAA Geophysical Fluid Dynamics Laboratory). The design and planning study proposes a public infrastructure system at the watershed scale combining coastal flood risk management with investment in ecological health and opportunities for public recreation.

Examining the eastern extents of New York's Jamaica Bay, known as the "Head of Bay," as a case study, the proposal develops novel measures for adapting to rising sea levels, king and spring tides, extreme rainfall, and storm surge. The following report offers a methodology for combining scientific research with inventive design to adapt to a changing climate. It is

intended to provide a model for approaching adaptation across disciplines and administrative boundaries.

The burning of fossil fuels and land use changes since the industrial revolution have led to a significant increase in greenhouse gases, including carbon dioxide and methane. These gases trap solar radiation within the planet's atmosphere, causing global temperatures to rise. As a result, human activities have fundamentally altered our climate. The climate is undergoing changes that are projected to accelerate as atmospheric concentrations of greenhouse gases continue to increase. 1

As global temperatures increase, the ocean and atmosphere of the Northeast are becoming warmer. Sea levels in the New York City area are projected to rise one to two feet by mid-century and by as much as six feet by the end of the century. This will raise the base water level such that flooding due to high tides and extreme storms will reach further inland. Additionally, a warmer ocean is likely to generate extreme weather of greater intensity, likely leading to more frequent or more intense hurricanes. In coastal areas such as Jamaica Bay, adaptation must account for these challenges in a way that allows for modification over time.

Jamaica Bay is a tidal estuary sheltered from the Atlantic Ocean by the south shore of the Rockaway Peninsula. The bay is at once a wilderness of wetlands and a dense urban environment. The salt marshes, mudflats, uplands, ponds, and forests are home to more than one hundred species of finfish, several types of endangered reptiles, and over 325 species of birds, approximately half of those found in the Northeast. It is bounded by Brooklyn to the west, Queens to the north and south, and Nassau County to the east.

Approximately three million people live within the Jamaica Bay watershed, or the area of land that drains into the bay. The immediate areas surrounding the bay, much of which were historically wetlands, are now highly-developed neighborhoods that sit just above sea level. Proximity to the shore makes these areas susceptible to tidal flooding and storm surges. The northern bounds of the Jamaica Bay watershed are formed by the terminal moraine, a ridge that runs the length of Long Island and rises several hundred feet above the shoreline. Rainwater falling on this upland area can collect in the lower lying regions at the bay's edge and cause flooding from inland.

New York City's susceptibility to flooding has been known for several decades. The United States Army Corps of Engineers (USACE) issued plans for sea walls and surge barriers along Jamaica Bay's inlets and barrier island beaches in the early 1960s, more than fifty years ago. These projections became reality in October 2012, when Hurricane Sandy made landfall near Atlantic City, New Jersey. The resulting damage was extensive and raised the issue of flood protection for many New Yorkers. However, the enormity of the task and its associated costs have delayed action, and proposals for a regional solution are still in the conceptual and planning phases.

Head of Bay Coastal Resilience considers an area of limited scope to suggest that smaller interventions can have large impacts, be completed more quickly in discrete installments, and tie into neighboring solutions for cost effectiveness and phasing. Rather than relying on a one-size-fits-all solution, this approach allows for a closer look at the particular challenges faced by each community.

The proposed system leverages existing

topography to reduce ecological impact and overall cost. A storm surge barrier, comprised of a berm and a closure structure, ties into existing high points at the east end of the bay to protect thousands of homes and businesses, including John F. Kennedy International Airport. This barrier is designed to prevent flooding during extreme storm events. A lower, passive barrier allows the gates of the closure structure to remain open during smaller storm and tidal flood events, reducing demand on the storm surge barrier and preventing damage to existing wetlands within the protected area. The two-layered system designates an area of transformation that allows for a variety of approaches to adaptation, including elevation and strategic retreat.

Building on previous initiatives conducted in Jamaica Bay, this report approaches climate adaptation through design at urban, ecological, and architectural scales. The project was funded by the National Science Foundation and is informed by advanced probabilistic computational modeling of future flood hazards incorporating sea level rise.

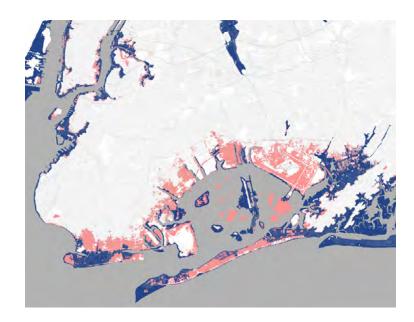
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introduction

The ecosystems and economies surrounding Jamaica Bay are characterized by their proximity to water. Yet many residents were unaware of the bay in their own backyards until Sandy inundated vast areas of typically dry land. While efforts to improve New York City's resilience existed before the storm, Sandy ushered in a new era of consciousness for many that experienced its damage or witnessed it from afar. At the same time, the detrimental effects that centuries of urbanization and development have wrought on the bay's natural ecosystems are becoming better understood. A recent paradigm shift in flood prevention infrastructure suggests moving away from standard concrete flood walls and other hard infrastructure in favor of naturebased solutions. With an increasing interest in this soft infrastructure, including wetlands, dunes, and living shorelines, a broader range of options is up for consideration. Head of Bay Coastal Resilience embraces a combination of hard and soft systems to support ecological health, offer new opportunities for recreation, encourage sustainable development, and reduce flood risk.

Flooding along Norton Drive in Bayswater during a high spring tide on July 12, 2018. The USGS tidal gage at Inwood recorded a water elevation of 4.46 feet above NAVD 88 at the time this photograph was taken, compared to 10.57 feet above NAVD 88 on October 29, 2012, during Hurricane Sandy. Photograph by Rennie Jones.

Historic Flooding

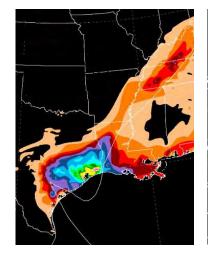


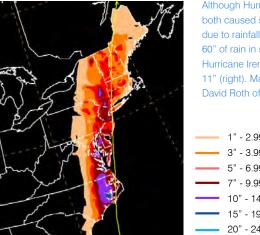
Inundation during Hurricane Sandy

FEMA 100-Year Floodplain (1% annual chance of flooding) Effective during Hurricane Sandy

Sources

FEMA Hurricane Sandy Impact Analysis was derived from USGS sensor data and issued in February 2013. FEMA National Flood Hazard Layer data, showing the area of the 100-Year floodplain, was effective for flood insurance rate maps (FIRMs) at the time Sandy occurred. FIRMs for New York City were last issued in 2007 using data from 1983. FIRMs for Nassau County were last issued in 2009 with updated data.





Although Hurricanes Harvey and Irene both caused significant flood damage due to rainfall, Harvey brought up to 60" of rain in some areas (left), while Hurricane Irene brought a maximum of 11" (right). Maps of rainfall maxima by David Roth of NOAA.

 1" - 2.99"	 25" - 29.99"
 3" - 3.99"	30" - 34.99"
 5" - 6.99"	 35" - 39.99"
 7" - 9.99"	 40" - 44.99"
 10" - 14.99"	45" - 49.99"
 15" - 19.99"	 50" - 59.99"
20" - 24.99"	60" - 60.58"

Hurricane Sandy made landfall near Atlantic City, New Jersey on October 29, 2012. Though the storm was downgraded from a Category 1 hurricane to a post-tropical cyclone by the time it hit the Northeast, its massive size generated a catastrophic storm surge that caused water levels to rise nearly 14' in some areas of New York City. The storm inflicted more than \$19 billion in damages to New York City alone and an estimated \$50 billion in damages overall. A 44 New Yorkers died as a result of Sandy and many more were left homeless or without running water and electricity.

In the United States, homeowners insurance policies rarely cover flooding. Flood insurance must be purchased through the National Flood Insurance Program (NFIP), which is administered by the Federal Emergency Management Agency (FEMA). Property owners with federally-

backed mortgages are required to purchase flood insurance if their property is within FEMA's 100-year floodplain. The extent of the floodplain is regulated by Flood Insurance Rate Maps (FIRMs). While the FIRMs for Nassau County were updated just a few years before Sandy, the New York City maps reflected data from 1983. The older data underrepresented the area likely to be flooded, so most New York City property owners affected by Sandy did not have flood insurance at the time of the storm.

In 2015, FEMA issued preliminary updated FIRMs for New York City. These maps showed a significantly expanded floodplain, greatly increasing flood insurance premiums for many New Yorkers. The city appealed FEMA's update, reducing insurance premiums for many residents but perpetuating the lack of insurance coverage.

In general, the NFIP has not been a reliable

mechanism for flood resilience. FEMA's mapping process does not consider the effects of sea level rise and ocean warming due to climate change, and likely underestimates the area at risk. By exempting communities behind flood control structures from insurance and building code requirements, these maps also promote detrimental development practices and create a false sense of security. By promising the possibility of rebuilding in risky areas, the program subsidizes development in places prone to costly and often cyclical damage. National flood insurance rates remain artificially low due to political pressure, and the program has not recouped the costs of rebuilding since before Hurricane Katrina in 2005.6

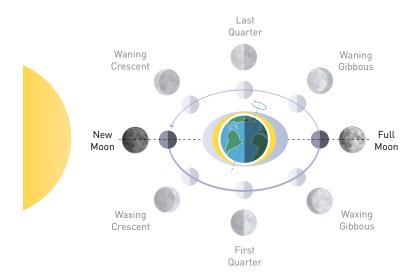
Sandy's storm surge created a breach between the bay and the ocean at Mantoloking, New Jersey. Photograph taken November 2, 2012 by Greg Thompson of the US Fish and Wildlife Service.



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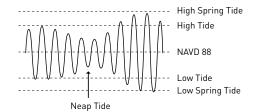
Types of Flooding

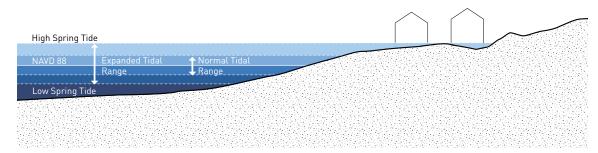
Hurricane Sandy brought a storm surge reaching up to 14 feet high in some coastal areas. It heavily damaged areas of Manhattan, Jamaica Bay, and Nassau County, putting this type of flooding on the map for many New Yorkers. But damaging and potentially dangerous flood waters can also come from upland rainfall, as in the case of Hurricane Harvey, or occur on sunny days during exceptionally high tides. As the sea level rises, it is becoming increasingly apparent that we must adapt to various types of flooding. This project considers flooding due to spring tides, extreme rainfall, and storm surges caused by hurricanes.



Spring Tides

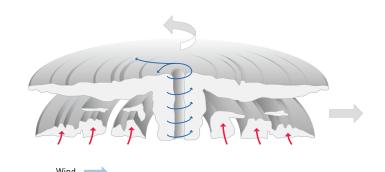
Spring tides occur twice per month, at the new moon and the full moon, when the moon's gravitational pull is in line with the sun's, amplifying changes in water level.

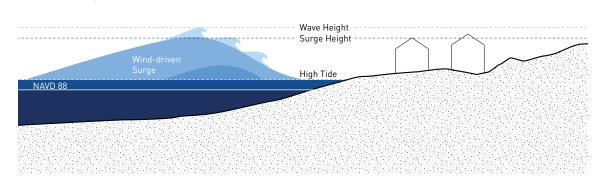




Storm Surge

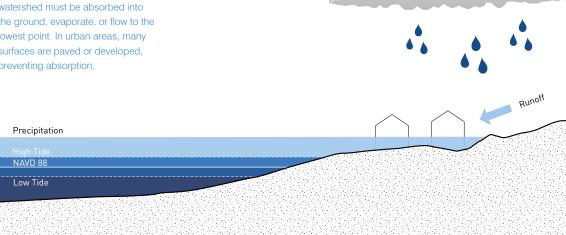
Hurricane winds push the ocean's surface to unusually high elevations. These tend to increase as the storm moves toward shallow shores. Waves may also add to water levels.





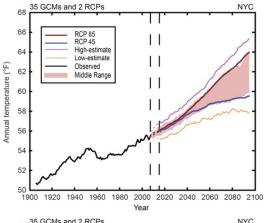


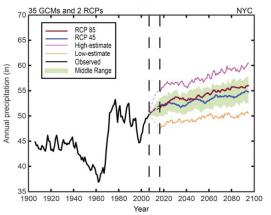
Each drop of rain that falls within a watershed must be absorbed into the ground, evaporate, or flow to the lowest point. In urban areas, many surfaces are paved or developed, preventing absorption.

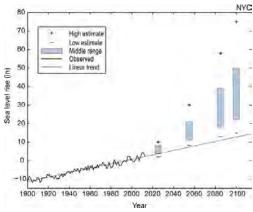


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Climate Projections







Source Building the Knowledge Base for Climate Resiliency: New York City Panel on Climate Change 2015 Report The climatic changes set in motion by human activities are expected to accelerate over the coming century. The effects will be much more drastic if business proceeds as usual, but the natural delay in the climatic system is such that the ramifications of the previous century's activity have yet to fully unfold. Global temperatures are increasing, but the effects differ at a local scale.

In the New York City area, the amount of total annual rainfall and number of extreme precipitation events are expected to increase. Sea level is on the rise, and water elevations are likely to rise by several feet within the next few decades and by as much as six feet by the end of the century. Scientists anticipate that there will be more of the most intense hurricanes in the North Atlantic, which will mean more of the heavy precipitation and storm surges they bring. These increasingly dynamic coastal conditions pose a significant hazard to communities, infrastructure, and ecosystems on the coast.

Opposite: The same location in Meadowmere, at the east end of Jamaica Bay, on July 12, 2018. The top image was taken during a high spring tide, showing minor coastal flooding, and the bottom image was taken approximately five hours earlier, during a low spring tide. The USGS tidal gage at Inwood recorded a water elevation of 4.46 feet above NAVD 88 at the time of the high spring tide, or 2.16 feet above the mean daily highest tide (mean higher high water). Photographs by Rennie Jones.





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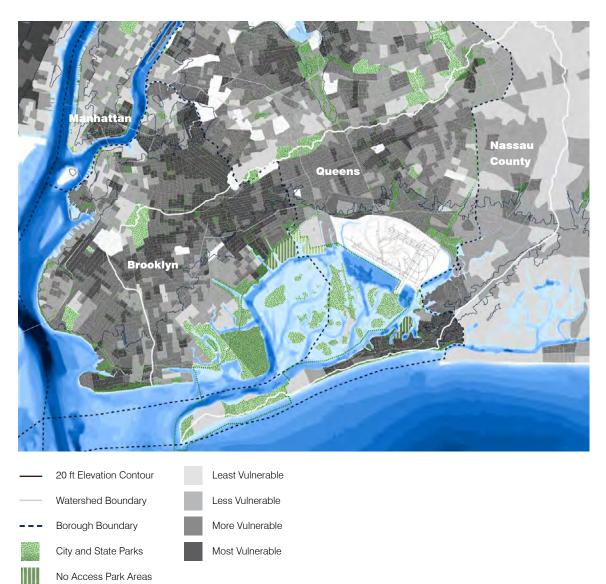
area at risk

The three million people who live within the Jamaica Bay watershed are a diverse group with varying histories, ages, languages, incomes, and access to resources. 1 Jamaica Bay also hosts a variety of the region's infrastructure, providing transportation to local residents and visitors from across the country and abroad. The Long Island Railroad and multiple expressways border the bay and allow access between Brooklyn, Queens, and Long Island. The A train trestle bridge and Cross Bay Boulevard span Jamaica Bay's waters and wetlands. At the east end, John F. Kennedy International Airport occupies an area of nearly 5,000 acres, more than one quarter the size of the bay itself.² Shipping and cargo routes rely on the bay's canals and water ways, and major oil storage facilities, large capacity power generators, and wastewater treatment plants sustain operations along the shore and throughout the region. A number of city and state parks and wildlife refuges border or sit within the bay, including Gateway National Recreation Area, the only national park accessible by subway. These communities, industries and ecologies are threatened by flooding due to sea level rise and extreme weather events.



A landscape architecture student tours the Jamaica Bay Wildlife Refuge in October 2017. The Fountain Avenue and Pennsylvania Landfills are visible in the background, obscuring portions of the Manhattan and Brooklyn skylines. Photograph by Rennie Jones.

Residents of Jamaica Bay



Sources

U.S. Census American Community Survey 2015, Centers for Disease Control and Prevention, Agency for Toxic Substances and Disease Registry, USGS National Hydrography Dataset (NHD)

Image at right: A girl swims in the Atlantic Ocean at Rockaway Beach along the south side of the Rockaway Peninsula



Jamaica Bay's status as a densely-populated urban estuary means it is highly vulnerable to catastrophic flooding. In New York City alone, approximately 400,000 people live within FEMA's 100-year floodplain.³ Many of these residents live in the flood zones surrounding Jamaica Bay. The Social Vulnerability Index (SVI) categorizes the anticipated resilience of communities under external stresses, including hurricanes and other natural disasters. The index is compiled by the federal Agency for Toxic Substances and Disease Registry and is intended to identify communities that may need additional attention during preparation and recovery phases. It is based on US Census variables, including poverty, vehicle access, number of residents with disabilities, English fluency, and prevalence of children and seniors. The map at far left depicts where areas of high social vulnerability exist in proximity to the shoreline and park space, revealing opportunities for new green spaces that could support community health and reduce flood risk.

Population Demographics

- Asian Descent
- African Descent
- European Descent
- Latinx Descent

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Hazardous Infrastructure



Waste Water Treatment Plant

+ Major Oil Storage Facility

+ Power Plant

Combined Sewer Overflow

City and State Parks

Capped Landfills

Sources

The Facility Registry Service (FRS) datasets from the Environmental Protection Agency, including: wastewater, power plants, hazardous waste sites, pollutant discharge sites, bulk storage facilities, toxic chemical sites. CSO data from Open Sewer Atlas and NYC Department of Environmental Protection.





Jamaica Bay Water Pollution Control Plant



Motiva Long Island Terminal



Jamaica Bay Peaking Facility



Allied Aviation Fueling Facility



Calpine Kennedy International Airport

New York City and Nassau County rely on power plants that burn natural gas and other fossil fuels to produce electricity. Several wastewater treatment plants, power generation facilities, and fields of oil storage tanks border Jamaica Bay. The area surrounding Head of Bay is an exceptionally concentrated area of potentially hazardous energy, fuel, and waste infrastructure. Many of these facilities are located at the shoreline to access the water for cooling, making them vulnerable to flooding. JFK Airport has its own 171.2 Mwh generation plant, located between the terminals, as well as a large fuel storage facility.

While wastewater treatment facilities are essential to treating the watershed's wastewater and stormwater before it flows into the bay, they can pose a threat if flooded. Ten of the city's fourteen wastewater treatment plants released partially treated or untreated sewage into the water during Sandy and nearly half of the pumping stations keeping the city's stormwater and sewage systems moving were out of service due to power failures.⁴ When Hurricane Harvey hit Houston, the largest energy corridor in the United States, floodwaters were contaminated with petroleum and other toxic chemicals that posed a health hazard to residents long after the water receded. In North Carolina, Hurricane Florence inundated coal ash pits and the stagnant poop lagoons of hog farms, trailing the contents into rivers, streams, and lakes as the floodwaters drained from the watershed.

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Transportation Infrastructure



Sources

National Geospatial Data Asset (NGDA) for New York State, New York City Metropolitan Transportation Authority (MTA), Open Street Map (existing runways), Regional Plan Association (proposed runways), Department of City Planning (NYC DCP)

Image at right: Three swans fly over the bay along Cross Bay Boulevard.



JFK International Airport serves 60 million passengers annually with 4 runways and 25 miles of taxiways, establishing it as sixth busiest in the nation and 22nd in the world. An estimated 1.4 million tons of cargo move through the airport each year, supporting 285,000 jobs and offering \$37 billion in regional benefits. As was typical in the 20th century, JFK Airport was constructed on filled marshlands that offered a flat expanse of readily available land. Much of the airport facility lies about 10' above the North American Vertical Datum of 1988 (NAVD 88), making it vulnerable to rising sea level and extreme storms.

Many residents and businesses of Jamaica Bay rely on New York City and Nassau County transportation infrastructure. Each weekday, 5.6 million people ride New York City subways and another 275,000 riders take the Long Island Railroad.⁷ The A Train, which connects to the Air Train to JFK Airport, is the only MTA subway line that serves the Rockaway Peninsula. This infrastructure is threatened by rising sea level and increasing storm activity. Sandy flooded all six subway, LIRR, and Amtrak tunnels under the East River, as well as the PATH and Amtrak tunnels under the Hudson River. Several lines were out of service for nearly a week, and the A Train causeway across Jamaica Bay was not restored until May 2013, more than six months after Sandy struck. 8

Infrastructure upgrades should be made in a way that increases the resiliency of train lines and roadways to prevent negative economic impacts to the communities that rely on them, and to ensure evacuation routes to coastal locations, including the Rockaway Peninsula, remain accessible prior to a severe storm.



Transportation to Work

- Car, truck, or van
- Public transportation
- Walking
- Biking

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To Elevate or Relocate?









































Many New Yorkers who sustained property damage during Sandy have opted to elevate their homes through New York City's Build it Back program. Elevating a home above the base flood elevation established by FEMA can reduce or eliminate mandatory flood insurance premiums imposed by the NFIP on buildings within the 100-year flood plain. Existing buildings can be modified and new buildings can be designed so the elevated foundations can sustain repeated flooding without compromising the aesthetic.

However, elevating a building can be prohibitively expensive or structurally infeasible. In some cases, relocation is the most practical option. Areas of Oakwood Beach, Ocean Breeze, and Graham Beach, three Staten Island neighborhoods built on former wetlands, sustained extensive damage during Sandy. Residents campaigned for a buyout program that would allow them to relocate without suffering the economic loss of their homes. Under the New York Rising Buyout and Acquisition Program, New York purchased hundreds of one-unit and two-unit residential properties heavily damaged by Hurricane Sandy, Hurricane Irene, or Tropical Storm Lee. In many cases, the state transformed these properties into open

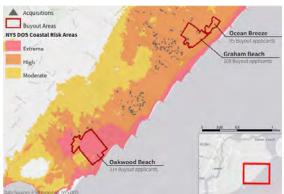
space or coastal buffer zones to protect against future flooding.

Build it Back and the New York Rising
Buyout and Acquisition Program represent two
different approaches to community resiliency.
One aims to make it more feasible to live in a
flood zone and the other makes managed retreat
a tenable option. Both recovery programs serve
as a template for the development of policies and
programs to increase New York's capacity to adapt
to climate change.

Opposite: Elevated houses in Broad Channel, Meadowmere, Edgemere, and Bayswater following Hurricane Sandy. Top: A resident of Ocean Breeze, Staten Island posted signs thanking Governor Cuomo for approving the state's buyout program for the area after it was heavily damaged by Hurricane Sandy. Photograph credit Matt Green via Flickr, December 14, 2014. Bottom: Designated buyout areas on Staten Island, including Ocean Breeze, Graham Beach, and Oakwood Beach. Image by the Governor's Office of Storm



Recovery, 2017.



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history of development

Jamaica Bay's shoreline has never been truly static. Tides, currents, and geomorphic processes have shaped the bay since glaciers retreated from the region 20,000 years ago. Sporadic extreme weather events have had a more instantaneous effect on this dynamic system.

However, within the past two centuries, anthropogenic forces have drastically altered the bay and its watershed. Dredging and filling operations, major infrastructure projects, population growth, and land development have increased the potential for damaging floods. Wetlands and many of the plant species that inhabit them act as natural storm surge buffers and floodways for the absorption and filtration of storm water. Well over half of Jamaica Bay's historic wetlands were lost during the 20th century, as advances in transportation made it possible to establish permanent communities and industrial facilities along the shore. Though these developed areas are no longer effective at absorbing flood waters, they are still at high risk of inundation during storms. Strategic policy and planning measures can help prevent further wetland loss, facilitate the adaptation of existing structures to wet conditions, and convert developed areas back into wetlands where possible.

This panoramic view of Belle Harbor on the Rockaway Peninsula, looking south toward the Atlantic Ocean, shows evidence of beach grass planting, suggesting that early residents of the peninsula already recognized the value of dunes and wetlands. Photograph taken on July 11, 1915. The New York Public Library Digital Collections.



From Seasonal Resort to Permanent Residence

Jamaica Bay was once a shallow embayment renowned for its shellfish. Its earliest known human inhabitants, the Canarsee and Rockaway Native Americans of the Lenape people, likely gathered oysters, softshell clams, razor clams, and mussels from the bay. When Dutch settlers established neighboring New Amsterdam in 1624, Canarsie, Queens was a Lenape commercial and civic center. By the time Manhattan was reincorporated as New York under the English, European expansion had pressured the Canarsee and Rockaway tribes to relinquish their claim to most of Brooklyn and Queens. ¹

The bay remained primarily agricultural, shrubland, and marshland until the mid-19th century, when seasonal fishing villages and a handful of factories cropped up among the farmsteads. The villages and their pedestrian thoroughfares were built directly over marshes and mudflats and elevated to allow tides to come and go. The bay's reputation as a resort began in 1833, when the Marine Pavilion Hotel was established in Far Rockaway, along the Atlantic coast. It catered to wealthy New Yorkers arriving by ferry or stagecoach along the Rockaway Turnpike, which was initially constructed of logs and padded with peat. ²

When the railroad reached Valley Stream and the Rockaways in the 1860s and 1870s, respectively, dozens of seaside resorts emerged along the beach front and offered bathing and boating activities. Many affluent communities, including Bayswater and Belle Harbor, established their own yacht clubs. The original stretch of the Rockaway Boardwalk

promenade was constructed in 1901 between Beach 59th Street and Beach 74th Street. At the east end of the peninsula, bathers enjoyed access to the Bay of Far Rockaway, which was protected by a barrier beach called Hog Island. Tidal creeks and inlets flowed from Jamaica Bay into this smaller body of water, then into the Atlantic Ocean. Hurricanes in 1893 and 1903 submerged Hog Island and its bathhouses, and Far Rockaway Bay became East Rockaway Inlet.

As Jamaica Bay gained familiarity among vacationing urbanites, oysters became a major export. Commercial fishing activities begun in







Top: Wooden houses constructed atop marshland in Ramblersville.

Center: Residents of Broad Channel fish from their doorstep.

Bottom: Broad Channel during low tide in the early 1900s. Homes were built on wooden stilts and accessed via piers, boardwalks, and boats.

the late 19th century sent 300,000 bushels to Manhattan markets each year for several decades. Development had its downsides, however. The burgeoning population of Brooklyn, Queens, and Long Island expelled sewage and other waste products into the bay. Though filter-feeding oysters flourished on the abundant bacteria and nutrients, their human consumers did not fare as well. At least as early as 1905, cases of typhoid were traced to the oysters plucked from Jamaica Bay, and by 1921 the bay was so polluted that the shellfish industry was shuttered completely.

Jamaica Bay's heyday as a seaside resort continued into the mid-20th century under the encouragement of Robert Moses, who held the title

of Commissioner of New York City's Department of Parks from 1934 to 1968 (in addition to several other positions). Between 1937 and 1940, Moses led the construction of the Shore Parkway, the Belt Parkway, and the Marine Parkway-Gil Hodges Memorial Bridge, and the replaced the smaller Cross Bay Boulevard with the Cross Bay Bridge and Parkway (which he would be responsible for replacing again in 1977). These motorways significantly increased automobile access and facilitated use of the expanding park system. Moses established linear parks along his new thoroughfares and created Jacob Riis Park and the Jamaica Bay Wildlife Refuge, effectively reconfiguring the popular conception of Jamaica Bay into a modern nature-based retreat.

By the 1950s, the land along the railroad tracks near Head of Bay had been converted into yearround residential developments, many of which were built on former marshland. At the same time, the Rockaways lost their allure as a seaside retreat. Moses, who wielded influence over all public housing projects of the New York City Housing Authority, replaced the declining resort facilities with several high rise public housing projects. Between 1951 and 1972, Moses constructed nearly 4,000 public housing units in the Rockaways. The decision to concentrate low-income residents in this remote area limited their access to transportation and economic opportunities. The isolation increased in 1969, when 58 blocks of beachfront from Arverne to Edgemere were razed to make way for an urban renewal scheme and remained vacant for decades.8

Top: Colonial Hall, a seaside resort in Arverne, in 1903. NYPL archives.
Center: Rockaway Boardwalk along the Atlantic Ocean in 1903. NYPL archives.
Bottom: Arverne Houses, pictured here, opened in 1951 with 418 units.
Hammels Houses followed with 712 units in 1955, Redfern Houses with 604 units in 1959, the 1395-unit Edgemere Houses opened in 1961, and the Beach 41st Street Houses added a final 712 units in 1972. Image from the LOC.







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Pathways to Development

The first railroad tracks on Long Island were laid in 1832 and projected from the East River to Jamaica, Queens under the Brooklyn and Jamaica Railroad Company. The track was soon acquired by the Long Island Railroad (LIRR), which formed in 1834. Nearly four decades later, the Rockaway Branch of the South Side Railroad (SS RR) stopped at Valley Stream before skirting the eastern end of Jamaica Bay and continuing on to Rockaway Beach. The following year, in 1870, the New York and Rockaway Railroad established its own Rockaway Branch, which provided access to Ocean Point (now Cedarhurst), Lawrence, and Far Rockaway. In 1880, the New York, Woodhaven, and Rockaway Railroad built a trestle across Jamaica Bay, providing more direct access to the peninsula after stopping in the wetland communities of Goose Creek, the Raunt, and Broad Channel.

The LIRR system subsumed each of these lines within a few years of their construction and continues to operate track along the original Rockaway Branch of the SS RR. Though the LIRR began depositing fill along its tracks by 1888, the Rockaway lines were constructed at grade. 10 The increase in vehicle traffic brought on by the Marine Parkway Bridge and Cross Bay Boulevard spurred the LIRR to elevate the Rockaway line in the early 1940s, eliminating grade crossings. The wooden train trestle south of Hamilton Beach went up in flames in 1950 and trains were unable to cross until 1956, when the city constructed a concrete bed at considerable cost. Today, the line operates under the Metropolitan Transportation Authority as the A Train. At exceptionally high tides, the tracks are subject to flooding, causing gaps in service. 11









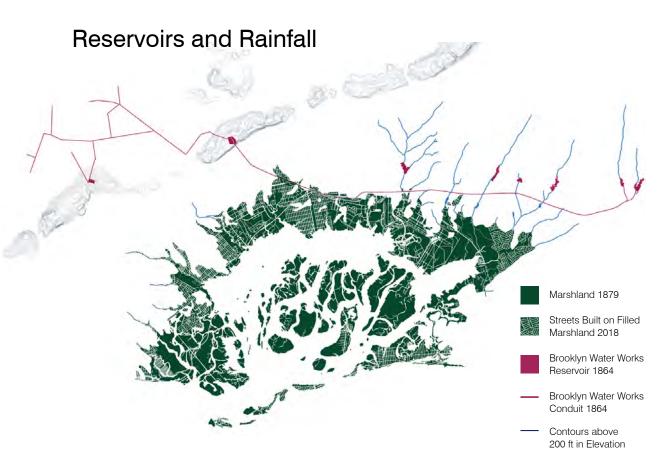






Top: 1938 aerial photograph of Inwood, looking southeast, from the New York City Department of Parks archive. This image shows the historic marshes and mudflats (lower left) and early power generation and oil storage facilities. Bottom left: 1929 NOAA nautical chart. Bottom right: 2018 satellite imagery of the same location, showing channelization and fill.

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"In the case of the Brooklyn water supply, the question was limited to a choice between a supply derived from large wells or from the small streams which water the southerly slopes of Long Island, the nearest of which is over ten miles from the heart of the city. This question was discussed for many years before the final preference was given to the supply from the pure and never-failing island streams." - The Brooklyn Water Works and Sewers, 1867

The Jamaica Bay watershed lies in the gently-sloping outwash plain below Long Island's terminal moraine. Historically, rain water flowing from higher elevations collected in twelve freshwater streams that became wetland creeks as they approached the bay. ¹² In the 1850s, the expanding city of Brooklyn began siphoning off stream water. Five of the natural ponds around

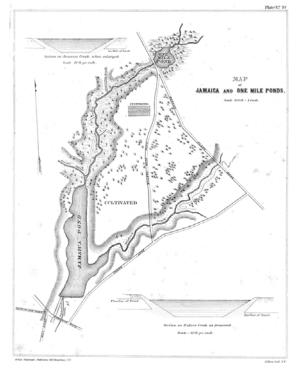
Head of Bay were converted into reservoirs, from which water flowed westward through brick conduit systems to Atlantic Avenue. From there it was pumped upward to Ridgewood Reservoir and distributed on the other side of the ridge, among the households, factories, and breweries of Brooklyn.¹³

In 1898, Brooklyn consolidated with the City of New York, in part to tap into Manhattan's water supply, which drew from much larger reservoirs upstate. The flat, contiguous land above the submerged conduit line was converted to a roadway in the 1920s and later rebranded by Robert Moses as a link in the broad Belt Parkway. Today, the Valley Stream, Hempstead, Jamaica, and Ridgewood Reservoirs are preserved as ponds within parks. Though the streams have all been altered through channelization and underground piping, they are part of the watershed's natural



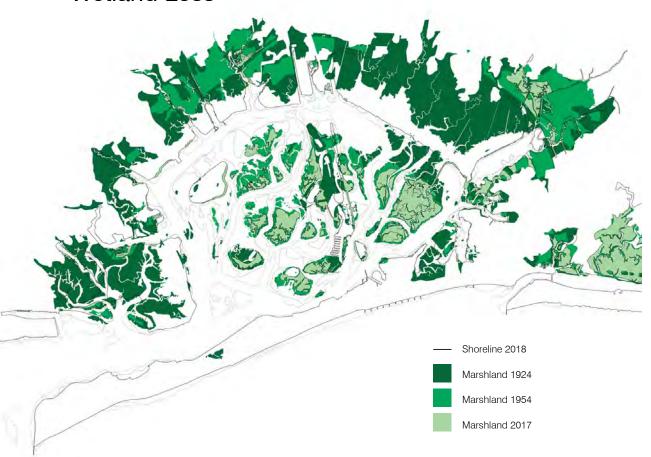
drainage system. The neighborhoods, businesses, and industries in these areas are subject to flooding from upland during large rainfall events in addition to flooding from the bay during high tides and extreme storms.

While barriers could be instrumental in preventing bayside flooding, it is important to keep the remaining streams open in order to maintain the ecological health of the bay below. For instance, the Brookfield Reservoir was buried beneath the Belt Parkway, but the stream below still flows into the marsh at Idlewild Park, one of the largest remaining wetland tracts within the bay. Upland storm sewer systems can be designed to facilitate drainage and delay floodwaters, and investments in green infrastructure can reduce impermeable surface area in order to filter and absorb rainfall runoff.



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History of Development

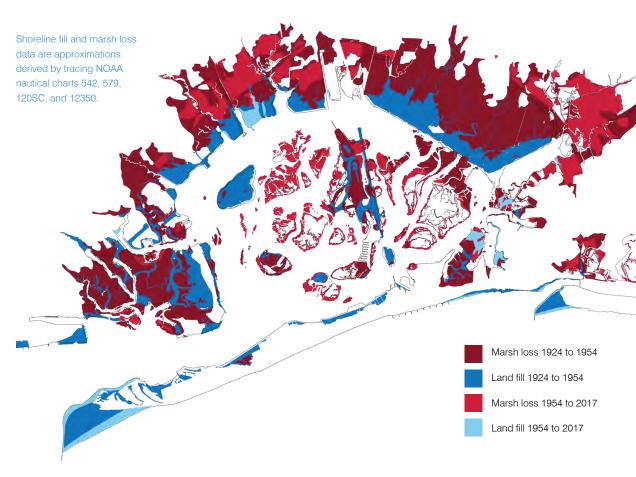
Wetland Loss



Historic maps suggest Jamaica Bay's marsh islands formed around the end of the 18th century, when littoral drift and offshore winds deposited enough sand to extend the barrier dune and shelter the bay from wave action. ¹⁴ Marshlands act as a natural buffer during floods, helping to absorb rainfall runoff and dampen rising water levels caused by storm surges and high tides. During the 20th century, more than half of the marshland around the perimeter of the bay was converted to other land uses. As developers swapped seasonal housing for conventional, suburban typologies and transportation projects required room for implementation, wetlands gave way to pavement.

In particular, investment in transportation infrastructure between the 1920s and 1940s largely reconfigured the landscape within the

bay. New York City's first municipal airport, Floyd Bennett Field, opened in 1931 atop a flat expanse of former marshes at the bay's west end. The existing islands were cobbled together with dredged fill, and cars were soon cruising over this land and the Rockaway Inlet via the Marine Parkway Bridge. In the late 1930s, Robert Moses led the construction of several hundred acres of contiguous land at the center of the bay. This new island supported the Cross Bay Bridge and Parkway, an expanded roadway that replaced the original Cross Bay Boulevard of 1923. Moses expanded the island again in the 1950s when the city took over the train trestle crossing the bay. He granted permission for the new trestle in exchange for two artificial freshwater ponds, which he designated the Jamaica Bay Wildlife Refuge. 15



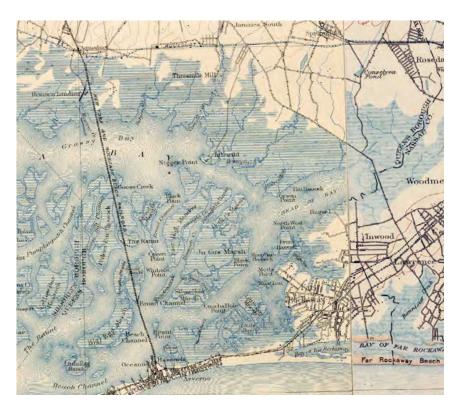
At the bay's east end, New York International Airport, commonly known as Idlewild Airport, opened in 1948. ¹⁶ Mudflats at Grassy Bay averaging a shallow depth of one to two feet prior to airport dredging operations became borrow pits that are now some of the deepest areas of the bay, reaching depths of over 50 feet in some locations. ¹⁷ The airport was expanded in subsequent decades and rechristened John F. Kennedy International Airport in 1963.

Dredging and filling operations took on new significance with the creation of three refuse landfills on the perimeter of the bay. The Pennsylvania Avenue, Fountain Avenue, and Edgemere Landfills top out at around 80 feet, towering over the natural landscape of the bay. Though these artificial land forms are designated under New York City, New York State, and National Parks Service park jurisdictions, there is currently no recreational access at these buried waste sites.¹⁸

This conversion of wetlands has had several ramifications. Homes and businesses have crept toward the shore, multiplying the assets vulnerable to flooding. The increase in impermeable surfaces throughout the watershed has diminished the capacity for rain water to percolate into the water table. Meanwhile, the marshland that might have helped reduce the extent of flood damage has been lost to development. Due to sea level rise and tidal amplification caused by dredging, mean high water is already about 1.5 feet higher today at Head of Bay than a century ago. ¹⁹

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Development and Marsh Loss



1900

USGS Topographic Sheet of New York City, Brooklyn Quadrangle from February 1900 combined with the Hempstead Quadrangle from April 1903.



1924

Aerial imagery undertaken by the NY Bureau of Engineering and sourced from the New York Public Library. The area to the right of the image was not included in the aerial survey, presumably because it was beyond the boundary shared by New York City and Nassau County.



1954

Individual aerial photograph frames sourced from USGS Earth Explorer and compiled.



2017

Google satellite imagery from Google Earth, September 2017.

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Rockaway Boulevard







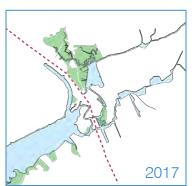






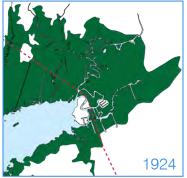












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existing approaches

bulkheads, and levees have been used to keep dynamic coastal and riverine waters in place, often to the detriment of natural ecosystems. As the effects of climate change continue to unfold, it is becoming apparent that attempting to maintain the existing shoreline would require measures of unprecedented cost and scale. As interest in the ecosystem benefits of marsh ecologies and other biomes has increased in recent decades, planners and policy makers have begun to expand their repertoire of risk reduction measures, embracing strategies that harness the resilience of natural features and systems to reduce the impacts of flooding. Marshes and mollusk beds can help dissipate wave energy. Dunes and barrier islands may retain surging waters. Green stormwater infrastructure and retention basins with soft edges are capable of storing and filtering excess water to minimize the duration of flooding. These green strategies can be coupled with innovative policies as well as traditional grey infrastructure to manage increasing flood risk. In order to make the best use of these investments, decision makers can opt for solutions that offer more than just flood protection. Designing flood protection systems that improve transportation infrastructure can increase access to economic and social opportunities for surrounding communities. Protecting and planting native plant species as part of the flood protection infrastructure could provide essential habitat to endangered species and create new possibilities for recreation.

Historically, flood protection systems in the United States have relied on hard edges with the goal of keeping water out. Flood walls,

A woman walks along Rockaway Beach at low tide in July 2018. Visible in the foreground are dune grasses planted to stabilize the sand along the Rockaway Boardwalk. The new boardwalk and barrier dunes are designed to provide protection against floodwaters along the Rockaway Peninsula's Atlantic coast. Photograph by Rennie Jones.



Storm Surge Barriers



Thames Barrier London, England

The Thames Barrier is about 1500 feet wide in total and composed of six rotary segment gates and four sector gates. It closes a few times each year, when water levels are forecast at 15 feet above sea level.



Stuw Amerongen Amerongen, Netherlands

This gate is 850 wide and part of a trio constructed between 1958 and 1970. When open, the gates are held above the water to allow vessels to pass.



Lake Borgne Surge Barrier New Orleans, Louisiana

At more than 1.8 miles long and 150 feet deep, this barrier is the largest project in the history of the US Army Corps of Engineers. It includes a vertical lift gate, sector gate, and barge gate.



Maeslantkering Hoek van Holland, Netherlands

The Maeslantkering is 700 feet wide and is expected to close every 7 to 10 years. When open, the gates rest in chambers along the waterway. They rotate to close and rest on a sill at the bottom of the river.



Iwabuchi Red Sluice Gate Tokyo, Japan

300 feet wide

attraction.

This vertical lift gate was constructed in 1924. It was decommissioned after 1982, when the new gate was completed upstream, and now serves as a tourist



Hollandse IJssel
Capelle aan den IJssel, Netherlands

This gate is 300 feet wide and 38 feet tall. It is expected to close two to three times each year, when water levels are 8 feet above sea level.

Natural and Nature-Based Features



Super Levee Osaka, Japan

This flood barrier features a wide footprint and gradual slope, which allows it to withstand overtopping without breaching and expands the available habitat and recreation options along the riverfront.



Beach Nourishment New York City, New York

The US Army Corps of Engineers has traditionally protected shorelines with beach nourishment, but is now encouraging the planting of dune grasses to stabilize the upper elevations of the beach.



Marsh Island Restoration Jamaica Bay, New York

The USACE's New York District, in partnership with city and state agencies and non-governmental organizations, has restored five marsh islands within Jamaica Bay since 2006, under the directive to beneficially reuse dredged materials for ecological resotration.



Living Shoreline New York City, New York

This wetland marsh shoreline at Brooklyn Bridge Park was implemented by Michael van Valkenburgh and reflects a citywide interest in softening vertical bulkheads to accommodate habitat through the use of riprap and vegetation.



Stormwater Canal Stockholm, Sweden

This stormwater system is designed to collect water and direct it toward nearby water bodies, reducing the potential for flooding in the courtyards and inhabited spaces surrounding the canal.



Eendragtspolder Rotterdam, Netherlands

This former agricultural land was restructured to retain more than 900 million gallons of water to prevent the flooding of neighboring areas. It doubles as a recreation space, offering cycling, kayaking, hiking, and rowing facilities.

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US Army Corps of Engineers

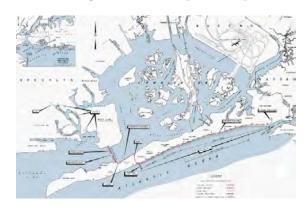
Since its inception during the Revolutionary War, the United States Army Corps of Engineers (USACE) has managed many of the nation's military fortifications and civil works projects. The military academy at West Point was the first school of engineering in the United States, and remained the country's only formal training program for engineers for some time after its establishment in 1802. National defense and inland navigation were considered interdependent, and Army Corps engineers were called upon to conduct surveys, construct roads and railways, dredge navigation channels, clear river obstacles, and build dams and other navigation features. ¹

After Hurricane Donna raised the waters of New York Harbor to record levels in 1960, the USACE conducted a survey to determine the possible extent of flooding in the event of another hurricane. The report, published in 1961, found that a storm surge of 15 feet would seriously impair subway service and paralyze railroad tunnels, and that "virtually all economic activity in the area would cease" – a prescient description of Hurricane Sandy's future impact. That year, the USACE recommended constructing a storm surge barrier from Sandy Hook to Rockaway Point, but local interests rejected the proposal because of "ship traffic difficulties, high cost and pollution."²

The USACE issued several subsequent reports outlining storm protection options for the New York City region, including Jamaica Bay. The proposed solutions favored hard infrastructure, including flood walls, levees, and surge gates. In recent decades, growing environmental concern has led the Corps to expand its range of approaches. Dunes and beaches, marsh and maritime vegetation, oyster reefs, barrier islands, and maritime forests are now part of the material palette, under the rubric of Natural and Nature-Based Features. Beginning in 2006, the USACE

and other governmental and non-governmental partners working in Jamaica Bay restored five marsh islands using dredged material from the New York and New Jersey Harbor Deepening Project.

Following Sandy, the USACE was involved in dune nourishment and the construction of a boardwalk along the Rockaway Peninsula, to help alleviate the risk of flooding from the Atlantic. The Corps has issued several rounds of flood protection options in recent years, many of which resemble strategies first proposed nearly six decades ago. This suggests that, though awareness of the flood risk is widespread, enacting proposals at the regional scale has so far proven insurmountable. Completing local projects as links in a larger system may expedite the process.



Seawall Proposal Gets Mixed Reaction



Top: A US Army Corps flood protection plan for Jamaica Bay, issued in 1984. Bottom: An article describing an Army Corps proposal for a floodwall along the Coney Island peninsula ran in The New York Times on April 16, 1972.













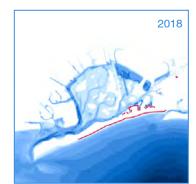








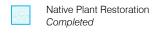




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Resilience Efforts in Jamaica Bay





Park Restoration Completed

Case Study: Howard Beach Study

Watershed Protection Plan Study

Southeast Queens Stormwater Improvements, Underway

Resilient Neighborhoods



Resilient Edgemere Study

Marsh Island Restoration Completed

Proposed Marsh Island Restoration, Study

Proposed Perimeter Sites

Storm Surge Barrier Plan



Idlewild Park Preserve Advocacy

Proposed Verge Enhancements

Proposed Overwash Plains

Proposed Runways at JFK Airport Study

Rockaway Boardwalk Completed

Oyster Pilot Underway



Canarsie Pier Reconstruction

Paerdegat Basin

Upgrades



Marine Park Trail Restoration



Marsh Island Restoration

Efforts to improve Jamaica Bay's capacity to adapt to climate change were underway before Hurricane Sandy, and they accelerated after the storm made landfall. Various community groups, policy makers, researchers, naturalists, government agencies, non-governmental organizations and other activists have been working to restore the bay's ecosystem and protect its inhabitants, human and non-human alike. In addition to reducing flood risk, the focus has been on neighborhood resilience, post-Sandy recovery, infrastructure improvements, sewershed and storm water management, and ecological health.

However, many of the strategies that could help communities and infrastructure weather the next big storm have yet to be realized. Protecting the bay at large is a tall order, and completing smaller, individual projects has helped to move things forward. But these efforts remain disjointed and have largely focused on the bay's western extents, within New York City jurisdiction. By expanding to a slightly larger scope at the scale of the watershed while continuing to advance discrete projects, this proposal could potentially link to a larger networked system and build resilience for more of the bay's residents.



Rockaway Boardwalk

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A Stronger, More Resilient New York - City of New York, Mayor Michael Bloomberg

A plan to improve the resilience along New York's coast that was catalyzed by Hurricane Sandy and issued as an update to PlaNYC. The recommended measures for power infrastructure and building protections include an economic analysis that weighs the costs of implementation against possible future losses.



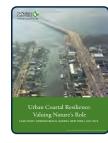
NY Rising Community
Reconstruction - Governor's
Office of Storm Recovery

A New York State program established under Governor Cuomo to plan and implement resiliency measures and provide financial assistance to rebuild in communities damaged by Hurricane Irene, Tropical Storm Lee, and Hurricane Sandy.



Structures of Coastal Resilience
- Princeton University, Harvard
University, City College of New York,
and the University of Pennsylvania

This project analyzed future flooding along the Atlantic Coast and developed designs to reduce the flood risk associated with hurricane-induced storm surges for Naragansett Bay, Jamaica Bay, Atlantic City, and Norfolk.



Urban Coastal Resilience: Valuing Nature's Role - *The Nature* Conservancy

Analyzed multiple combinations of hard infrastructure and natural and nature-based solutions to determine which flood protection system would be most cost effective for Howard Beach, Queens.



Draft Integrated Hurricane Sandy General Reevaluation Report and Environmental Impact Statement -US Army Corps of Engineers

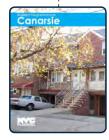
A look at the issues and opportunities surrounding coastal storm risk management for East Rockaway Inlet to Rockaway Inlet and Jamaica Bay. The report recommended a continuous barrier from East Rockaway Inlet to Gravesend, with a surge gate at the Rockaway Inlet.



Revised Draft Integrated Hurricane Sandy General Reevaluation Report and Environmental Impact Statement

- US Army Corps of Engineers

This report assumes a storm surge barrier that would impact Jamaica Bay is under consideration as part of the NY and NJ Harbor and Tributaries Feasibility Study. It focuses on smaller, local features (HFFRFFs) to reduce the risk of high frequency flooding, such as flooding due to tidal fluctuation.



Resilient Neighborhoods - NYC Department of City Planning

A planning initiative intended to complement the updated zoning in the floodplain by facilitating resilience. Where the citwide zoning changes and guidelines could not address elevated flood risks or damage due to Sandy, the NYC Department of City Planning worked with neighborhoods to develop specific measures to adapt to increasing flood risk.



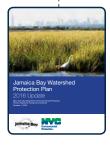
Rebuild by Design - Department of Housing and Urban Development

Design proposals for New York
City developed in response to
Hurricane Sandy, aimed at providing
methodologies researching,
designing, and implementing
ideas for a more resilient future.
Aspects of particular proposals are
in planning and implementation
phases, including the BIG U and
Living Breakwaters.



One New York: The Plan for a Strong and Just City - The City of New York, Mavor Bill de Blasio

A plan intended to address New York City's challenges surrounding growth, equity, sustainability, and resilience. The report proposes measures for building the resilience of the city's neighborhoods, buildings, infrastructure, and coastal defenses.



Jamaica Bay Watershed Protection Plan 2016 Update - NYC Department of Environmental Protection

A strategy to improve the water quality and ecological health of Jamaica Bay. The 2016 update assess the feasibility of proposed measures, including restoring natural species, managing stormwater and wastewater, and encouraging public outreach and stewardship.



Hudson-Raritan Ecosystem Restoration Feasibility Study - US Army Corps of Engineers with the Port Authority of NY & NJ alongside several agencies

This report assesses the feasibility of restoration opportunites throughout the estuary and recommends a new round of feasibility studies. It includes the Jamaica Bay, Marine Park, Plumb Beach Ecosystem Restoration Feasibility Study.



The New Shoreline: Integrating Community and Ecological Resilience around Tidal Wetlands -Regional Plan Association

As part of the Regional Plan
Association's 4th Regional Plan,
the RPA developed and suggested
measures for combining efforts
to build resilience in coastal
communities with the need to
prepare upland areas and tidal
wetlands for upward marsh
migration due to sea level rise.

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projected flooding

Understanding the probability and potential impacts of future flooding can provide policy makers, planners, and designers with a projection of a probabilistic future that encourages actionable adaptive design strategies, despite indeterminacy. For this study, researchers at Princeton University determined the probable extent and depth of flooding around Jamaica Bay for a range of hurricane return periods extending through several time "slices" up to the year 2100. This analysis incorporated the characteristics of 29,000 synthetic hurricane tracks under current and future climate scenarios and accounted for storm surge, tidal cycles, sea level rise, and rainfall runoff. These probabilistic results were used to develop the initial design proposition for a flood risk reduction system at Head of Bay, which was then tested for effectiveness in an analysis using individual storm scenarios.

Because these projections represent complex systems projecting well into the future, they necessarily incorporate uncertainty as a result of both natural variability and modeling methodologies. Though the most advanced modeling systems, including those used in this study, are capable of picturing the extent of flooding at a very high level of spatial resolution - suggesting, for example, where one should park a car so that it is not impacted by a hurricane - the actual flooding that results from any particular hurricane will vary from all existing predictions. For this reason, it is critical to design flood protection as redundant, resilient, and layered systems to account for potential variations, especially as the many impacts of climate change remain unclear.





Projected extent of flooding caused by a single simulated hurricane in 2100 assuming a warming climate and 7.0 ft of sea level rise.

Combining Scientific Analysis and Design

Probabilistic ADCIRC Analysis

Probabilistic storm tide projections for multiple return periods over time were generated using a hydrodynamic model (ADCIRC) of the Atlantic Basin forced with thousands of synthetic hurricane tracks generated using four global climate models.



Bathtub Method Mapping

The projected water levels resulting from the probabilistic ADCIRC analysis were mapped to visualize flood depths throughout Jamaica Bay. For each time scale and return period, a digital elevation model (DEM) of the bay was subtracted from a single plane at the water elevation. This static approach is referred to as the "bathtub method."



Design of Layered System

The projected water elevations and corresponding maps were used to design a layered flood protection system that would both passively mitigate tidal flooding with a fixedelevation berm as well as incorporate an operable storm surge barrier designed to protect everyone within the project scope against catastrophic storm surge flooding.



Scenario-based ADCIRC Analysis for Jamaica Bay

To test the efficacy of the proposed layered flood protection system, the barriers were built into a unique high-resolution computational mesh for Jamaica Bay and forced with individual hurricane scenarios using a coupled hydrodynamic and wave model (ADCIRC + SWAN).







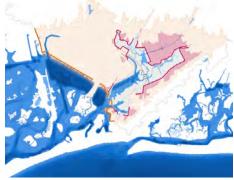
USGS Tidal Gage Data

Projected water elevations for Mean Higher High Water and mean spring tides were derived from current USGS tidal gage data at Inwood combined with estimates of sea level rise over time.









Evaluate and Amend Design Accordingly



Projected Flood Elevations

Time Scales

2.6 ft	3.9 ft	6.5 ft
4.0 ft	5.7 ft	8.3 ft
5.9 ft	6.8 ft	10.4 ft
7.8 ft	8.7 ft	12.7 ft
9.9 ft	11.0 ft	15.6 ft

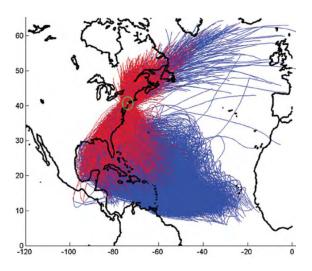


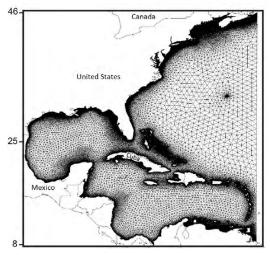
Storm Surge Analysis

When hurricanes make landfall, storm surges are a leading cause of destruction and the primary cause of death. Due to its natural topography, the New York Bight is particularly vulnerable to flooding due to storm surges. As the base water elevation rises with local sea levels, storm surges are expected to cause greater damage.

Historically, flood projections have relied on observed data, which is limited to a small number of storms that have made landfall in the New York City region. For this study, Ning Lin and Reza Marsooli at Princeton University simulated storm surges using hydrodynamic models forced with the wind and pressure fields of synthetic hurricanes according to the methodology of Lin et al.² The synthetic hurricane tracks were generated with a statistical-deterministic model³ under historical and future climate scenarios, including the periods from 2030-2050 and 2080-2100 under RCP 8.5 scenario.

A series of synthetic storms for a historical period between 1981 and 2000 were used to simulate flood return levels during this period and bias-correct projections from climate models. The historical database was generated based on climate observations from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). The climate models were bias-corrected by comparing the NCEP-based flood return levels calculated for the historical period with the flood return levels projected by climate models for the same historical period. It was assumed that these calculated biases remain constant over time and can be use to bias-correct the modeled flood return levels for the future periods. Four climate models in the Coupled Model Intercomparison Project (CMIP5) were used to derive the hurricane model to generate synthetic storms for the future climate senarios.



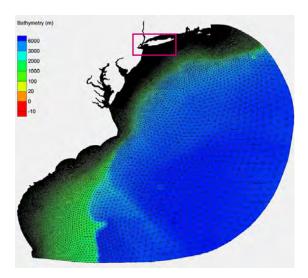


Top: NCEP-based hurricane tracks of synthetic storms passing within 200 km of New York City. The storm tracks were generated by Kerry Emmanuel at MIT. Above: Computational mesh of the Atlantic Basin used to simulate extreme flooding caused by hurricane storm tracks using ADCIRC. The mesh was generated by Reza Marsooli and Ning Lin at Princeton University.

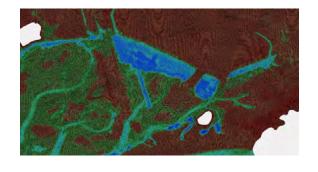
Each synthetic storm track generated under these climate conditions represents the hurricane's intensity, size, and position in time. Wind and pressure fields were generated for each track to force a hydrodynamic model simulating hurricane storm surge. For this study, Advanced Circulation (ADCIRC)⁵ was the hydrodynamic model of choice, as it allows for high resolution using uniquely-produced computational meshes. ADCIRC numerically solves the shallow water equations (SWEs), which describe the motion of fluids relative to gradual horizontal slopes, such as the deep ocean.⁶ In addition to using storm tracks modeled under future climate scenarios, the storm surge analysis accounted for climate change by including sea level rise. The resulting probability distribution of water elevations was a convolution of the probability distributions for storm tide (combined tide and storm surge) and sea level rise.

In this project, the storm tide analysis was conducted twice using this methodology. The first analysis utilized thousands of synthetic storm tracks passing through the New York City area to determine the probabilistic water elevations for the given time scales and return periods. This analysis was carried out using a lower resolution mesh to optimize computational expense, and the water elevations correspond to a single point in Jamaica Bay. These results were used to represent projected flooding in the first phase of the project, and informed the initial design of the flood protection system.

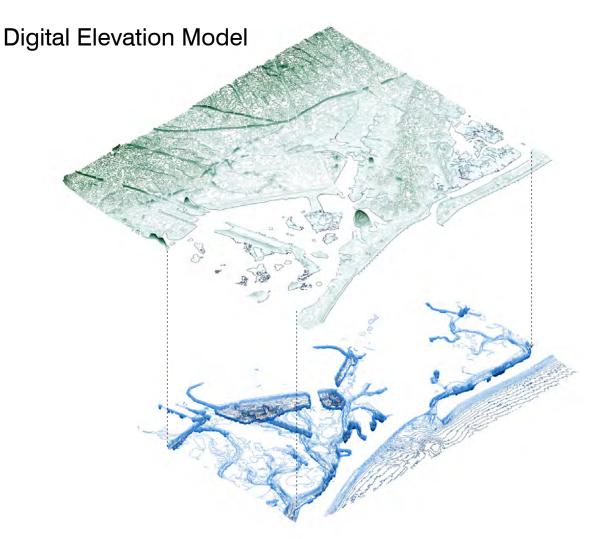
For the second analysis, tracks were selected that resulted in storm tide levels close to the probabilistic results for each return period under each of the climate conditions. To test the efficacy of the proposed flood protection system, eight storm scenarios were run using a mesh with the proposed system modeled and a control mesh representing the existing topography.







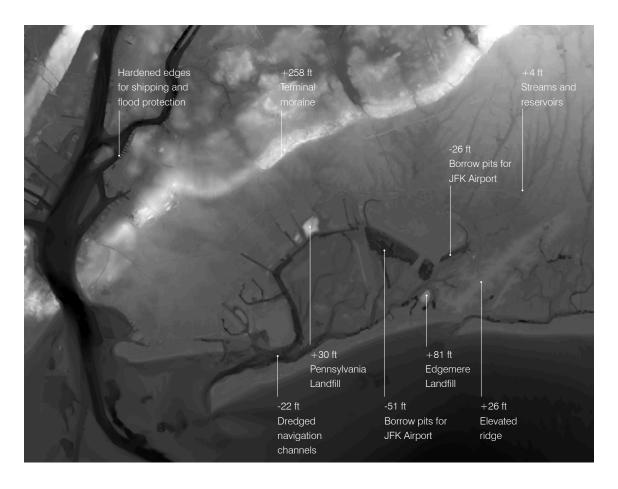
High-resolution computational mesh for ADCIRC + SWAN by Reza Marsooli and Ning Lin at Princeton University. Resolution in Jamaica Bay varies between 20 m in shallow waters floodplains and 100 m in deep shipping channels. The resolution outside the bay gradually increases to 25 km in the deep ocean.



Historically, topography and bathymetry have been represented as two distinct data sets. In the United States, the US Geological Survey (USGS) is responsible for surveying and mapping topography, or land that is not typically under water. The National Oceanic and Atmospheric Administration (NOAA), is responsible for the charting of bathymetry, or the ground surface that is typically below water. A digital elevation model (DEM) represents geomorphology as a continuous surface, merging topography and bathymetry. Rather than relying on representation of the water's edge as a single, static line, this surface allows for an understanding of the water's edge as constantly fluctuating. This is essential to analyzing tidal cycles, storm surges, rainfall runoff, and sea level rise.

Topographic surveys are now regularly conducted using lidar (Light Detection and Ranging), a laser technology that measures distance by recording the time required for a laser pulse emitted from an airplane flying over a given area to reach the ground surface

Contours derived from the Digital Elevation Model (DEM) at intervals of 2 feet using ArcGIS and imported to Rhino using Grasshopper. The DEM acts as a seamless surface representing topographic information (green) and bathymetric information (blue). The 0 contour lies at the vertical datum of NAVD 88.



below. The surface is then represented through the amalgamation of millions of these points. Likewise, bathymetric soundings are increasingly conducted using sonar, which measures distance by recording the time required for sound waves to reflect off of a surface.

The DEM served as a point of departure for each aspect of the flood analysis in this study. The DEMs produced by NOAA's National Centers for Environmental Information (NCEI) after Hurricane Sandy were selected for use, as they represent the most recent continuous data within our study area at a high level of resolution. The elevation data can be visualized in three dimensions as points in a cloud or vertices in a mesh, or in two dimensions as topographic contours or a raster in which each cell corresponds to an elevation value. This allowed us to work with the data in a variety of formats, including GIS, 3D modeling, and vector drawing software.

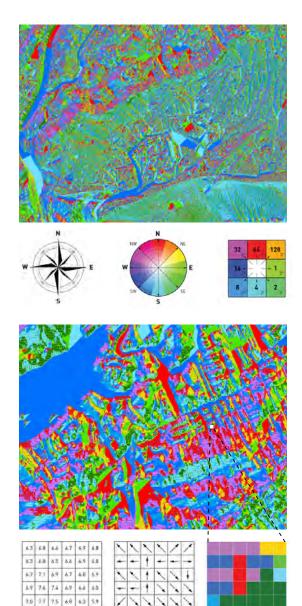
308 feet above NAVD 88

154 feet below NAVD 88

Source

NOAA NCEI Hurricane Sandy Digital Elevation Model, 2014. The elevation data is relative to the North American Vertical Datum of 1988 (NAVD 88) at a resolution of 1/9 arc second (3.4m) along the coast and 3 arc seconds (90m) along the deep ocean floor. A shade gradient helps visualize the geomorphic features.

Rainfall Runoff



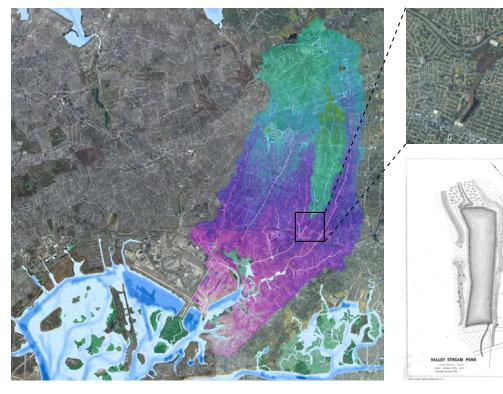
Above: Flow direction rasters of the watershed and an area of Inwood, derived from the DEM. The diagrams describe the conventions used to analyze and visualize the data.

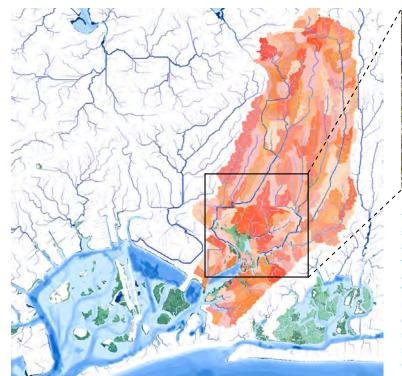
5.7 5.8 5.5 5.9 5.A 4.7

The extreme rainfall associated with large storms can collect at areas of low elevation within a watershed, and could potentially build up behind a closed storm surge barrier during a hurricane. This is particularly relevant at Head of Bay, where several streams drain into Jamaica Bay. Green infrastructure and storm water management can be designed in combination with a flood protection system to effectively route runoff to reduce flood extent and duration.

In order to determine approximately where water would collect within the project area, we analyzed the expected accumulation of runoff at Head of Bay. Using the DEM in ArcGIS, we produced flow direction and slope rasters that allowed us to visualize the flow accumulation routes runoff would take and the order of streams as the water collected. We used this information to visualize the length of time a water droplet falling on any area of the subwatershed would take to reach the bay, and the smaller catchment basins that would drain into each flow path.

This very preliminary analysis showed that the natural streams draining into the Head of Bay area appear to be disrupted by artificial topographic changes, especially along the Belt Parkway and Sunrise Highway. Because the DEM used in the analysis is a single, continuous surface, it does not represent culverts, pipes, or other ways that water could pass through the highway. However, we can likely anticipate that less rainfall runoff will collect along these interrupted streams, and more water would accumulate along the forced paths. These modified flow paths are considered in the placement of flood barriers within the scope of this study.







9 000

10.800

16.200

18,000 19,800

23,400

Top: Flow time for the Head of Bay subwatershed depicted in isochrones of 30 minute intervals (1800 seconds). The water draining into Valley Stream Pond, a former reservoir of the Brooklyn Water Works, is effectively absorbed.

Bottom: Flow accumulation and stream order for the Jamaica Bay watershed, showing catchment basins at a 15000 meter threshold at Head of Bay. The inset depicts points where flow along historic streams is interrupted by the highway.

Projected Flood Levels

Mean Higher High Water

Average of the higher of two

daily high tides

Mean Spring Tide
Average of the higher of two
monthly highest tides

100-Year Flood 40% probability of exceedance in 50 years

500-Year Flood 10% probability of exceedance in 50 years

2500-Year Flood

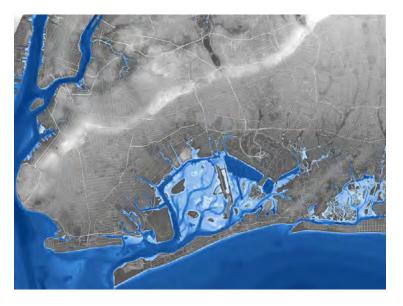
exceedance in 50 years

2% probability of

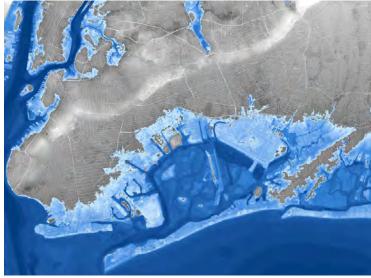
Time Scales

	2025	2050	2100	
1			-	-
	2.6 ft	3.9 ft	6.5 ft	oodina
	4.0 ft	5.7 ft	8.3 ft	Tidal Flooding
	5.9 ft	6.8 ft	10.4 ft	es
	7.8 ft	8.7 ft	12.7 ft	Tropical Cyclones
	9.9 ft	11.0 ft	15.6 ft	<u></u>

Projected extent of Mean Spring Tide Flooding in 2025, depicting still water levels of 4.0 feet above NAVD 88.



Projected extent of 2500-Year Flood in 2100, depicting still water levels of 15.6 feet above NAVD 88.



Sources

Return Periods

USGS datums for tide gage
01311850 Jamaica Bay at Inwood NY
Projections for 2050 and 2100
include 19.7" and 50.8" of sea level
rise, respectively. These are the
80th percentile values for New York
City under RCP 8.5 in Kopp et al
2014. NPCC's 2015 75th percentile
projections compare favorably at
21" and 50", respectively. ADCIRC
stormtide analysis conducted
by Reza Marsooli and Ning Lin
at Princeton University in 2018.
The probability distribution of sea
level rise in Kopp et al 2014 is
incorporated into the flood levels.

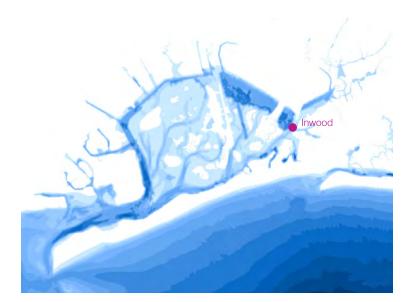
Bathtub Method

The projected flood levels represent still water elevations for a particular area of Jamaica Bay and were applied to the bay at large using the bathtub method. Probabilistic hurricane storm tide projections were determined using the hydrodynamic ADCIRC model for a single point near Inwood, at the east end of Jamaica Bay. Tidal elevations were determined by adding sea level rise projections to current tidal data relative to USGS gage 01311850 Jamaica Bay at Inwood. In order to model these results across the full bay, the DEM was subtracted from a plane representing each projected flood elevation level. The resulting flood depth raster was edited to remove any flooded areas that were not hydrologically connected to the bay.



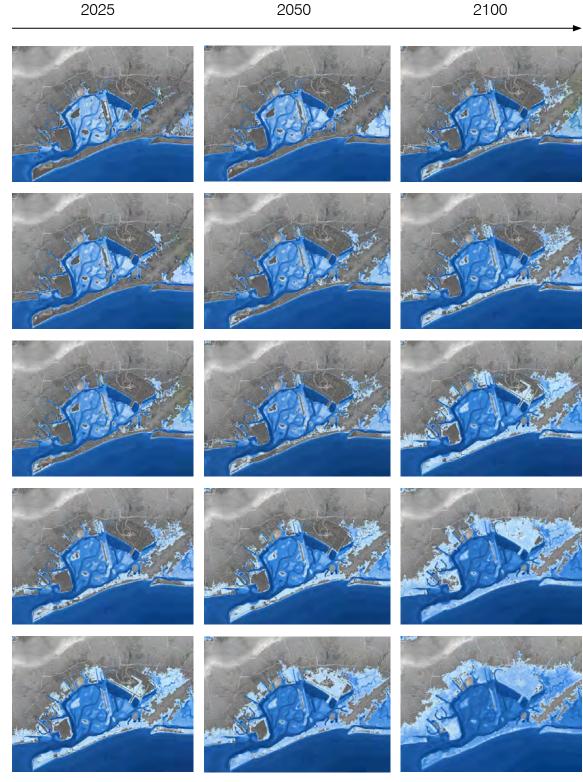
Mean Spring Tide Average of the higher of two monthly highest tides

100-Year Flood 40% probability of exceedance in 50 years



500-Year Flood 10% probability of exceedance in 50 years

2500-Year Flood 2% probability of exceedance in 50 years



proposed approach

We envision a layered system of storm mitigation features, from marsh islands to levees and surge barriers, to address the impacts of a range of conditions without obstructing downstream storm water runoff, sediment flow, and marsh migration. The proposed system leverages existing topography to reduce ecological impact and overall cost. A storm surge barrier, comprised of a high berm and a closure structure, ties into existing high points at the east end of the bay to protect thousands of homes and businesses, including New York City's John F. Kennedy International Airport. A pathway for bicycles and pedestrians is built atop the barrier's berm and closure structure, creating connective recreational space for the adjacent communities. The bayside of the berm features a gradual vegetated slope, and the landside of the berm is designed to withstand overtopping. This barrier is designed to prevent extensive flooding in extreme storm surge events.

A lower, passive tidal barrier allows the gates of the higher storm surge barrier to remain open during smaller storm and tidal flood events, reducing demand on the storm surge barrier and preventing damage to existing wetlands within the protected area. The tidal barrier inscribes a floodway – a designated water retention area – that would absorb the impact of exceptionally high tides, small storms, and extreme rainfall events. The two-layered system inscribes a zone of transformation that offers adaptation options and encourages strategic retreat and ecological restoration at selected areas that are likely to be permanently inundated as sea levels rise.





Project Goals

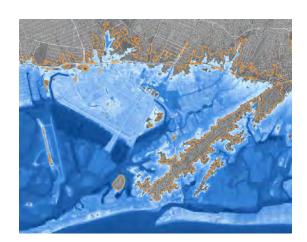
Health and Safety	Provide protection against catastrophic flooding for everyone within the project scope.	Planning for the Future	Allow for adaptation and incremental, equitable decision-making over time.
	Design a flood protection system that doubles as social infrastructure, providing recreational opportunities and health benefits, making it a vital part of the community even when water		Acknowledge a multitude of possible future scenarios based on a sequence of decisions and implementation.
	levels are low.	Ecological	Support and sustain ecological health. Natural features can
Economic Development	Support air traffic safety, transportation connectivity, and unimpeded navigation for shipping in the bay.	Stewardship	contribute to flood protection, and damaging these ecosystems could affect the ability of vulnerable plant and animal species to adapt to climate change.
	Take advantage of the opportunity to upgrade infrastructure and invest in socio-economic growth for communities upland and along the shore.	Cost-Effective Solutions	Leverage natural features, including topography and natural ecosystems, to reduce dependence on hard infrastructure and human intervention.
Scientific Basis	Assess flood projections according to the highest scientific standards to allow us to make informed decisions about the future under uncertainty.		Balance costs of initial construction against operational costs over the lifetime of the system.
	Further a methodology that closely intertwines scientific research, policy, and design	Parks and Open Space	Create open space that connects adjacent communities and allows access to the bay for boating, fishing, swimming, and other forms of recreation.
Flood Protection	Consider the big picture of flood risk, including frequent tidal flooding, extreme rainfall, and catastrophic storm surge.		Envision new ways of living with and alongside the water.
	Approach flood issues at a watershed scale, with the understanding that flood risk is not limited by administrative boundaries.	Strategic Decisions	Recognize that coastline systems are dynamic, and current land uses cannot be maintained in every case.
	Provide layered protection to reduce flood risk.		Provide a strategic framework for moving forward, including a wide range of equitable choices and solutions to allow all residents to make their own informed decisions.

60 Proposed Approach 61

Connecting to High Ground



Projected extent of flooding during a 2500-year storm in 2100. The probabilistic projected water level of 15.6 ft above NAVD 88 was mapped across the bay using the bathtub method.



A storm surge barrier protecting only JFK Airport would be 11.2 miles long and protect an area of only 6.2 miles².



At the east end of Jamaica Bay, a ridge forms a basin of low-lying land subjected to flooding. Many of the neighborhoods, businesses, and industries in this area lie on former wetlands, and rainfall runoff from the watershed's higher elevations pools at this location before draining into the bay. By tying into the higher elevations at the northwest, along the A Train line at Howard Beach, and southeast, at Far Rockaway, a single, continuous storm surge barrier could protect everyone within the basin.

A storm surge barrier following Rockaway Boulevard would be 4.8 miles long and protect an area of 11.5 miles².



A storm surge barrier protecting the airport and the surrounding community by linking to high ground to the north and south of the bay would be 6.7 miles long and protect an area of 21.5 miles².



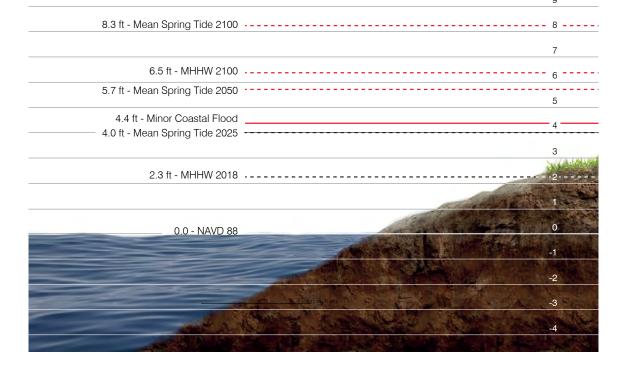
62 Proposed Approach Proposed Approach 63

Advantages of a Dual Barrier System

As sea level rises, a single surge barrier would need to close increasingly often to prevent tidal flooding. While a storm surge barrier alone would be effective, it would be costly to operate and damaging to the environment if closed frequently. Rainfall runoff from upland might also pool on the backside of the barrier. A passive, nonoperable tidal barrier could protect against more frequent, less extreme flooding without relying on closure structures. This second tidal barrier would be constructed to an elevation of 10 feet above NAVD 88, requiring less material and cost per unit length. To optimize the length of this lower tide barrier, it would be constructed along the first inland roadway. This would avoid constricting marshland along the shoreline and would not necessitate the appropriation of private land.

	2025	2050	2100
Flood Event	Annual King Tides	Monthly Spring Tides	Daily High Tides
Rate of Surge Barrier Closure	Surge Barrier 2x per year		2x per day
Total Annual Closures (with Surge Barrier Alone)	2	24	730

In the Head of Bay area, flooding occurs when water levels reach 4.4 ft above NAVD 88. Water elevations and tidal datums refer to USGS Gage 01311850 Jamaica Bay at Inwood. The datums for this gage are depicted on the opposite page alongside probabilistic water elevations projected in this study.



Projected extent of flooding during a mean spring tide in 2050. The probabilistic projected water level of 5.7 ft above NAVD 88 was mapped across the bay using the bathtub method.



A tidal barrier directly following the shoreline would be extremely long relative to the area it could potentially protect. It would be the most costly to build and the most difficult to maintain under sea level rise.



A tidal barrier following the Rockaway Turnpike would protect a large area with a relatively short barrier. However, it would require multiple closure structures or, if passive, would cause extensive damage to Idlewild Marsh and the surrounding waterways.

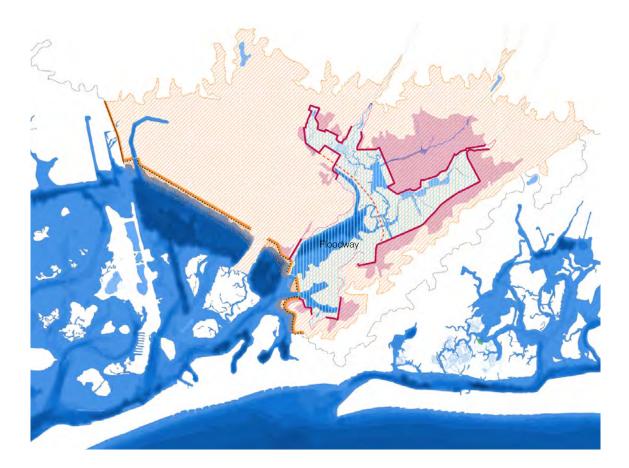


A tidal barrier following the first continuous inland roads would be relatively short in length and could protect a significant area from tidal flooding and minor storm events. This barrier could operate passively without causing damage to the existing marshes.



64 Proposed Approach
Proposed Approach

Layered System



Tidal Barrier

Top of barrier at 10 ft above NAVD 88 Follows local roadways



Surge Barrier

Top of barrier at 20 ft above NAVD 88 Creates new recreation areas

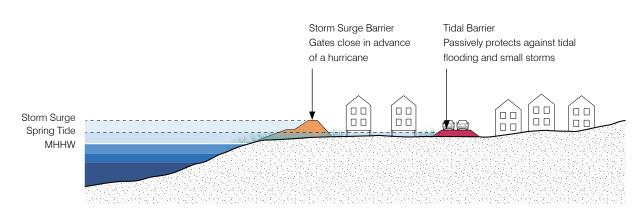


Protected Area

Floodway

A retention area formed by the tidal barrier and existing topography Top of floodway at 10 ft above NAVD 88

--- Elevated Evacuation Route



Time Scales

	2025	2050	2100
1			-
	2.6 ft	3.9 ft	6.5 ft
	4.0 ft	5.7 ft	8.3 ft
	5.9 ft	6.8 ft	10.4 ft
	7.8 ft	8.7 ft	12.7 ft
	9.9 ft	11.0 ft	15.6 ft

Tidal Barrier passively protects against low flooding



Storm Surge Barrier gates close to protect against extreme flooding

Sources

Return Periods

USGS datums for tide gage 01311850 Jamaica Bay at Inwood NY Projections for 2050 and 2100 include 19.7" and 50.8" of sea level rise, respectively. These are the 80th percentile values for New York City under RCP 8.5 in Kopp et al 2014. NPCC's 2015 75th percentile projections compare favorably at 21" and 50", respectively. 2 ADCIRC stormtide analysis conducted by Reza Marsooli and Ning Lin at Princeton University in 2018. The probability distribution of sea level rise in Kopp et al 2014 is incorporated into the flood levels.

Mean Higher High Water Average of the higher of two

daily high tides

Mean Spring Tide

Average of the higher of two
monthly highest tides

100-Year Flood 40% probability of exceedance in 50 years

500-Year Flood 10% probability of exceedance in 50 years

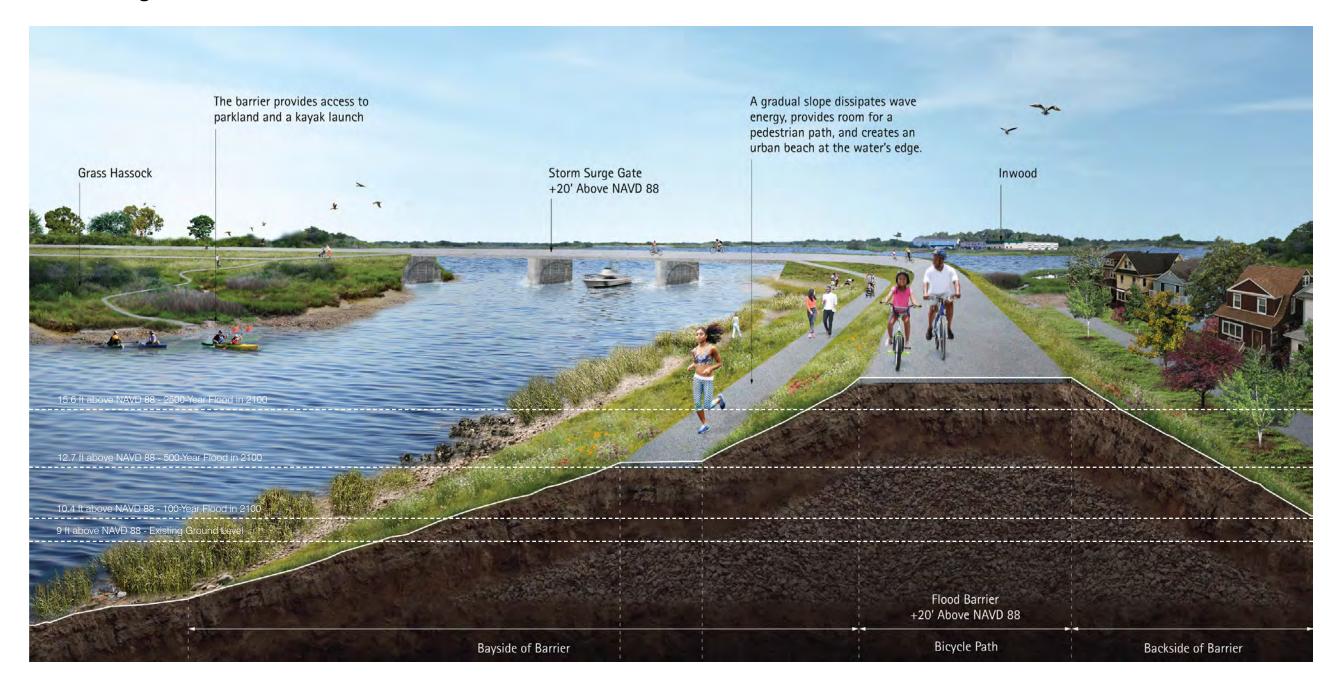
2500-Year Flood 2% probability of exceedance in 50 years

66 Proposed Approach 67

Layered System



Storm Surge Barrier



The storm surge barrier is designed so its top surface reaches 20 feet above NAVD 88. It would operate during more intense, less frequent storms. As the existing grade level along the barrier's path is 2 to 12 feet above NAVD 88, the barrier would average only about 10 feet in height. The gentle

bayside slope creates new habitat for marshland and aquatic life, and the top surface doubles as a biking and jogging path to offer new recreational opportunities. The backside is designed to resist overtopping, so it would prevent or greatly reduce flooding in even the most extreme storms.

70 Proposed Approach Proposed Approach 71

Storm Surge Barrier



The storm surge barrier is designed so its top surface reaches 20 feet above NAVD 88. It would operate during more intense, less frequent storms. At JFK Airport, the barrier would need to remain open to allow access to the runways. During an

extreme storm, a temporary inflatable barrier would be installed at these gaps. As the airport's shoreline is already about 10 feet above NAVD 88, the barrier would be about 10 feet in height along its length.

72 Proposed Approach Proposed Approach 73

Tidal Barrier



The tidal barrier is designed to a height of 10 feet above NAVD 88 along its top surface. The barrier follows the path of existing roads, so it could be built on public land and provide a means of upgrading transportation infrastructure. This protective measure would be passive, so it would

prevent tidal flooding during monthly spring tides and annual king tides as well as smaller storms without requiring the closure of any storm surge gates. Bike lanes could be easily integrated into the new roadways, improving circulation in the area and reducing dependence on automobile traffic.

74 Proposed Approach 75

Elevated Evacuation Route



The length of Rockaway Boulevard and Rockaway Turnpike spanning the floodway could be elevated to create an evacuation route that would remain passable during any flood event. Over time, the commercial lots surrounding the raised causeway

could be relocated, allowing these largely impervious areas to return to support migrating wetlands. As sea levels rise, these marshes would help absorb tidal flooding and rainfall for residents living around Head of Bay.

76 Proposed Approach Proposed Approach 77

area of transformation

The tidal barrier and the natural topography circumscribe an area of low-lying land along the shore at Head of Bay. This area was predominately marshland prior to development and is projected to flood first and more frequently as sea levels rise. Like the rest of the site, it would be completely protected against flooding when the storm surge barrier gates were closed. However, closing the gates for daily or monthly tidal flooding would strain resources and damage the ecosystem. Instead, the tidal barrier is designed to passively absorb excess water during exceptionally high tides, small storms, and rainfall events.

This provides an opportunity to manage and gradually transform this dynamic shoreline. Over time, residents and businesses in this area would need to elevate to a base flood elevation of 10 feet above NAVD 88. In some cases, relocation would be a more cost-effective option, and an equitable buyout program is proposed for particular cases. As the tides rise, selected areas would be restored as wetlands, serving as a buffer for future floods.

As a way of imagining a suite of options for adapting to climate change within the area of transformation, two case study areas serve as sites to project urban and architectural scenarios. These images are hypothetical, and represent only a few of the many possible options for adapting to rising water levels over the next century.



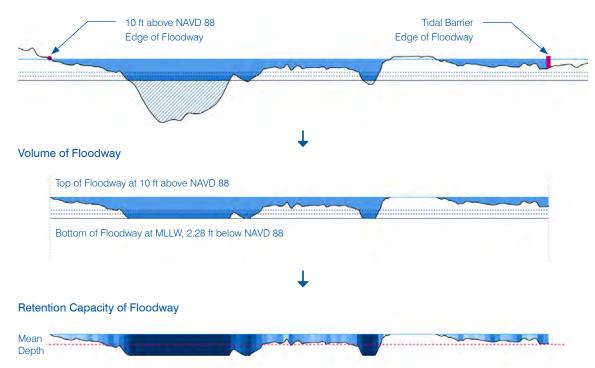


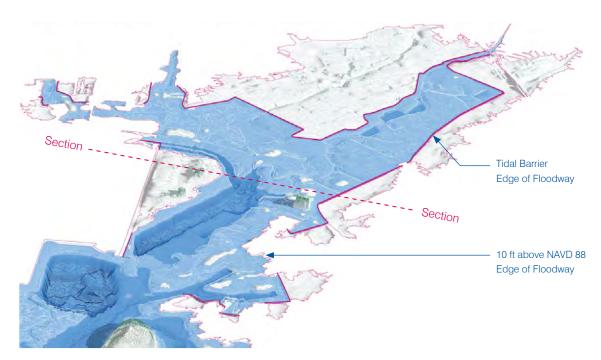
The Floodway

The tidal barrier and natural topography at Head of Bay form a retention basin designed to passively retain elevated water levels up to 10 feet above NAVD 88. During exceptionally high tides, the storm surge gates would remain open, preventing damage to Idlewild Marsh and the Head of Bay ecosystem. In advance of a hurricane, the surge gates could be closed to protect everyone in the area from a dangerous storm surge. In order to maximize the floodway's capacity to collect rainfall, the gates could be closed when water levels are at low tide. Rainfall runoff would be directed toward the floodway and slowed, detained, and absorbed. Roughly estimated, the floodway could manage an 8" rainfall event within the Head of Bay subwatershed.



Topobathymetry of Floodway





The area of transformation offers an opportunity to think critically about how to contend with rising sea levels. We developed a database of existing buildings within the tidal barrier and a set of factors that might influence decision making for residents and business owners under the proposed system. These factors are hypothetical and would require a more extensive analysis. They are designed to weigh the cost of elevating against the value of each building and its likelihood of being flooded over time. It is assumed to be structurally feasible to elevate residential housing and structurally infeasible to elevate large industrial and commercial buildings. Where it makes sense to relocate rather than elevate, a buyout program could be used to manage selective and equitable retreat.

- Location with FEMA flood zones
 100-year flood zone, 500-year flood zone,
 or outside of flood zone
- 2 Flood Depth Depth of flooding, based on elevation above NAVD 88 in feet
- 3 Estimated insurance premium \$500 per year in 500-year flood zone \$5000 per year in 100-year flood zone
- 4 Estimated market value
 Based on neighboring property values
 listed on Zillow
- Estimated cost to elevate
 Rate of \$75/ft² with a deduction of
 \$5/ft² * x ft elevation above NAVD 88
- 6 Property land use
- One- and Two-Family Residential

 Multifamily Residential

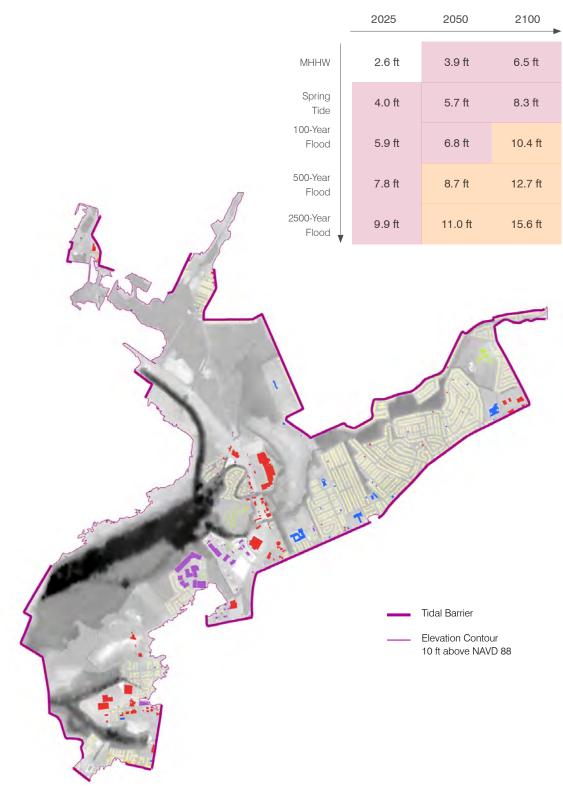
 Commercial

 Industrial

 Institutional

 Hazardous Infrastructure

2018

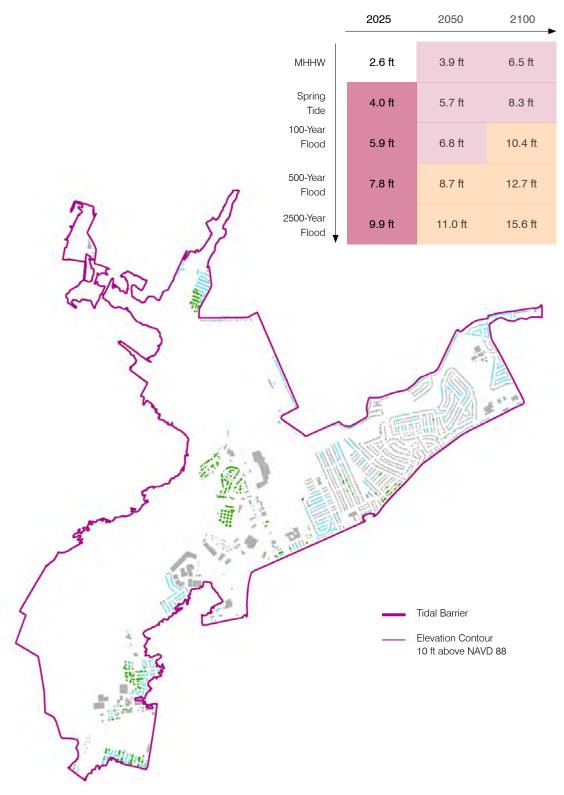


82 Area of Transformation Area of Transformation

In the year 2025, it is assumed that the tidal barrier would be constructed. By this time, only a few areas are likely to flood on a consistent basis. These areas are primarily single-family residential, and elevation is highly recommended at these select sites.

- Elevation Highly Recommended 306 Buildings
 - IF the building is within the 100-year flood zone
 - AND the owner would otherwise pay half the cost to elevate in FEMA flood insurance premiums by 2025
 - AND the cost to elevate is less than half of the building's market value
- Elevation Recommended 767 Buildings
 - IF the building is within the 100-year flood zone
 - AND the owner would likely pay half the cost to elevate in FEMA flood insurance premiums by 2025
 - AND the cost to elevate is less than half of the building's market value
- Relocation Recommended
 1 Building
 - IF the building is within the mean spring tide zone
 - AND the cost to elevate is more than half the building's estimated market value
- No Action Recommended
 1922 Buildings

2025

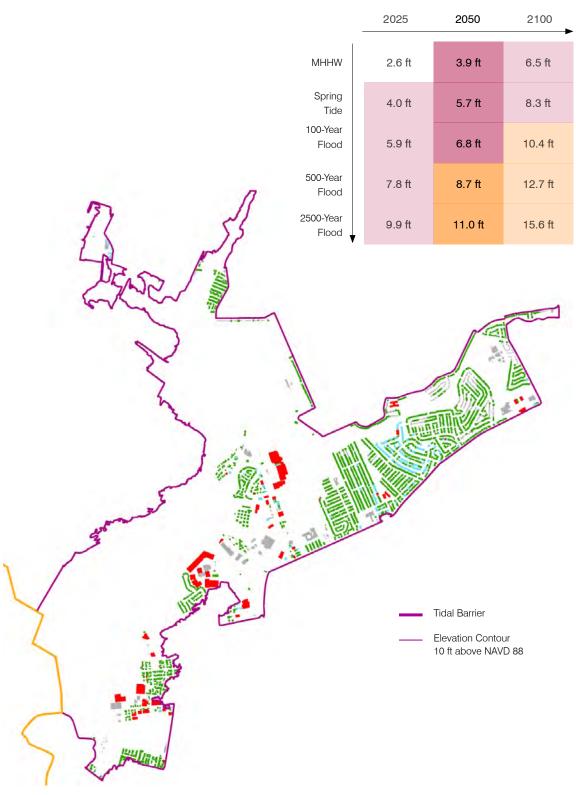


4 Area of Transformation Area of Transformation

In the year 2050, it is assumed that the tidal barrier and storm surge barrier would be fully operational. By this time, a larger area is expected to flood on a monthly basis and some areas may be inundated twice daily. Elevation is recommended for most buildings within the area of transformation. Where elevation is structurally infeasible or is not cost efficient, relocation is suggested.

- Elevation Highly Recommended 2326 Buildings
 - IF the owner would otherwise pay more in FEMA flood insurance premiums by 2050 than the cost to elevate
 - AND the cost to elevate is less than half of the building's market value
- Elevation Recommended
 134 Buildings
 - IF the building is within the 100-year flood zone
 - AND the cost to elevate is more than the owner would likely pay in FEMA flood insurance premiums by 2050
 - AND the cost to elevate is less than half of the building's market value
- Relocation Recommended 60 Building
 - IF the building is within the 100-year flood zone
 - AND the cost to elevate is more than half of the building's market value
- No Action Recommended 476 Buildings

2050



Area of Transformation

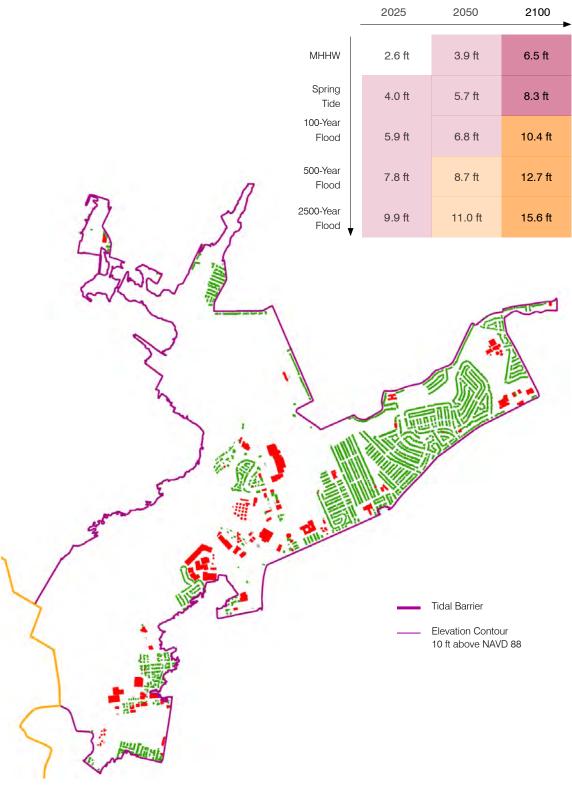
Area of Transformation

In the year 2100, it is assumed that the tidal barrier and storm surge barrier would be fully operational. By this time, rising sea levels are expected to have drastically altered the shoreline. Much of the area of transformation would be underwater on a daily basis, and most woud be inundated monthly. Elevation is recommended for any buildings that sit below 10 feet above NAVD 88. Where elevation is structurally infeasible or is not cost efficient, relocation is suggested.

- Elevation Highly Recommended 2793 Buildings
 - IF the cost to elevate is less than half of the building's market value
- Relocation Recommended 167 Building
 - IF the building is within the 100-year flood zone
 - AND the cost to elevate is more than half of the building's market value

No Action Recommended
36 Buildings

2100



8 Area of Transformation Area of Transformation

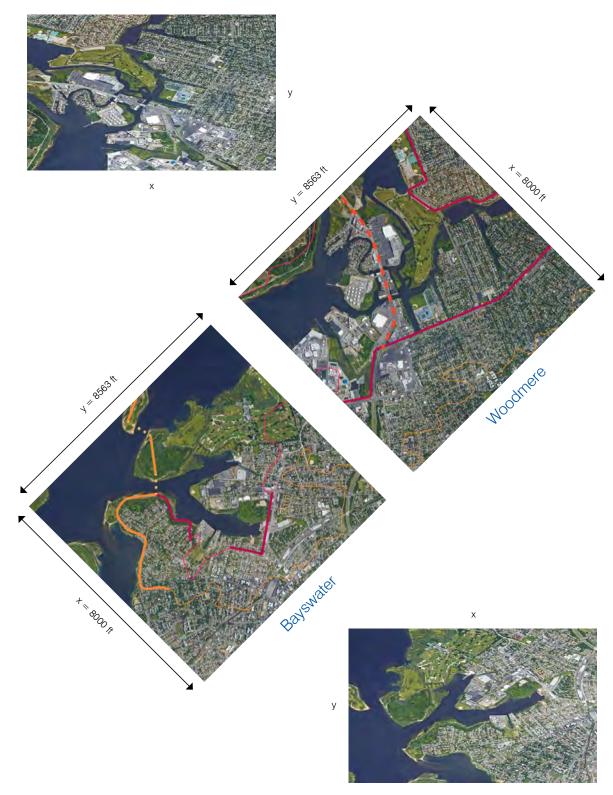
Case study sites

We selected two case study sites near Head of Bay to test how the proposed flood protection system might be deployed over time. Each represents a square area approximately 8,000 feet long on either side and is projected isometrically to create a three-dimensional view.

The Bayswater site encompasses the areas of Bayswater, which lies in Queens, and Inwood, which is part of Nassau County. This case study features portions of the surge barrier and the tidal barrier in addition to the area of transformation.

The Woodmere site depicts areas of Woodmere, Cedarhurst, Meadowmere, and Inwood and straddles the border between Queens and Nassau County. This case study allows for a closer look at the tidal barrier and area of transformation, as well as the elevated evacuation route.





Analysis of Flood Risk in Bayswater

The matrix at right depicts projected flood risk reduction in Bayswater under the proposed system. The tidal barrier would be constructed by 2025 and the storm surge barrier would be constructed before 2050. In 2025, the tidal barrier would reduce flooding for all analyzed return periods. By 2050, the storm surge barrier would be closed for 500-year events and greater, protecting everyone in the project scope from catastrophic flooding. By 2100, rising sea levels would necessitate closure of the surge gates for 100-year events and greater. When the barrier is closed (indicated by orange border), the water level in the floodway is shown at Mean Higher High Water as projected for that year.

Property Land Use

One- and Two-Family Residential

Multifamily Residential

Commercial

Industrial

Institutional

Hazardous Infrastructure

Flooded

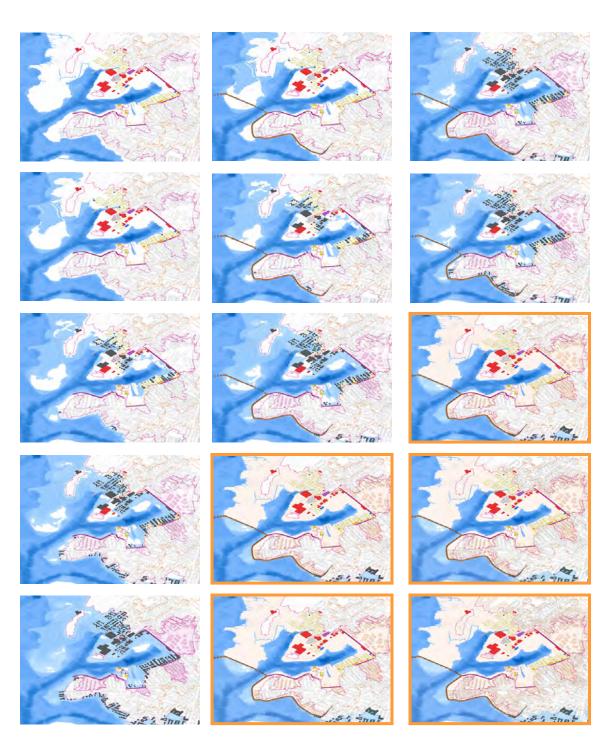
Mean Higher
High Water
Average of the higher
of two daily high tides

Mean Spring Tide
Average of the higher of two
monthly highest tides

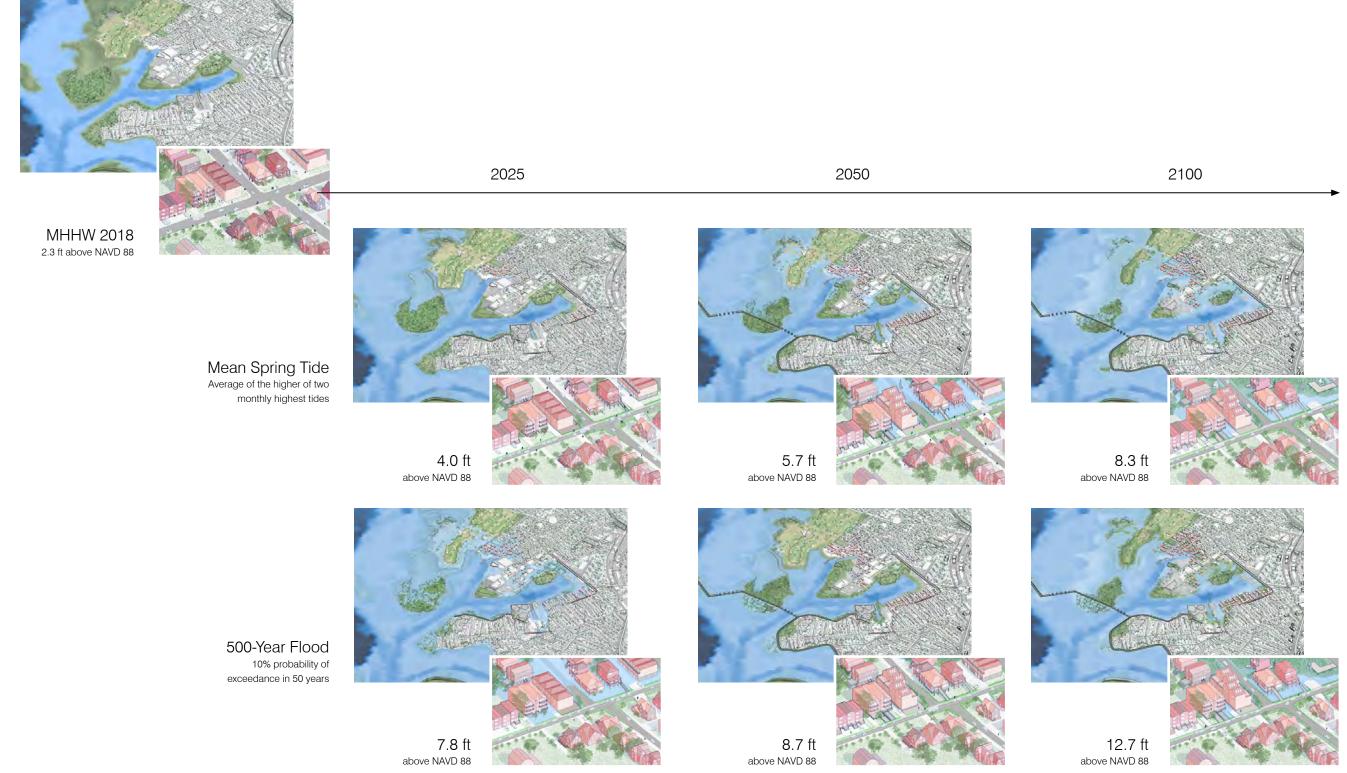
100-Year Flood 40% probability of exceedance in 50 years

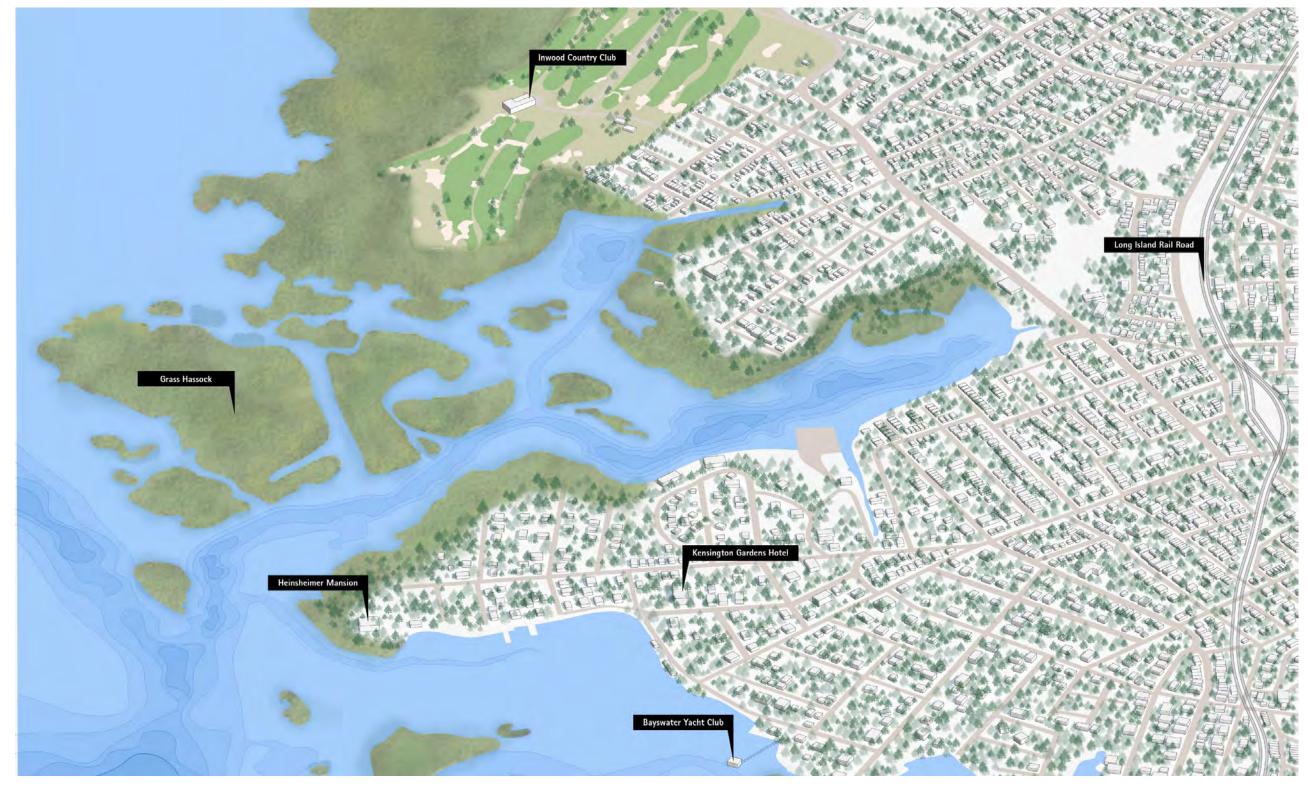
500-Year Flood 10% probability of exceedance in 50 years

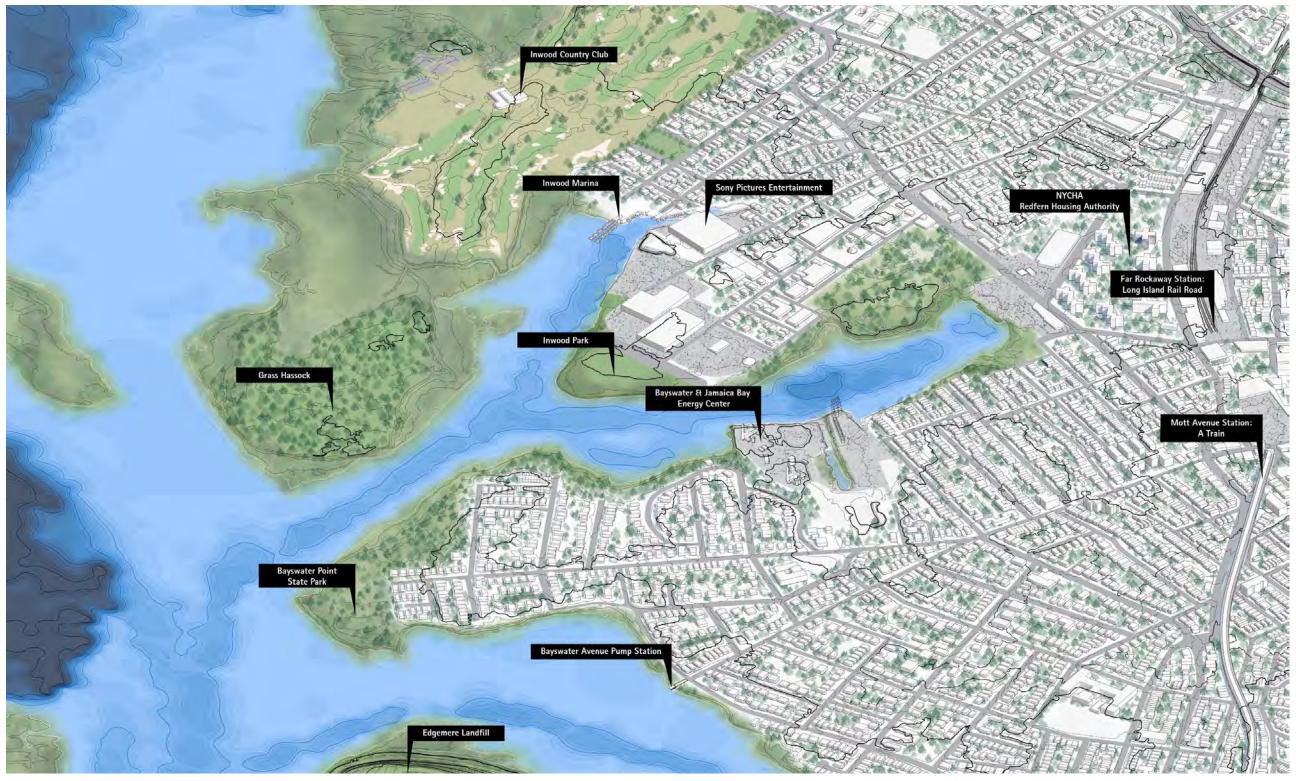
2500-Year Flood 2% probability of exceedance in 50 years 2025 2050 2100



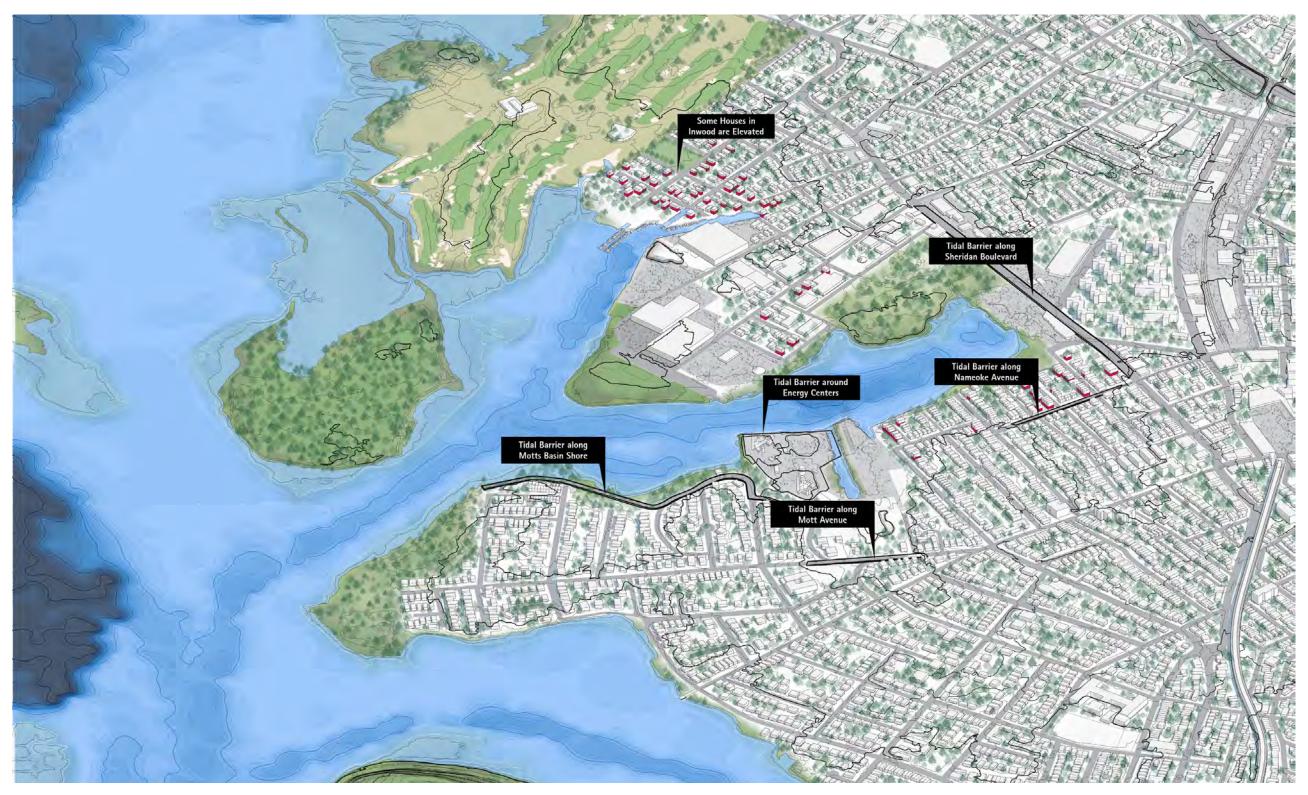
Envisioning Possible Futures in Bayswater

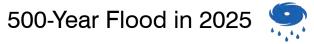


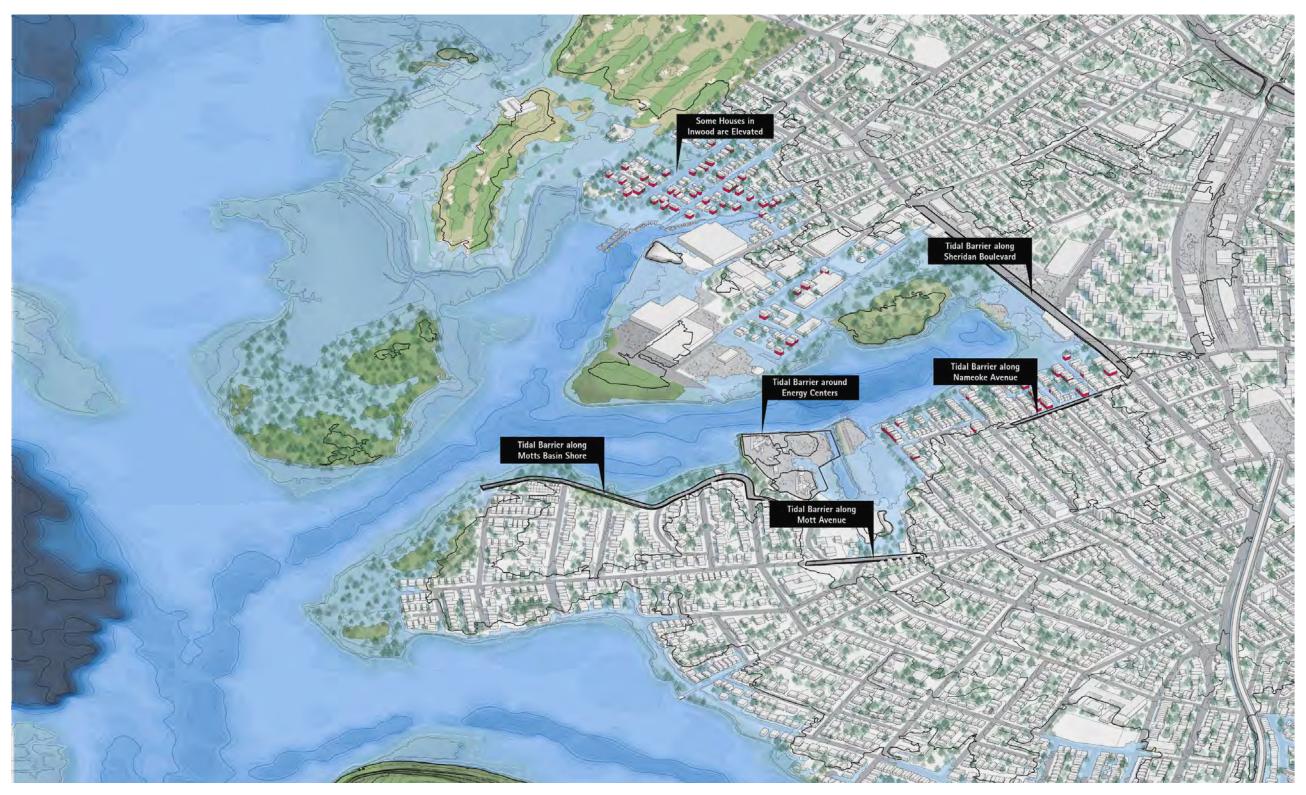




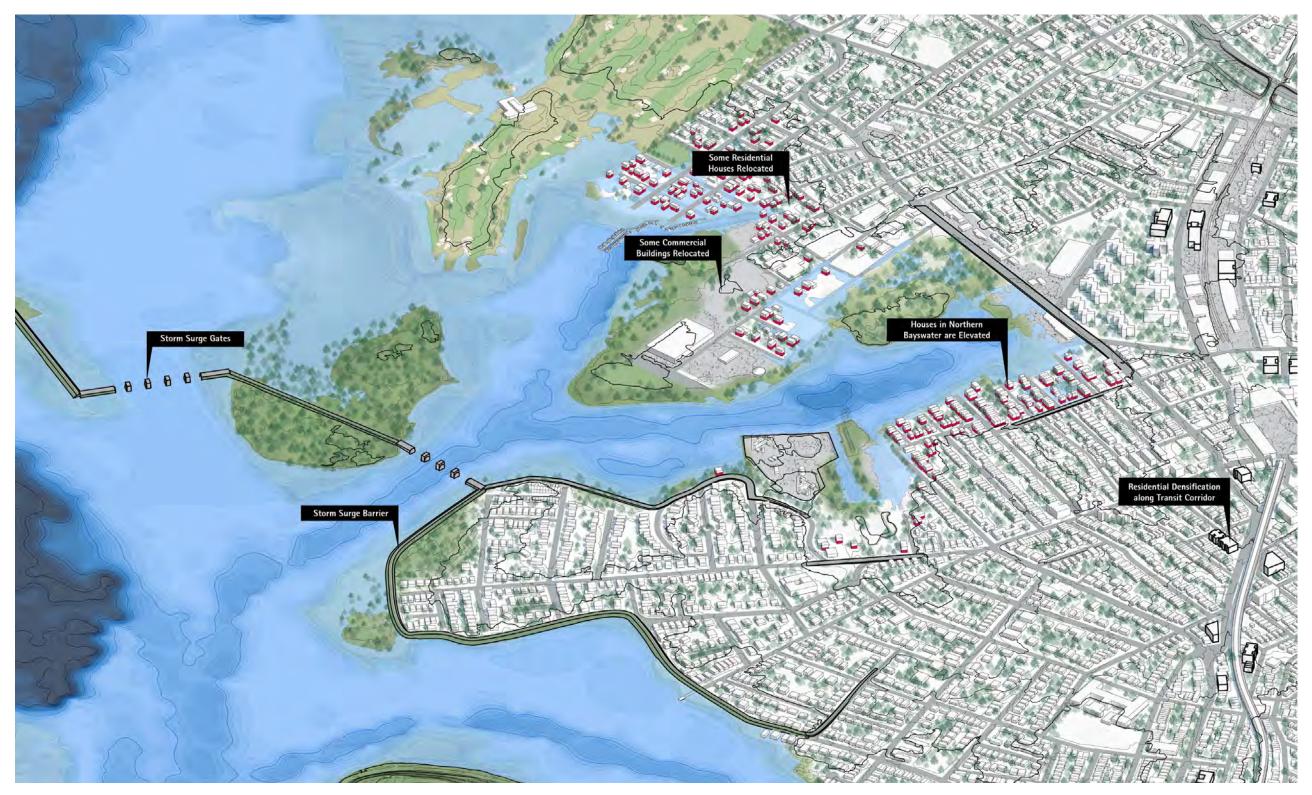




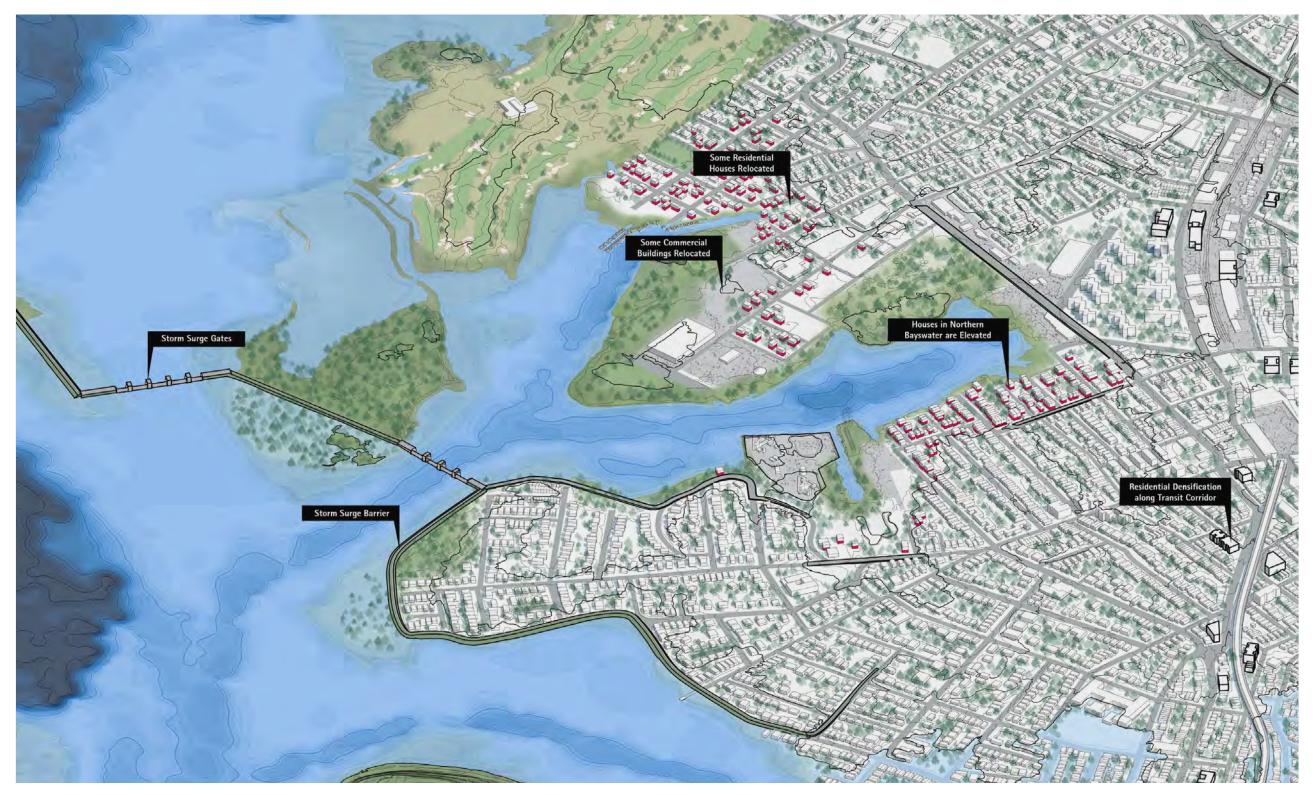




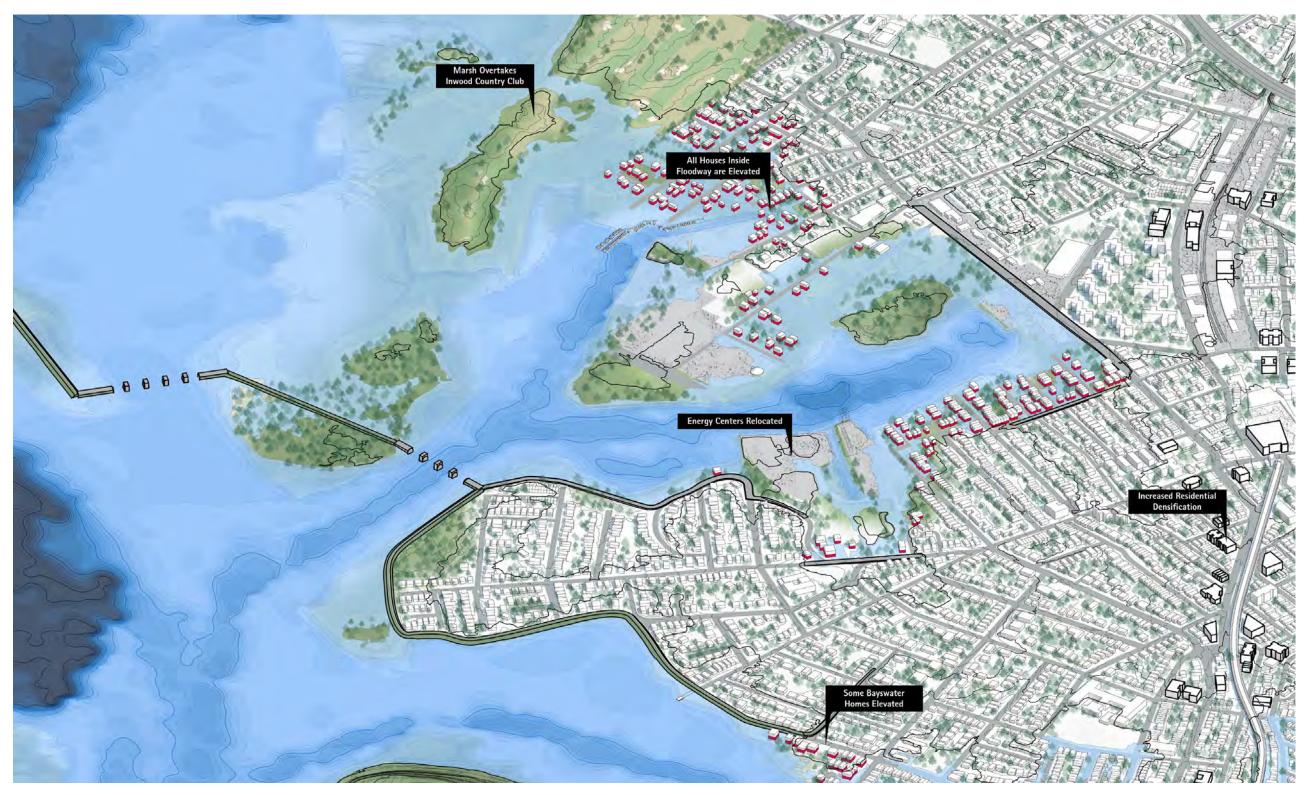




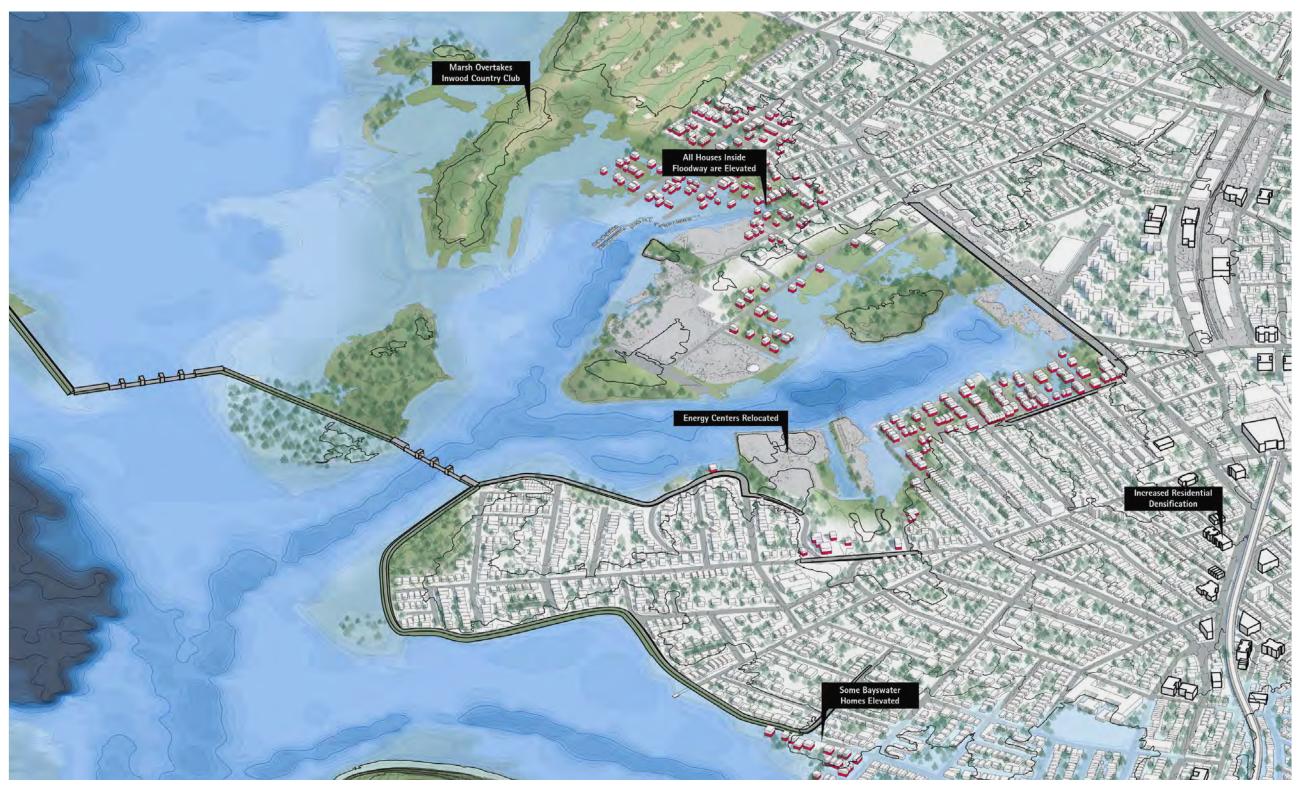






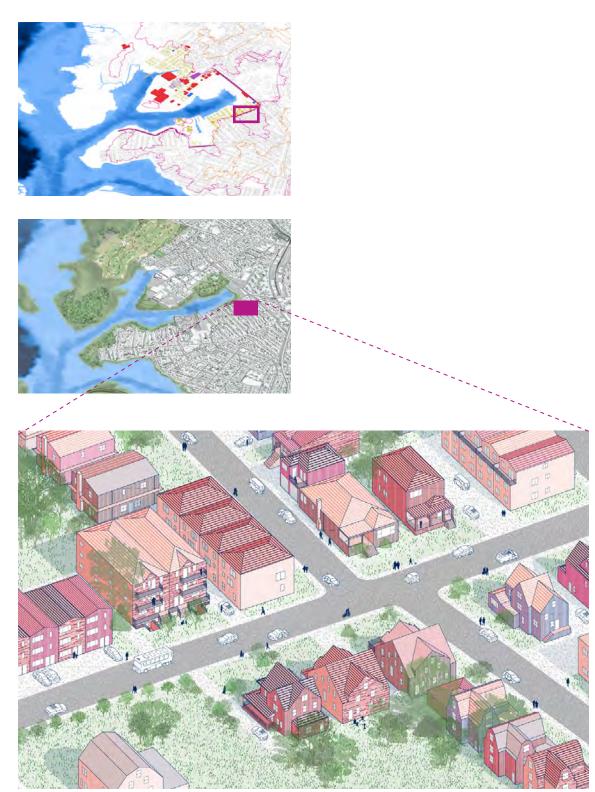








Google satellite imagery of Bayswater and Far Rockaway in Queens and Inwood in Nassau County, September 2017.



Spring Tide in 2025

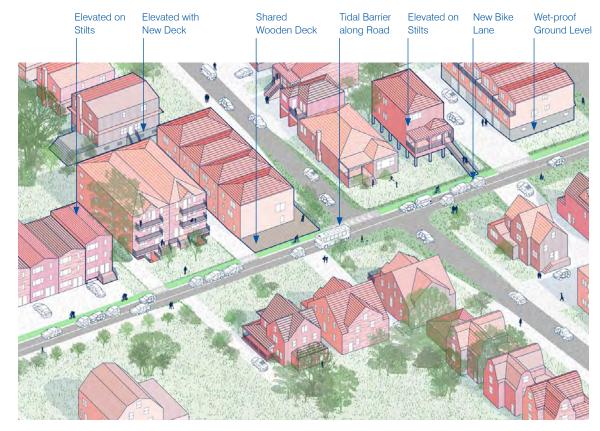
500-Year Flood in 2025



	2025	2050	2100
MHHW	2.6 ft	3.9 ft	6.5 ft
Spring Tide	4.0 ft	5.7 ft	8.3 ft
100-Year Flood	5.9 ft	6.8 ft	10.4 ft
500-Year Flood	7.8 ft	8.7 ft	12.7 ft
2500-Year Flood	9.9 ft	11.0 ft	15.6 ft



	2025	2050	2100
MHHW	2.6 ft	3.9 ft	6.5 ft
Spring Tide	4.0 ft	5.7 ft	8.3 ft
100-Year Flood	5.9 ft	6.8 ft	10.4 ft
500-Year Flood	7.8 ft	8.7 ft	12.7 ft
2500-Year Flood	9.9 ft	11.0 ft	15.6 ft





Spring Tide in 2050

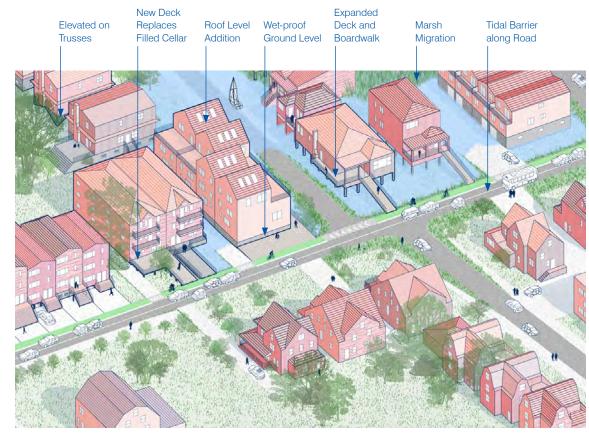
500-Year Flood in 2050



	2025	2050	2100
1			_
MHHW	2.6 ft	3.9 ft	6.5 ft
Spring Tide	4.0 ft	5.7 ft	8.3 ft
100-Year Flood	5.9 ft	6.8 ft	10.4 ft
500-Year Flood	7.8 ft	8.7 ft	12.7 ft
2500-Year Flood	9.9 ft	11.0 ft	15.6 ft



	2025	2050	2100
MHHW	2.6 ft	3.9 ft	6.5 ft
Spring Tide	4.0 ft	5.7 ft	8.3 ft
100-Year Flood	5.9 ft	6.8 ft	10.4 ft
500-Year Flood	7.8 ft	8.7 ft	12.7 ft
2500-Year Flood	9.9 ft	11.0 ft	15.6 ft





Spring Tide in 2100

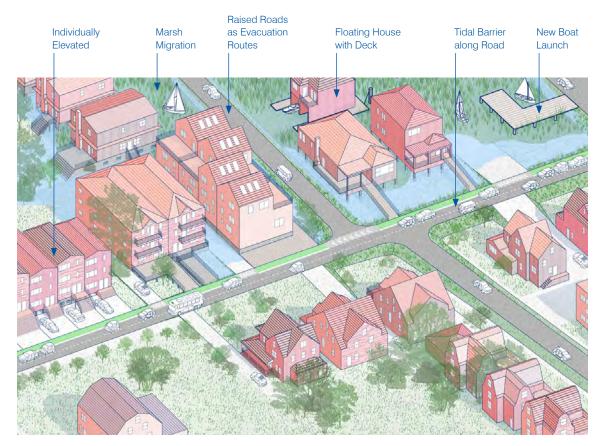
500-Year Flood in 2100



	2025	2050	2100
I			_
MHHW	2.6 ft	3.9 ft	6.5 ft
Spring Tide	4.0 ft	5.7 ft	8.3 ft
100-Year Flood	5.9 ft	6.8 ft	10.4 ft
500-Year Flood	7.8 ft	8.7 ft	12.7 ft
2500-Year Flood	9.9 ft	11.0 ft	15.6 ft



	2025	2050	2100
MHHW	2.6 ft	3.9 ft	6.5 ft
Spring Tide	4.0 ft	5.7 ft	8.3 ft
100-Year Flood	5.9 ft	6.8 ft	10.4 ft
500-Year Flood	7.8 ft	8.7 ft	12.7 ft
2500-Year Flood	9.9 ft	11.0 ft	15.6 ft





Analysis of Flood Risk in Woodmere

The matrix at right depicts projected flood risk reduction in Woodmere under the proposed system. The tidal barrier would be constructed by 2025, and the storm surge barrier would be constructed before 2050. In 2025, the tidal barrier would reduce flooding for all analyzed return periods. By 2050, the storm surge barrier would be closed for 500-year events and greater, protecting everyone in the project scope from catastrophic flooding. By 2100, rising sea levels would necessitate closure of the surge gates for 100-year events and greater. When the barrier is closed (indicated by orange border), the water level in the floodway is shown at Mean Higher High Water as projected for that year.

Property Land Use

One- and Two-Family Residential

Multifamily Residential

Commercial

Industrial

Institutional

Hazardous Infrastructure

Flooded

Mean Higher High Water Average of the higher

of two daily high tides

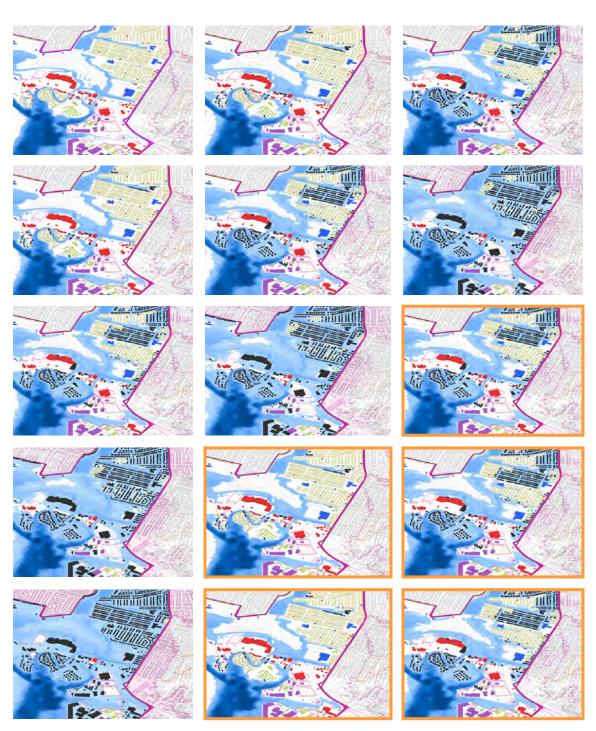
Mean Spring Tide
Average of the higher of two

monthly highest tides

100-Year Flood 40% probability of exceedance in 50 years

500-Year Flood 10% probability of exceedance in 50 years

2500-Year Flood 2% probability of exceedance in 50 years 2025 2050 2100



Envisioning Possible Futures in Woodmere



2025 2050 2100 4.0 ft 5.7 ft 8.3 ft above NAVD 88 above NAVD 88 above NAVD 88

Mean Spring Tide Average of the higher of two monthly highest tides



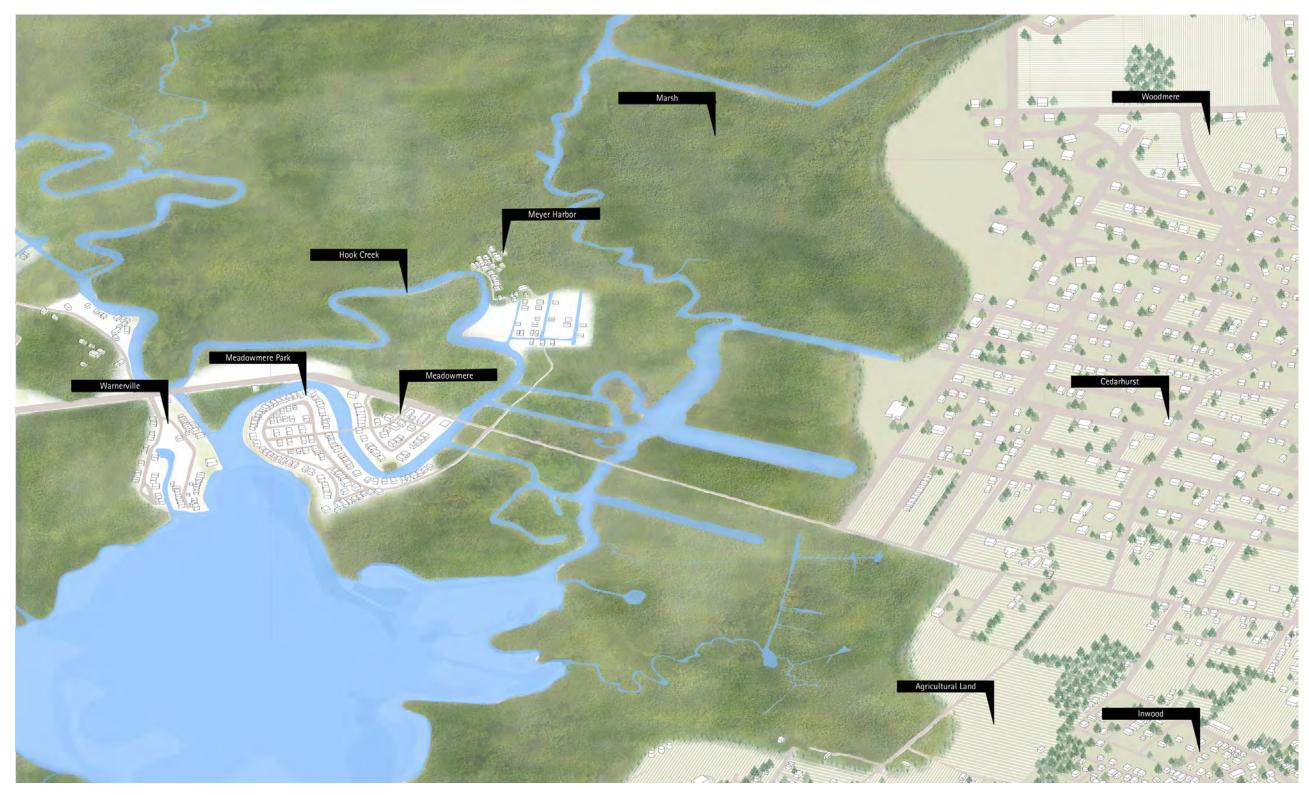
8.7 ft above NAVD 88

12.7 ft

above NAVD 88

500-Year Flood 10% probability of exceedance in 50 years

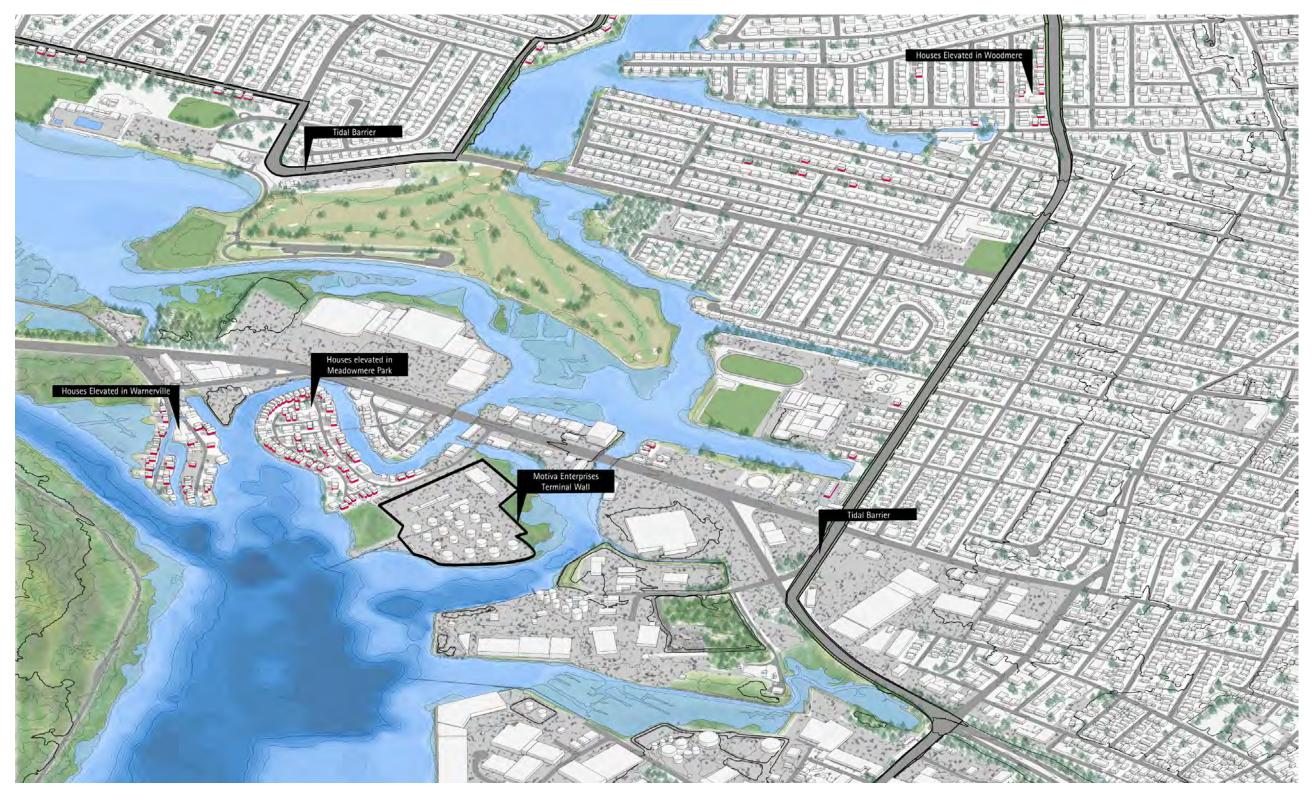
122 Area of Transformation Area of Transformation 123 Woodmere 1925



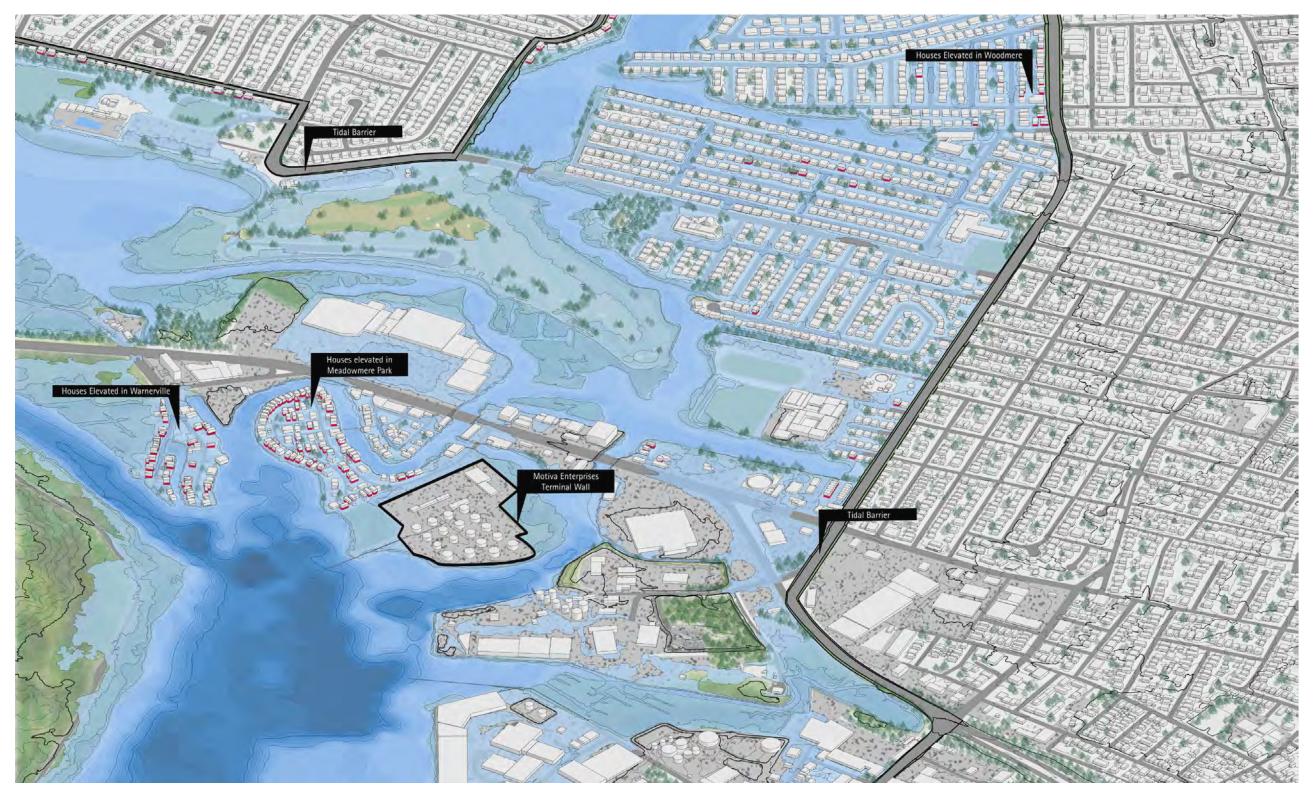
Woodmere 2018





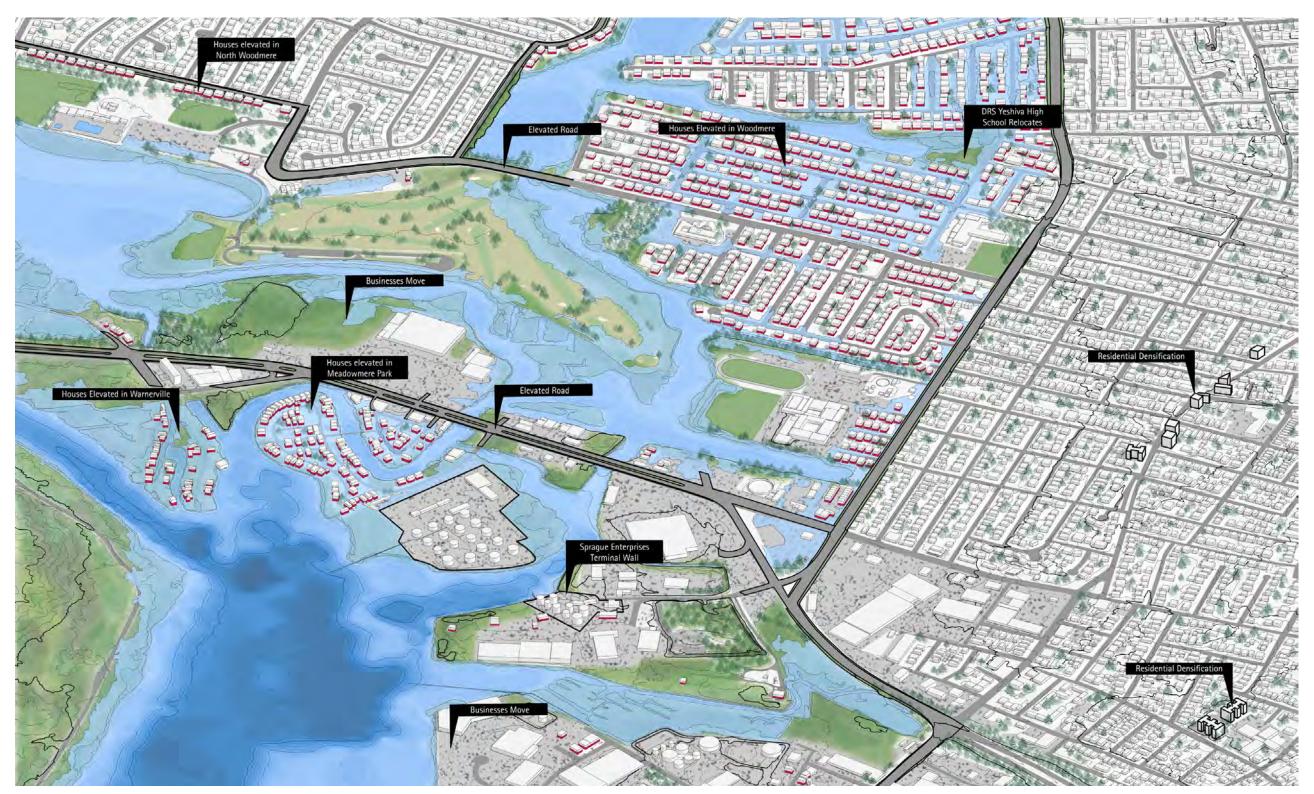




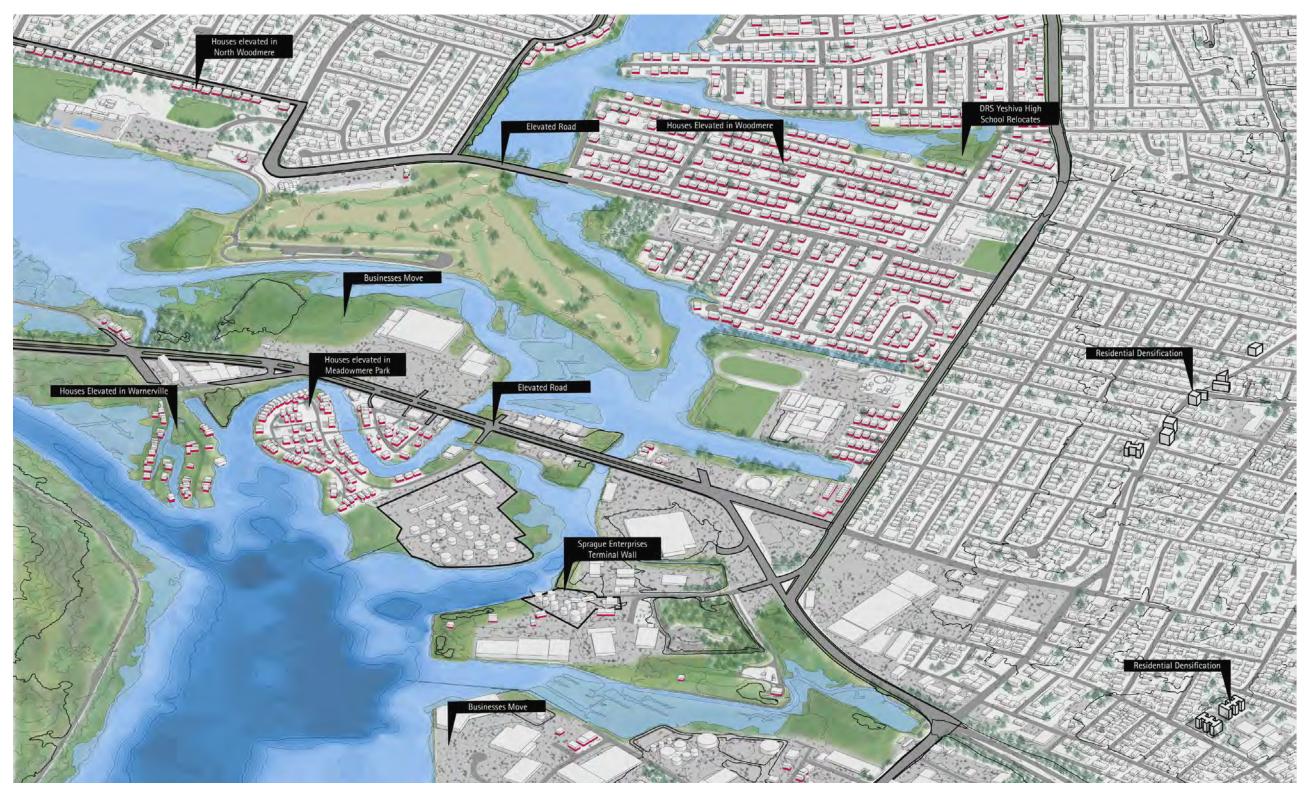


Spring Tide in 2050

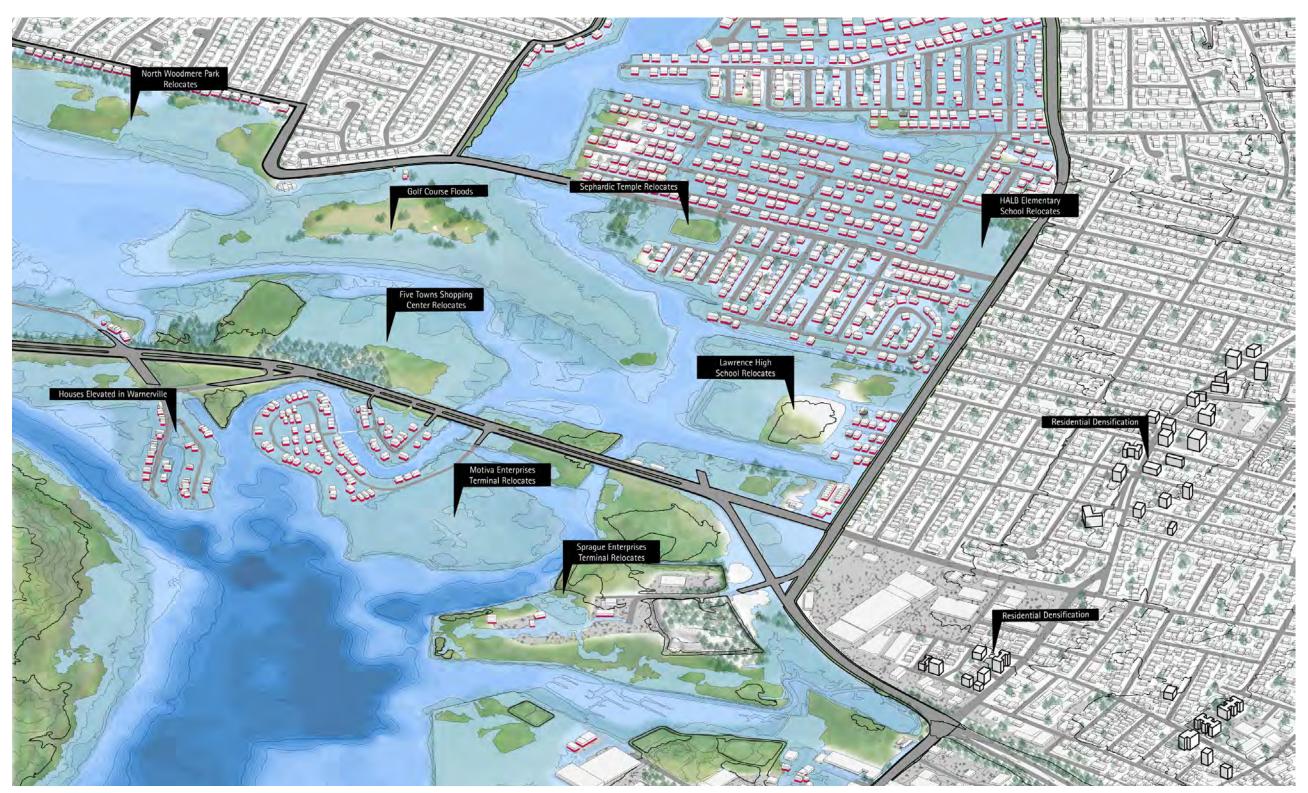


















Google satellite imagery of Woodmere and Cedarhurst in Nassau County and Meadowmere in Queens, September 2017.







140 Area of Transformation 141

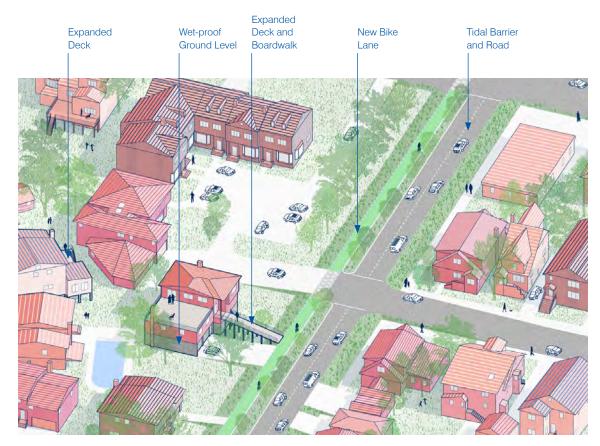
Spring Tide in 2025

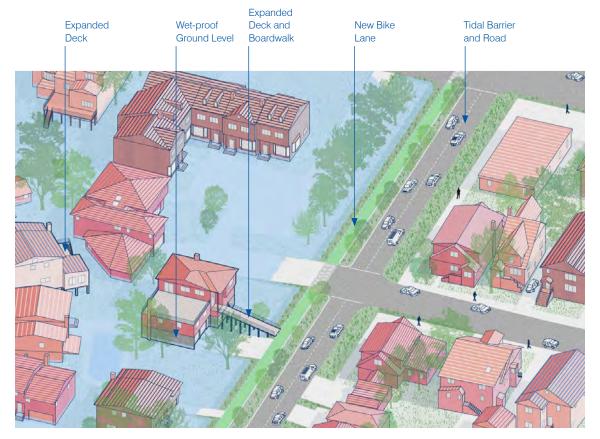
	2025	2050	2100
MHHW	2.6 ft	3.9 ft	6.5 ft
Spring Tide	4.0 ft	5.7 ft	8.3 ft
100-Year Flood	5.9 ft	6.8 ft	10.4 ft
500-Year Flood	7.8 ft	8.7 ft	12.7 ft
2500-Year Flood	9.9 ft	11.0 ft	15.6 ft
Tide 100-Year Flood 500-Year Flood 2500-Year	5.9 ft 7.8 ft	6.8 ft 8.7 ft	10.4 ft 12.7 ft

500-Year Flood in 2025



	2025	2050	2100
MHHW	2.6 ft	3.9 ft	6.5 ft
Spring Tide	4.0 ft	5.7 ft	8.3 ft
100-Year Flood	5.9 ft	6.8 ft	10.4 ft
500-Year Flood	7.8 ft	8.7 ft	12.7 ft
2500-Year Flood	9.9 ft	11.0 ft	15.6 ft

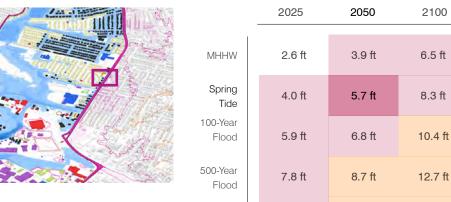




Spring Tide in 2050 2025 2050 2100

11.0 ft

15.6 ft



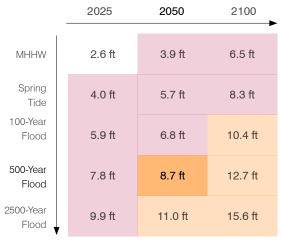
2500-Year

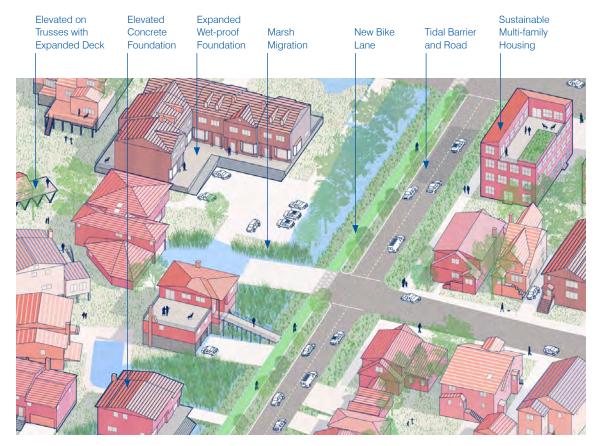
Flood

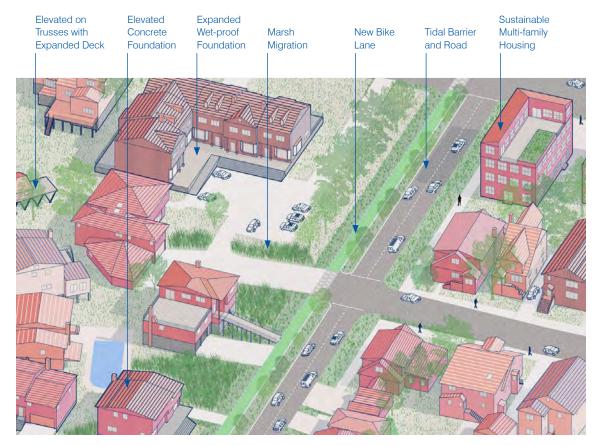
9.9 ft

500-Year Flood in 2050









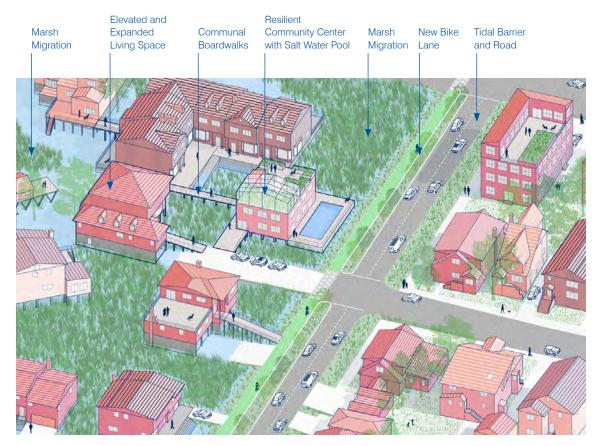
Spring Tide in 2100

	2025	2050	2100
MHHW	2.6 ft	3.9 ft	6.5 ft
Spring Tide	4.0 ft	5.7 ft	8.3 ft
100-Year Flood	5.9 ft	6.8 ft	10.4 ft
500-Year Flood	7.8 ft	8.7 ft	12.7 ft
2500-Year	9.9 ft	11.0 ft	15.6 ft

500-Year Flood in 2100



	2025	2050	2100
MHHW	2.6 ft	3.9 ft	6.5 ft
Spring Tide	4.0 ft	5.7 ft	8.3 ft
100-Year Flood	5.9 ft	6.8 ft	10.4 ft
500-Year Flood	7.8 ft	8.7 ft	12.7 ft
2500-Year Flood	9.9 ft	11.0 ft	15.6 ft







Following the initial design phase, the efficacy of the proposed flood protection system is tested through a second hydrodynamic analysis. This analysis involved determining projected flooding for individual storm tracks on a very high resolution mesh of Jamaica Bay. Tracks were selected that resulted in storm tide levels close to the probabilistic results for particular return periods in 2025, 2050, and 2100. Each of the eight storm scenarios was analyzed twice: once with a control mesh lacking flood protection features, and a second time, with the proposed layered system modeled in the computational mesh.

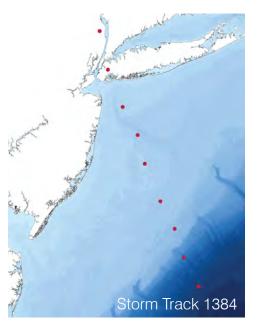
The following results show that the layered system operates well under each of the eight hurricane scenarios analyzed.

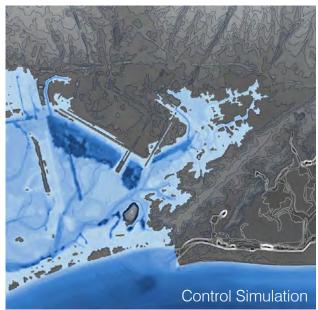
8.1 ft above NAVD 88 Tidal Barrier Only Scenario 2 Single Track 2500-Year Flood in 2025

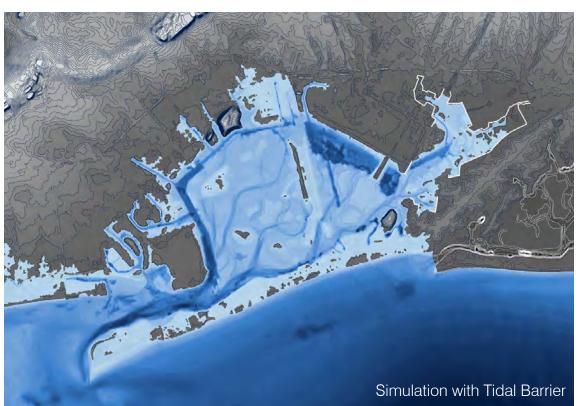












Scenario 3

Single Track 100-Year Flood in 2050 Assuming 1.3 ft of sea level rise 6.23 ft above NAVD 88 Storm Surge Barrier Open

Scenario 4

Single Track 500-Year Flood in 2050 Assuming 1.3 ft of sea level rise

8.0 ft above NAVD 88 Storm Surge Barrier Closed













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10.9 ft above NAVD 88 Storm Surge Barrier Closed

Scenario 6

Single Track 500-Year Flood in 2100

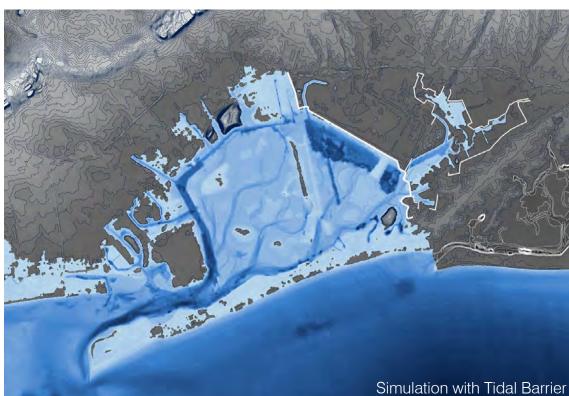
Assuming 3.9 ft of sea level rise

11.9 ft above NAVD 88 Storm Surge Barrier Closed

Single Track 100-Year Flood in 2100 Assuming 3.1 ft of sea level rise

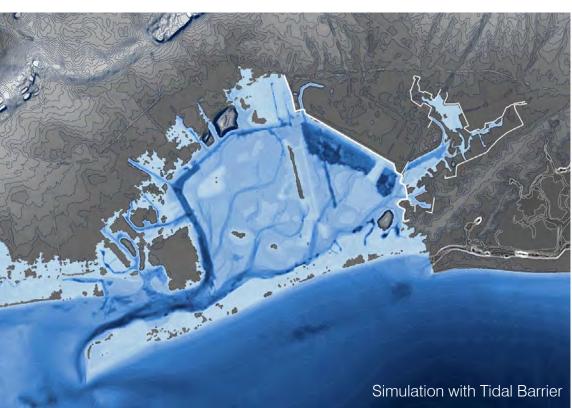








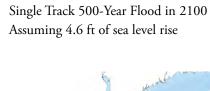




12.4 ft above NAVD 88 Storm Surge Barrier Closed Scenario 8
Single Track 2500-Year Flood in 2100

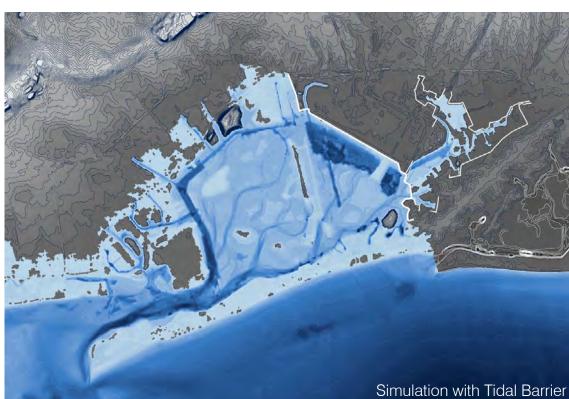
Assuming 7.0 ft of sea level rise

14.8 ft above NAVD 88 Storm Surge Barrier Closed

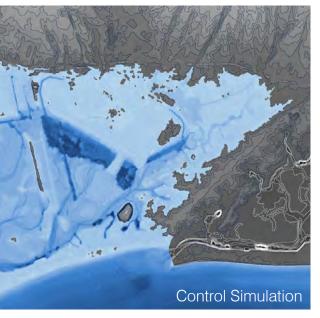


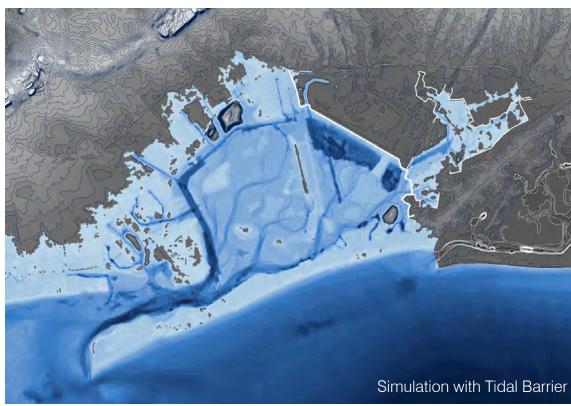












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Comparison of 100-Year and 500-Year Floodplains

The maps at right represent the flooded areas induced by a 100-year and 500-year storm event using three different methods of projection. The top two projections depict the extent of flooding mapped from projected 100-year and 500-year levels, while the bottom projection depicts the expected flooding from specific hurricane events, and is therefore not probabilistic. The projected risk of flooding varies significantly, underscoring the need to design flood risk reduction systems that allow for variability.

Projections under a 2000 climate

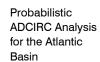


Projections under a 2050 climate, including sea level rise

Projections under a 2100 climate, including sea level rise

No Data

No Data



FEMA

Floodplains

events under

conditions.

Projected using

current climatic

100-Year

500-Year Floodplain

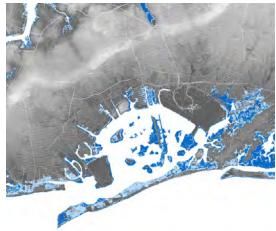
Floodplain

historic hurricane

Extent determined by mapping results to the bay using the bathtub method.

100-Year Floodplain

500-Year Floodplain

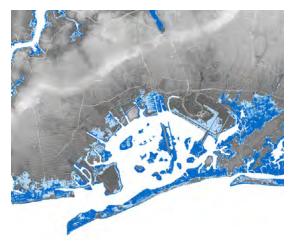


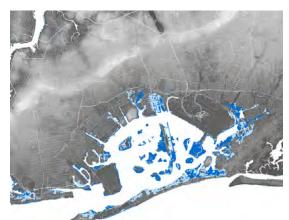
Scenario-based ADCIRC Analysis for Jamaica Bay Extent determined during hydrodynamic modeling.

100-Year Floodplain

500-Year Floodplain





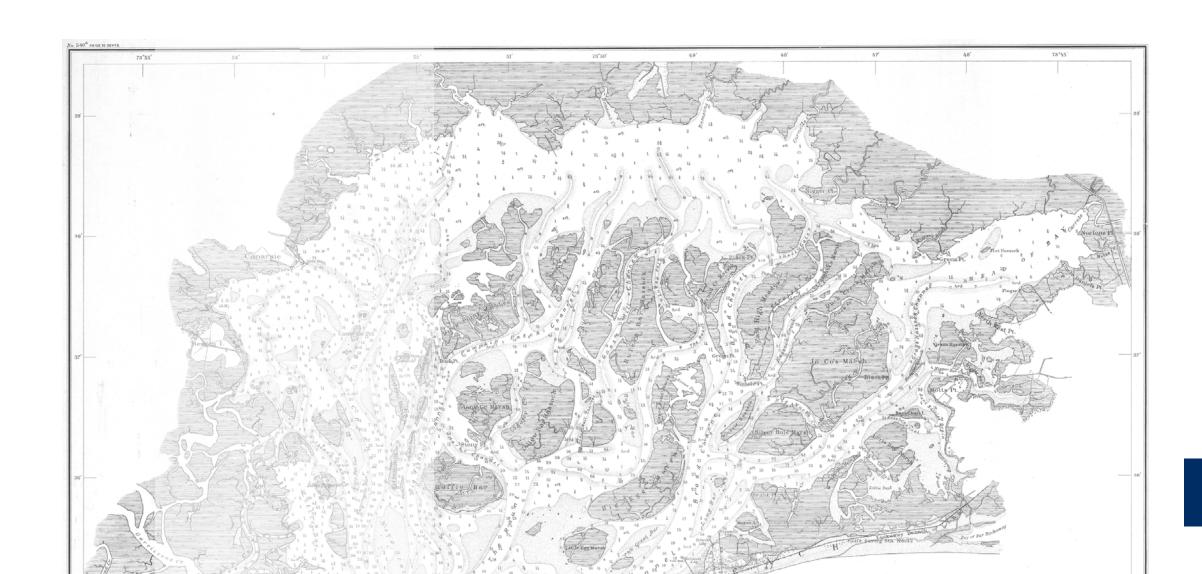






158 Storm Simulations Storm Simulations 159

appendices



Notes

Executive Summary

- 1 "Building the Knowledge Base for Climate Resiliency: New York City Panel on Climate Change 2015 Report." *Annals of the New York Academy of Sciences* 1336 (2015).
- 2 Climate Science Special Report: Fourth National Climate Assessment, Volume I. Wuebbles, DJ, DW Fahey, KA Hibbard, DJ Dokken, BC Steward, and TK Maycock, eds. U.S. Global Change Research Program, Washington, DC.
- 3 "Jamaica Bay Wildlife Refuge." New York City Audubon. Accessed October 16, 2018. http://www.nycaudubon.org/queens-birding/jamaica-bay-wildlife-refuge

Introduction

- 1 Ramasubramanian, Laxmi, Mike Menser, Erin Reiser, Leah Feder, Racquel Forrester, Robin Leichenko, Shorna Allred, Gretchen Ferenz, Mia Brezin, Jennifer Bolstad, Walter Meyer, and Keith Tidball. "Strategies for Community Resilience Practice for the Jamaica Bay Watershed." In *Prospects for Resilience: Insights from New York City's Jamaica Bay.* Island Press, 2016: 274; Buchanan, M. K. "Household Adaptive Behavior in Response to Coastal Flood Risk and External Stressors." American Geophysical Union, Fall Meeting 2017, December 2017.
- 2 Hurricane Sandy made landfall near Atlantic City, New Jersey with a windfield of over 1000 miles. Blake, Eric S, Todd B Kimberlain, Robert J Berg, John P Cangialosi, and John L Beven II. "Tropical Cyclone Report: Hurricane Sandy, (AL182012), 22 - 29 October 2012." National Hurricane Center, 2013.
- 3 A Stronger, More Resilient New York. The City of New York, Mayor Michael R. Bloomberg, 2013.
- 4 Blake et al. "Tropical Cyclone Report: Hurricane Sandy, (AL182012), 22 29 October 2012," 15.
- 5 A Stronger, More Resilient New York.
- 6 Williams Walsh, Mary. "A Broke, and Broken, Flood Insurance Program." *The New York Times*, November 4, 2017.
- 7 "Building the Knowledge Base for Climate Resiliency: New York City Panel on Climate Change 2015 Report."

Area at Risk

- 1 Data derived from a GIS analysis of US Census population data by census tract for 2017 within the Jamaica Bay watershed as delineated by the USGS National Hydrography Dataset (NHD) Best Resolution 20170316 data for New York State.
- 2 "Jamaica Bay Park." New York City Department of Parks and Recreation. Accessed October 16, 2018. https://www.nycgovparks.org/parks/jamaica-bay-park
- 3 Data derived from FEMA Preliminary Flood Insurance Rate Maps (FIRMs) for New York City, issued in 2015.
- 4 A Stronger, More Resilient New York, 15.

- 5 Breaking New Ground: 2017 Annual Report. The Port Authority of New York and New Jersey, 2017.
- 6 The Fourth Regional Plan for the New York-New Jersey-Connecticut Metropolitan Area: Making the Region Work for All of Us. Regional Plan Association, 2017.
- 7 2017 Annual Report. Metropolitan Transportation Authority, 2017.
- 8 A Stronger, More Resilient New York, 179.

History of Development

- 1 Black, Frederick R. *Jamaica Bay: A History, Cultural Resource Management Study No. 3.* Washington, DC: National Park Service, US Department of the Interior, 1981: 7.
- 2 Lucey, Emil R. *The Rockaways*. New York: Arcadia Publishing, 2007.
- 3 Chart No. 540a: Jamaica Bay and Rockaway Inlet, Long Island, New York. National Oceanic and Atmospheric Administration, 1879.
- 4 "Jamaica Bay, Foul with Sewage, Closed to Oyster Beds; 300,000 Bushels Gone." *The New York Times*, January 30, 1921.
- 5 "Jamaica Bay Oysters Blamed for Typhoid." The New York Times, March 5, 1905.
- 6 "Jamaica Bay, Foul with Sewage, Closed to Oyster Beds; 300,000 Bushels Gone."
- 7 "Housing on the edge: A brief history of Arverne." The Architectural League of New York. Accessed October 16, 2018. https://archleague.org/article/housing-on-the-edge-a-brief-history-of-arverne/
- 8 Plan for New York City 1969: A Proposal. New York City Planning Commission, 1969.
- 9 Colton, GW and CB Colton. Map showing the Route & Connections of the Central Rail Road Extension Company of Long Island. Office of the Librarian of Congress, at Washington, 1973.
- 10 Black, 74.
- 11 A Train service across Jamaica Bay was partially shut down on July 12, 2018, due to flooding during a high spring tide. The USGS tidal gage at Inwood recorded a water elevation of 4.46 feet above NAVD 88 at the time.
- 12 Swanson, Larry, Michael Dorsch, Mario Giampieri, Philip Orton, Adam S Parris, and Eric W Sanderson. "Dynamics of the Biophysical Systems of Jamaica Bay." In *Prospects for Resilience: Insights from New York City's Jamaica Bay.* Island Press, 2016: 72.
- 13 *The Brooklyn Waterworks and Sewers: A Descriptive Memoir.* The Brooklyn Board of Water Commissioners. New York: D. Van Nostrand, 1867.
- 14 Handel, Steven N, John Marra, Christina MK Kaunzinger, V Monica Bricelj, Joanna Burger, Russell L Burke, Merry Camhi, Christina P Colón, Olaf P Jensen, Jake LaBelle, Howard C Rosenbaum, Eric W Sanderson, Matthew D Schlesinger, John R Waldman, and Chester B Zarnoch. "Ecology of Jamaica Bay: History, Status, and Resilience." In Prospects for Resilience: Insights from New York City's Jamaica Bay. Island Press, 2016: 93.
- 15 Black, 75.
- 16 "The Light That Does Not Fail." The New York Times, December 29, 1963.

- 17 This comparison was made using NOAA's Chart No. 540a: Jamaica Bay and Rockaway Inlet, Long Island, New York, issued in 1879 and NOAA's NCEI Bathymetric-Topographic Digital Elevation Models for the U.S. Mid-Atlantic Coast impacted by Hurricane Sandy, issued in 2014 and 2015.
- 18 "Gateway National Recreation Area Jamaica Bay Unit." National Park Service. Accessed October 16, 2018. https://www.nps.gov/gate/planyourvisit/map_jbu.htm
- 19 Swanson et al, 80.

Existing Approaches

- 1 "Improving Transporation, The U.S. Army Corps of Engineers: A Brief History." US Army Corps of Engineers. Accessed October 16, 2018. https://www.usace.army.mil/About/History/Brief-History-of-the-Corps/Improving-Transportation/
- 2 Devlin, John C. "U.S. Survey Sees City Flood Peril." *The New York Times*, October 18, 1961.
- 3 Coastal Risk Reduction and Resilience: Using the Full Array of Measures. US Army Corps of Engineers, 2013.
- 4 See the following US Army Corps of Engineers reports: Atlantic Coast of New York City from East Rockaway Inlet to Rockaway Inlet and Jamaica Bay, New York: Cooperative Beach Erosion Control and Hurricane Sandy Interim Survey Report, April 1964; Atlantic Coast of New York, East Rockaway Inlet to Rockaway Inlet and Jamaica Bay: Draft Integrated Hurricane Sandy General Reevaluation Report and Environmental Impact Statement, August 2016; New York New Jersey Harbor and Tributaries Coastal Storm Risk Management Feasibility Study, October 2017; and Revised Draft, Integrated Hurricane Sandy General Reevaluation Report and Environmental Impact Statement, Atlantic Coast of New York, East Rockaway Inlet to Rockaway Inlet and Jamaica Bay, August 2018.

Projected Flooding

- 1 Lin, Ning and Talea Mayo. "Hurricane Storm Surge Risk Assessment for Structures of Coastal Resilience." In Structures of Coastal Resilience: Phase 1, Context, Site, and Vulnerability Analysis, 2014.
- 2 Lin, Ning, Kerry Emanuel, Michael Oppenheimer, and Erik Varmarcke. "Physically based assessment of hurricane surge threat under climate change." *Nature Climate Change*, 2:6 (2012) 462-467.
- 3 Emmanuel, Kerry, Sai Ravela, Emmanuel Vivant, and Camille Risi. "A statistical deterministic approach to hurricane risk assessment." *Bulletin of the American Meterological Society*, 87:3 (2006) 299-314.
- 4 Kalnay, E, M Kanamitsu, R Kistler, W Collins, D Deaven, L Gandin, M Iredell, S Saha, G White, J Woollen, et al. "The NCEP/NCAR 40-Year Reanalysis Project." Bulletin of the American Meterological Society 77:3 (1996) 437-471.
- 5 Luettich Jr, RA, JJ Westerink, and NW Scheffner. "ADCIRC: An Advanced Three-Dimensional circulation Model for Shelves, Coasts, and Estuaries. Report 1. Theory and Methodology of

- ADCIRC-2ddi and ADCIRC-3dl." Technical report, DTIC Document, 1992; Westerink, JJ, RA Luettich Jr, CA Blain, and NW Scheffner. "ADCIRC: An Advanced Three-Dimensional circulation Model for Shelves, Coasts, and Estuaries. Report 2. Theory and Methodology of ADCIRC-2ddi." Technical report, DTIC Document, 1994.
- 6 Lin, Ning and Talea Mayo, 13.
- Kopp, Robert E, Radley M Horton, Christopher M Little, Jerry X Mitrovica, Michael Oppenheimer, DJ Rasmussen, Benjamin H Strauss, and Claudia Tebaldi. "Probabilistic 21st and 22nd century sealevel projections at a global network of tide-gauge sites," *Earth's Future* 2 (2014) 383-406.
- 8 "Building the Knowledge Base for Climate Resiliency: New York City Panel on Climate Change 2015 Report."

Proposed Approach

- 1 Kopp et al. "Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites."
- 2 "Building the Knowledge Base for Climate Resiliency: New York City Panel on Climate Change 2015 Report."

References

A Stronger, More Resilient New York. The City of New York, Mayor Michael R. Bloomberg, 2013.

Aerts, Jeroen, Wouter Botzen, Malcolm J Bowman, Philip J Ward, and Piet Dircke, eds. *Climate Adaptation and Flood Risk in Coastal Cities*. New York: Earthscan, 2012.

Anarde, Katherine A, Sabarethinam Kameshwar, John N Irza, Jeffrey A Nittrouer, Jorge Lorenzo-Trueba, Jamie E Padgett, Antonia Sebastian, and Philip B Bedient. "Impacts of hurricane storm surge on infrastructure vulnerability for an evolving coastal landscape." *Natural Hazards Review* 19:1 (2018).

Annual Report. Metropolitan Transportation Authority, 2017.

Atlantic Coast of New York City from East Rockaway Inlet to Rockaway Inlet and Jamaica Bay, New York: Cooperative Beach Erosion Control and Hurricane Sandy Interim Survey Report. US Army Corps of Engineers, 1964.

Atlantic Coast of New York City from East Rockaway Inlet to Rockaway Inlet and Jamaica Bay, New York: Beach Erosion Control and Hurricane Protection. US Army Corps of Engineers New York District, 1986.

Atlantic Coast of New York, East Rockaway Inlet to Rockaway Inlet and Jamaica Bay: Draft Integrated Hurricane Sandy General Reevaluation Report and Environmental Impact Statement. US Army Corps of Engineers New York District, 2016.

Black, Frederick R. *Jamaica Bay: A History, Cultural Resource Management Study No. 3.* Washington, DC: National Park Service, US Department of the Interior, 1981.

Blake, Eric S, Todd B Kimberlain, Robert J Berg, John P Cangialosi, and John L Beven II. "Tropical Cyclone Report: Hurricane Sandy, (AL182012), 22 - 29 October 2012." National Hurricane Center, 2013.

Bowron, Tony, Nancy Neatt, Danika van Proosdij, Jeremy Lundholm, and Jennie Graham. "Macro-Tidal Salt Marsh Ecosystem Response to Culvert Expansion." *Restoration Ecology* 19:3 (2009) 307-322.

Breaking New Ground: 2017 Annual Report. The Port Authority of New York and New Jersey, 2017.

Buchanan, Maya, Michael Oppenheimer, and Robert E Kopp. "Amplification of flood frequencies with local sea level rise and emerging flood regimes." *Environmental Research Letters* 12 (2017).

"Building the Knowledge Base for Climate Resiliency: New York City Panel on Climate Change 2015 Report." *Annals of the New York Academy of Sciences* 1336 (2015).

Climate Science Special Report: Fourth National Climate Assessment, Volume I. Wuebbles, DJ, DW Fahey, KA Hibbard, DJ Dokken, BC Steward, and TK Maycock, eds. U.S. Global Change Research Program, Washington, DC.

Coastal Risk Reduction and Resilience: Using the Full Array of Measures. US Army Corps of Engineers, 2013.

Davis, Thomas H. *Birds of Jamaica Bay.* National Park Service, US Department of the Interior: Gateway National Recreation Area, Jamaica Bay Wildlife Refuge, 2014.

Design of Coastal Revetments, Seawalls, and Bulkheads. US Army Corps of Engineers, 1995.

Elliott, Rebecca. "Who Pays for the Next Wave? The American Welfare State and Responsibility for Flood Risk." *Politics and Society* 45:3 (2017) 415-440.

Emmanuel, Kerry, Sai Ravela, Emmanuel Vivant, and Camille Risi. "A statistical deterministic approach to hurricane risk assessment." *Bulletin of the American Meterological Society*, 87:3 (2006) 299-314.

Hallegatte, Stephane, Colin Green, Robert J Nicholls, and Jan Corfee-Morlot. "Future flood losses in major coastal cities." *Nature Climate Change* 3 (2013) 802-806.

Hsiang, Solomon, Robert Kopp, Amir Jina, James Rising, Michael Delgado, Shashank Mohan, DJ Rasmussen, Robert Muir-Wood, Paul Wilson, Michael Oppenheimer, Kate Larsen, and Trevor Hauser. "Estimating economic damage from climate change in the United States." *Science* 356:6345 (2017) 1362-1370.

Hudson-Raritan Estuary Ecosystem Restoration Feasibility Study: Draft Integrated Feasibility Report and Environmental Assessment. US Army Corps of Engineers New York District, 2017.

Info Brief: Flood Risk in NYC, Flood Resilient Construction, and Flood Insurance. New York City Department of City Planning, 2016.

Jamaica Bay Watershed Protection Plan, Volumes I and II. New York City Department of Environmental Protection, 2007.

Jamaica Bay Watershed Protection Plan: 2016 Update. New York City Department of Environmental Protection, 2016.

Kalnay, E, M Kanamitsu, R Kistler, W Collins, D Deaven, L Gandin, M Iredell, S Saha, G White, J Woollen, et al. "The NCEP/NCAR 40-Year Reanalysis Project." *Bulletin of the American Meterological Society* 77:3 (1996) 437-471.

Kaplan, Lawrence and Carol P Kaplan. *Between Ocean and City.* New York: Columbia University Press, 2003.

Keenan, Jesse M and Claire Weisz, eds. *Blue Dunes – Climate Change by Design.* New York: Columbia Books on Architecture and the City, 2016.

Kopp, Robert E, Radley M Horton, Christopher M Little, Jerry X Mitrovica, Michael Oppenheimer, DJ Rasmussen, Benjamin H Strauss, and Claudia Tebaldi. "Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites," *Earth's Future* 2 (2014) 383-406.

Koslov, Liz. "The Case for Retreat." Public Culture 28:2 (2016) 359-387.

Lade, Steven J, Alessandro Tavoni, Simon A Levin, and Maja Schlüter. "Regime shifts in a social-ecological system." *Theoretical Ecology* 6:3 (2013) 359-372.

Lin, Ning, Kerry Emanuel, Michael Oppenheimer, and Erik Varmarcke. "Physically based assessment of hurricane surge threat under climate change." *Nature Climate Change*, 2:6 (2012) 462-467.

Lucev, Emil R. *The Rockaways*. New York: Arcadia Publishing, 2007.

Luettich Jr, RA, JJ Westerink, and NW Scheffner. "ADCIRC: An Advanced Three-Dimensional circulation Model for Shelves, Coasts, and Estuaries. Report 1. Theory and Methodology of ADCIRC-2ddi and ADCIRC-3dl." Technical report, DTIC Document, 1992.

Marsooli, Reza, Philip M Orton, and George Mellor. "Modelling wave attentuation by salt marshes in Jamaica Bay, New York, using a new rapid wave model." *Journal of Geophysical Research: Oceans* 122 (2017) 1-19.

New York - New Jersey Harbor and Tributaries Coastal Storm Risk Management Feasibility Study. US Army Corps of Engineers New York District, 2017.

NY Rising Community Reconstruction Committee Plans. Governor's Office of Storm Recovery, Governor Andrew Cuomo, 2013.

One New York: The Plan for a Strong and Just City. The City of New York, Mayor Bill de Blasio, 2015.

Plan for New York City 1969: A Proposal. New York City Planning Commission, 1969.

Pleister, Eric-Jan and Cees van der Veeken. *Dutch Dikes*. Rotterdam: nai010, 2014. Sanderson, Eric W, William D Solecki, John R Waldman, and Adam S Parris, eds. *Prospects for Resilience: Insights from New York City's Jamaica Bay.* Washington, DC: Island Press, 2016.

Rebuild by Design. Department of Housing and Urban Development, 2015.

Resilient Edgemere: Community Plan. New York City Department of Housing Preservation and Development, 2017.

Resilient Neighborhoods. New York City Department of City Planning, 2013.

Revised Draft Integrated Hurricane Sandy General Reevaluation Report and Environmental Impact Statement: Atlantic Coast of New York, East Rockaway Inlet to Rockaway Inlet and Jamaica Bay. US Army Corps of Engineers New York District, 2018.

Seavitt Nordenson, Catherine, Guy Nordenson, and Julia Chapman. *Structures of Coastal Resilience*. Washington, DC: Island Press, 2018.

Seeking Higher Ground: How to Break the Cycle of Repeated Flooding with Climate-Smart Insurance Reforms. Natural Resources Defense Council, 2017.

Structures of Coastal Resilience: Phase 1, Context, Site, and Vulnerability Analysis. Princeton University, Harvard University, City College of New York, and University of Pennsylvania, 2014.

Sutton-Grier, Ariana E, Kateryna Wowk, and Holly Bamford. "Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems." *Environmental Science and Policy* 51 (2015) 137-148.

The Brooklyn Waterworks and Sewers: A Descriptive Memoir. The Brooklyn Board of Water Commissioners. New York: D. Van Nostrand, 1867.

The Fourth Regional Plan for the New York-New Jersey-Connecticut Metropolitan Area: Making the Region Work for All of Us. Regional Plan Association, 2017.

Urban Coastal Resilience: Valuing Nature's Role, Case Study: Howard Beach, Queens, New York. The Nature Conservancy, 2015.

Urban Waterfront Adaptive Strategies. The City of New York and the Department of City Planning, 2013.

van der Ree, Rodney, Danial J Smith, and Clara Grilo. *Handbook of Road Ecology.* New York: John Wiley and Sons, 2015.

Westerink, JJ, RA Luettich Jr, CA Blain, and NW Scheffner. "ADCIRC: An Advanced Three-Dimensional circulation Model for Shelves, Coasts, and Estuaries. Report 2. Theory and Methodology of ADCIRC-2ddi." Technical report, DTIC Document, 1994.

Williams Walsh, Mary. "A Broke, and Broken, Flood Insurance Program." *The New York Times*, November 4, 2017.

Xian, Siyuan, Ning Lin, and Adam Hatzikyriakou. "Storm surge damage to residential areas: a quantitative analysis for Hurricane Sandy in comparison with FEMA flood map." *Natural Hazards* 79:3 (2015).

Yin, Jie, Ning Lin, and Dapeng Yu. "Coupled modeling of storm surge and coastal inundation: A case study in New York City during Hurricane Sandy." *Water Resources Research* 52 (2016).

A man collects shellfish on exposed mudflats near Bayswater Point during a low spring tide in 2018. Spartina Alterniflora marsh grasses and a layer of Ulva sea lettuce algae are seen in the foreground, marsh islands and mudflats in the middle ground, and the skyline of Manhattan in the distance.

